(Subbe et al., 'Effect of introducing the Modified Early Warning score on clinical outcomes, cardio-pulmonary arrests and intensive care utilization in acute medical admissions', *Anaesthesia* 2003; 58: 797-802). Goldhill et al. reported that 21% of ward patients with a RR of 25–29 breaths/minute assessed by a critical care outreach service died in hospital (Goldhill et al., 'A physiologically-based early warning score for ward patients: the association between score and outcome', *Anaesthesia* 2005; 60: 547-553). Those with a higher RR had even higher mortality rates. In another study, just over half of all patients suffering a serious adverse event on the general wards (e.g. a cardiac arrest or ICU admission) had a RR greater than 24 breaths/minute. These patients could have been identified as high risk up to 24 hours before the event with a specificity of over 95% (Cretikos et al., 'The Objective Medical Emergency Team Activation Criteria: a case–control study', *Resuscitation* 2007; 73: 62-72). Medical references such as these clearly indicate that an accurate, easy-to-use device for measuring RR is an important component for patient monitoring within the hospital.

[0009] Despite its importance and the large number of available monitoring techniques, RR is notoriously difficult to measure, particularly when a patient is moving. During periods of motion, non-invasive techniques based on IP and PPG signals are usually overwhelmed by artifacts, and thus completely ineffective. This makes it difficult or impossible to measure RR from an ambulatory patient. Measurements based on et-CO2 are typically less susceptible to motion, but require a plastic tube inserted in the patient's mouth, which is uncomfortable and typically impractical for ambulatory patients.

SUMMARY OF THE INVENTION

[0010] This invention provides a technique for measuring RR using multiple input signals, including IP and accelerometer waveforms (ACC). After being measured with a

triggers a false alarm. Such a situation can be avoided with an independent measurement of motion, such as that described herein. Other heuristic rules based on analysis of ACC waveforms may also be deployed according to this invention.

[0014] Sensors attached to the wrist and bicep each measure signals that are collectively analyzed to estimate the patient's arm height; this can be used to improve accuracy of a continuous blood pressure measurement (cNIBP), as described below, that measures systolic (SYS), diastolic (DIA), and mean (MAP) arterial blood pressures. And the sensor attached to the patient's chest measures signals that are analyzed to determine posture and activity level, which can affect measurements for RR, SpO2, cNIBP, and other vital signs. Algorithms for processing information from the accelerometers for these purposes are described in detail in the following patent applications, the contents of which are fully incorporated herein by reference: BODY-WORN MONITOR FEATURING ALARM SYSTEM THAT PROCESSES A PATIENT'S MOTION AND VITAL SIGNS (U.S.S.N 12/469,182; filed May 20, 2009) and BODY-WORN VITAL SIGN MONITOR WITH SYSTEM FOR DETECTING AND ANALYZING MOTION (U.S.S.N 12/469,094; filed May 20, 2009). As described therein, knowledge of a patient's motion, activity level, and posture can greatly enhance the accuracy of alarms/alerts generated by the body-worn monitor.

[0015] The body-worn monitor features systems for continuously monitoring patients in a hospital environment, and as the patient transfers from different areas in the hospital, and ultimately to the home. Both SpO2 and cNIBP rely on accurate measurement of PPG and ACC waveforms, along with an ECG, from patients that are both moving and at rest. cNIBP is typically measured with the 'Composite Technique', which is described in detail in the co-pending patent applications entitled: VITAL SIGN MONITOR FOR MEASURING BLOOD PRESSURE USING OPTICAL, ELECTRICAL, AND

applications, the contents of which have been previously incorporated herein by reference.

[0018] In one aspect, the invention features a system for measuring RR from a patient. The system includes an IP sensor, connected to at least two electrodes, and a processing system that receives and processes signals from the electrodes to measure an IP signal. The electrodes can connect to the IP sensor through either wired or wireless means. A motion sensor (e.g. an accelerometer) measures at least one motion signal (e.g. an ACC waveform) describing movement of a portion of the patient's body to which it is attached. The processing system receives the IP and motion signals, and processes them to determine, respectfully, frequency-domain IP and motion spectra. Both spectra are then collectively processed to remove motion components from the IP spectrum and determine RR. For example, during the processing, an algorithm determines motion frequency components from the frequency-domain motion spectrum, and then using a digital filter removes these, or parameters calculated therefrom, from the IP spectrum.

[0019] In embodiments, a single sensor module, adapted to be worn on the patient's torso, encloses both the IP sensor and the motion sensor. The sensor module typically includes at least one analog-to-digital converter configured to digitize the IP signal; this component may be integrated directly into a single-chip circuit (e.g. an application-specific integrated circuit, or ASIC), or in a circuit consisting of a collection of discrete components (e.g. individual resistors and capacitors). The sensor module can also include at least one analog-to-digital converter configured to digitize the motion signal. Similarly, this component can be integrated directly into the accelerometer circuitry. Digitizing the IP and motion signals before transmitting them to the processing system has several advantages, as described in detail below.

[0020] In other embodiments, the sensor module includes a temperature sensor for measuring the patient's skin temperature, and an ECG circuit (corresponding to a three, five, or twelve-lead ECG) for measuring an ECG waveform. In embodiments, the sensor module simply rests on the patient's chest during a measurement, or can be connected with a small piece of medical tape. Alternatively, the housing features a connector that connects directly to an ECG electrode worn on the patient's torso.

[0021] The processing system is typically worn on the patient's wrist. Alternatively, this system can be within the sensor module, or within a remote computer server (located, e.g., in a hospital's IT system). Typically a wireless transceiver (e.g. a transceiver based on 802.11 or 802.15.4 transmission protocols) is included in the system, typically within the processing module. Such a transceiver, for example, can wirelessly transmit IP and ACC waveforms to a remote processing system for further analysis. In this case, the processing system is further configured to wireless transmit a RR value back to a second processor worn on the patient's body, where it can then be displayed (using, e.g., a conventional display).

[0022] Accelerometers used within the system typically generate a unique ACC waveform corresponding to each axis of a coordinate system. In embodiments the system can include three accelerometers, each worn on a different portion of the patient's body. Waveforms generated by the accelerometers can then be processed as described in detail below to determine the patient's posture.

[0023] In another aspect, the invention features an algorithm, typically implemented using compiled computer code, a computer memory, and a microprocessor, that processes IP and ACC waveforms by calculating their power spectra by way of a Fourier transform (e.g. a fast Fourier transform, of FFT). The algorithm then determines motion components from the frequency-dependent ACC spectrum, and using a digital filter

removes these, or components calculated therefrom, from the frequency-dependent IP spectrum. This yields a processed, frequency-dependent IP spectrum which can then be analyzed as described in detail below to estimate RR, even when large amounts of motion-induced noise are evident on the IP signal.

[0024] In embodiments, power spectra for both the IP and ACC waveforms are calculated from a complex FFT that includes both real and imaginary components. In other embodiments, alternative mathematical transforms, such as a Laplace transform, can be used in place of the FFT.

[0025] To determine a digital filter from the ACC power spectrum, the algorithm typically includes a method for first finding a peak corresponding to one or more frequencies related to the patient's motion. A bandpass filter, characterized by a passband which filters out these (and related) frequencies, is then generated and used to process the IP spectrum. Alternatively, these frequencies can simply be divided or subtracted from the IP spectrum. In all cases, this yields a processed IP spectrum which is then further analyzed to determine a frequency corresponding to RR. Analysis can include smoothing, averaging, or related methodologies uses to extract a single frequency, corresponding to RR, from a collection of frequencies. In embodiments, the algorithm can also include a component that generates an alarm if the patient's RR is greater than a first pre-determined threshold, or less than a second pre-determined threshold. The alarm can be generated by considering both the patient's RR and posture.

[0026] In another aspect, the invention features a multi-component algorithm for determining RR. The multi-component algorithm first determines a motion parameter from the ACC waveform. The motion parameter indicates the patient's degree of motion, activity level, or posture. Based on the motion parameter, the multi-component algorithm then selects one of the following algorithms to process one or both of the ACC and IP

waveforms to determine RR: i) a first algorithm featuring counting breathing-induced pulses in the IP waveform; and ii) a second algorithm featuring collectively processing both the ACC and IP waveform to determine a digital adaptive filter, and then processing one of these waveforms with the adaptive filter to determine RR; and iii) a third algorithm featuring mathematically transforming both the ACC and IP waveforms into frequency-domain spectra, and then collectively processing the spectra to determine RR. Typically the first, second, and third algorithms are deployed, respectively, when the motion parameter indicates the patient's motion is non-existent, minimal, or large. For example, the first algorithm is typically deployed when the patient is resting; the second algorithm deployed when the patient is moving about somewhat; and the third algorithm deployed when the patient is standing up, and possibly walking or even running.

[0027] In another aspect, the multi-component algorithm is deployed on one or more microprocessors associated with the system. For example, to conserve battery life of the body-worn monitor, numerically intensive calculations (such as the FFT or those used to generate the digital filter) can be performed on a remote server; intermediate or final parameters associated with these calculations can then be wirelessly transmitted back to the body-worn monitor for further processing or display. In another embodiment, portions of the multi-component algorithm can be carried out by microprocessors located in both the wrist-worn transceiver and chest-worn sensor module. The microprocessors can communicate through serial or wireless interfaces. This latter approach will have little impact on battery life, but can reduce processing time by simultaneously performing different portions of the calculation.

[0028] In another aspect, the invention provides a method for measuring RR from a patient using an algorithm based on a digital adaptive filter. In this approach, the body-worn monitor measures both IP and ACC waveforms as described above. The waveforms

are then collectively processed to determine a set of coefficients associated with the adaptive filter. Once calculated, the coefficients are stored in a computer memory. At a later point in time, the monitor measures a second set of IP and ACC waveforms, and analyzes these to determine a motion parameter. When the motion parameter exceeds a pre-determined threshold, the algorithm processes the set of coefficients and the latest IP waveform to determine a processed IP waveform, and then analyzes this to determine RR.

[0029] In embodiments, the digital adaptive filter is calculated from an impulse response function, which in turn is calculated from either a FIR function or an autoregressive moving average model. The order of the adaptive filter calculated from the impulse response function is typically between 20 and 30, while the order of the filter calculated from the autoregressive moving average model is typically between 1 and 5. A specific mathematic approach for calculating the digital adaptive filter is described below with reference to Eqs. 1-16. As described above, the coefficients can be calculated using a microprocessor located on the wrist-worn transceiver, sensor module, or a remote server.

[0030] In yet another aspect, the invention provides a system for measuring RR featuring a sensor module configured to be worn on the patient's torso. The sensor module includes sensors for measuring both IP and ACC waveforms, and a serial transceiver configured to transmit the digital signals through a cable to a wrist-worn processing system. This system features a connector that receives the cable, and a processor that receives digital signals from the cable and collectively processes them with a multi-component algorithm to determine RR. In embodiments, the sensor module digitally filters the IP and ACC waveforms before they pass through the cable. The cable can also include one or more embedded accelerometers, and is configured to attach to the patient's arm.

[0031] In all embodiments, the wrist-worn transceiver can include a display configured to render the patient's RR and other vital signs, along with a touchpanel interface. A wireless transceiver within the wrist-worn transceiver can transmit information to a remote computer using conventional protocols such as 802.11, 802.15.4, and cellular (e.g. CDMA or GSM). The remote computer, for example, can be connected to a hospital network. It can also be a portable computer, such as a tablet computer, personal digital assistant, or cellular phone.

[0032] Many advantages are associated with this invention. In general, it provides an accurate measurement of RR, along with an independent measurement of a patient's posture, activity level, and motion. These parameters can be collectively analyzed to monitor a hospitalized patient and improve true positive alarms while reducing the occurrence of false positive alarms. Additionally, the measurement of RR is performed with a body-worn monitor that is comfortable, lightweight, and low-profile, making it particularly well suited for ambulatory patients. Such a monitor could continuously monitor a patient as, for example, they transition from the emergency department to the ICU, and ultimately to the home after hospitalization.

[0033] Still other embodiments are found in the following detailed description of the invention and in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] Fig. 1 shows a schematic view of a patient wearing a sensor module on their chest that connects to three electrodes arranged in an Einthoven's triangle configuration and measures both ACC and IP waveforms;

[0035] Fig. 2 shows a schematic view of a patient wearing a sensor module on their belly that connects to three electrodes arranged in an Einthoven's triangle configuration and measures both ACC and IP waveforms;

[0036] Fig. 3A is a schematic view of a patient wearing an alternate embodiment of the invention featuring a sensor module for measuring IP and ACC waveforms that connects directly through an electrode to the patient's belly;

[0037] Fig. 3B is a schematic, cross-sectional view of the sensor module of Fig. 3A connected to the patient's belly with the electrode;

[0038] Figs. 4A and 4B show, respectively, a three-dimensional image of the body-worn monitor of the invention attached to a patient during and after an initial indexing measurement;

[0039] Fig. 5 shows a three-dimensional image of the wrist-worn transceiver used with the body-worn monitor from Figs. 4A and 4B;

[0040] Fig. 6 shows a schematic view of a multi-component algorithm used to collectively process ACC and IP waveforms to measure RR according to the invention;

[0041] Fig. 7 shows a schematic drawing of Algorithm 1 used in the multi-component algorithm of Fig. 6;

[0042] Fig. 8 shows a schematic drawing of computation steps used in Algorithm 1 to calculate RR;

[0043] Fig. 9 shows a series of time-dependent IP waveforms (left-hand side) and their corresponding mathematical derivatives (right-hand side) measured from a slowly breathing patient and processed with digital filters featuring gradually decreasing passbands;

[0044] Fig. 10 shows a series of time-dependent IP waveforms (left-hand side) and their corresponding mathematical derivatives (right-hand side) measured from a rapidly breathing patient and processed with digital filters featuring gradually decreasing passbands;

simultaneously measures acceleration (e.g. motion) along x, y, and z axes of a local coordinate system, such as that shown in Fig. 29. As shown in this figure, and described in more detail below, the accelerometer 12 is preferably aligned so the z axis points into the patient's torso. Within the accelerometer 12 is an internal analog-to-digital converter that generates a digital ACC waveform corresponding to each axis.

[0074] Also within the sensor module 25 is a microprocessor 33 and analog-to-digital converter (not shown in the figure) that digitize the IP and ACC waveforms, and sends them through a serial protocol (e.g. the control area network, or CAN protocol) to the wrist-worn transceiver for further processing. There, IP and ACC waveforms are processed with the multi-component algorithm to determine the patient's RR. Alternatively, the algorithms can be performed in part with a remote server, or with the microprocessor 33 mounted within the sensor module. Additional properties such as the patient's posture, degree of motion, and activity level are determined from these same digital ACC waveforms. The axis within the accelerometer's coordinate system that is aligned along the patient's torso (and thus orthogonal to their respiration-induced torso movement) is typically more sensitive to events not related to respiration, e.g. walking and falling.

[0075] In a preferred embodiment, digital accelerometers manufactured by Analog Devices (e.g. the ADXL345 component) are used in the configuration shown in Fig. 1. These sensors detect acceleration over a range of +/-2 g (or, alternatively, up to +/-8 g) with a small-scale, low-power circuit.

[0076] Many patient's are classified as 'belly breathers', meaning during respiration their belly undergoes larger movements than their chest. A relative minority of patients are 'chest breathers', indicating that it is the chest that undergoes the larger movements. For this reason it is preferred that RR is determined using an ACC waveform detected

generated by different sensors. This includes multiple ECG waveforms (corresponding, e.g., to vectors associated with three, five, and twelve-lead ECG systems) from the ECG circuit 26, the IP waveform from the IP circuit 27, and ACC waveforms associated with the x, y, and z axes of accelerometers 10, 12 attached to the patient's chest. Limiting the transmission line to a single cable reduces the number of wires attached to the patient, thereby decreasing the weight and cable-related clutter of the body-worn monitor. Second, cable motion induced by an ambulatory patient can change the electrical properties (e.g. electrical impendence) of its internal wires. This, in turn, can add noise to an analog signal and ultimately the vital sign calculated from it. A digital signal, in contrast, is relatively immune to such motion-induced artifacts. More sophisticated ECG circuits can plug into the wrist-worn transceiver to replace the three-lead system shown in Figs. 1 and 2. These ECG circuits, for example, can include, e.g., five and twelve leads.

[0080] Digital data streams are typically transmitted to the wrist-worn transceiver using a serial protocol, such as the CAN protocol, USB protocol, or RS-232 protocol. CAN is the preferred protocol for the body-worn monitor described in Figs. 4A, 4B.

[0081] Multi-Component Algorithm for Determining RR

[0082] Fig. 6 shows an overview of a multi-component algorithm 149, implemented with the body-worn monitor shown in Figs. 4A, 4B, and 5 and an accompanying server, which determines a patient's RR according to the invention. The algorithm features the following components for determining RR from a hospitalized patient undergoing different levels of motion:

Algorithm 1 – simple peak-counting calculation implemented on the wrist-worn transceiver; used when patient motion is minimal or non-existent

Algorithm 2 – adaptive filtering calculation with filtering parameters calculated on the wrist-worn transceiver; used when some patient motion is evident

sampled at the same rate. If the IP waveform is sampled at a higher frequency than that used for the ACC waveform (e.g. 50 Hz), then this waveform must be converted into a 50 Hz waveform using conventional mathematical techniques, such as decimation or a numerical 'mapping' operation.

[0101] At this point zero mean input and output signals for u[i] and y[i] are constructed by subtracting the ensemble signal mean from each signal. This operation, shown below in Eqs. 2 and 3, effectively removes any DC offset (step 252).

$$u[i] = u[i] - \left(\frac{1}{N}\right)\sum_{k=1}^{N} u[k] \tag{2}$$

$$y[i] = y[i] - \left(\frac{1}{N}\right)\sum_{k=1}^{N} y[k] \tag{3}$$

[0102] A mathematical model used to define the impulse response function of the adaptive filter must be chosen, with the two primary options being filters based on FIR (finite impulse response) or ARMA (autoregressive moving average) models. Both models are indicated below in Eqs. 4 and 5, but only one should be chosen and implemented during the algorithm (step 254):

FIR Model

$$H[z] = b_0 + b_1 z^{-1} + \cdots + b_L z^{-L} \tag{4}$$

ARMA Model

$$H[z] = \frac{b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-p}} \tag{5}$$

At this point the order of the filter is determined. For the FIR model, the order is L; for the ARMA model, the order is m and p. In a preferred embodiment, the orders for L, m, and p are, respectively, 25, 2, and 2; these values may vary depending on the degree of motion and the computational capabilities on the wrist-worn transceiver. A column

[0122] Fig. 26 shows an alternate embodiment of the invention wherein a rolling average is used in place of the smoothing filter described above with reference to Fig. 25. Here, the rolling average is gradually increased from 0 points (Fig. 26A, at the top of the page) to 100 points. When the average is increased above about 20 points the features in the frequency spectrum begin to blend together to form a well-defined peak that can be easily analyzed using the peak-finding algorithm referenced above.

[0123] Referring to Figs. 27 and 28, the number of time-domain samples used to calculate an associated Fourier Transform and power spectrum will have a significant influence on the resolution of the power spectrum. In general, increasing the number of time-domain samples will increase resolution in the power spectrum. According to this invention, the frequency-domain resolution can be arbitrarily increased by adding constant values to the time-domain ACC and IP waveform. In this technique, typically called 'zero padding', the constant values are typically 0, or alternatively a constant value.

[0124] Both Fig. 27 and 28 show a time-domain IP waveform (Figs. 27A and 28A, shown at the top of the page) along with associated power spectra calculated, respectively, using 1000 points (Figs. 27B, 28B), 500 points (Fig. 27C, 28C), and 250 points (Fig. 27D, 28D). The IP waveform for this figure was sampled at 25 Hz, and thus the time-domain markers that correspond to the above-mentioned points are indicated by a light gray circle (1000 points), a dark gray circle (500 points), and a black circle (250 points). As shown in Figs. 27B, 28B, 27C, 28C, power spectra determined with both 1000-point and 500-point Fourier Transforms feature roughly the same frequency profile, with, as expected, the 1000-point spectra showing relatively greater resolution. Power spectra calculated from the 250-point Fourier Transform show one or more very broad peaks, and, importantly, undergo a frequency shift which trends toward higher frequencies for the dominant peak. Such a frequency shift will result in an erroneous

determined using DC signals from the accelerometers 413, 414 disposed, respectively, on the patient's bicep and wrist. Posture, in contrast, can be exclusively determined by the accelerometer 412 worn on the patient's chest. An algorithm operating on the wrist-worn transceiver extracts DC values from waveforms measured from this accelerometer and processes them with an algorithm described below to determine posture.

[0127] Specifically, torso posture is determined for a patient 410 using angles determined between the measured gravitational vector and the axes of a torso coordinate space 411. The axes of this space 411 are defined in a three-dimensional Euclidean space where $\vec{R}_{CV}$ is the vertical axis, $\vec{R}_{CH}$ is the horizontal axis, and $\vec{R}_{CN}$ is the normal axis. These axes must be identified relative to a 'chest accelerometer coordinate space' before the patient's posture can be determined.

[0128] The first step in determining a patient's posture is to identify alignment of $\vec{R}_{CV}$ in the chest accelerometer coordinate space. This can be determined in either of two approaches. In the first approach, $\vec{R}_{CV}$ is assumed based on a typical alignment of the body-worn monitor relative to the patient. During a manufacturing process, these parameters are then preprogrammed into firmware operating on the wrist-worn transceiver. In this procedure it is assumed that accelerometers within the body-worn monitor are applied to each patient with essentially the same configuration. In the second approach, $\vec{R}_{CV}$ is identified on a patient-specific basis. Here, an algorithm operating on the wrist-worn transceiver prompts the patient (using, e.g., video instruction operating on the wrist-worn transceiver, or audio instructions transmitted through a speaker) to assume a known position with respect to gravity (e.g., standing upright with arms pointed straight down). The algorithm then calculates $\vec{R}_{CV}$ from DC values corresponding to the x, y, and z axes of the chest accelerometer while the patient is in this position. This case, however, still requires knowledge of which arm (left or right) the monitor is worn on, as the chest

[0156] Figs. 3A, 3B show yet another alternate embodiment of the invention wherein a sensor module 25 attaches to the belly of a patient 10 using an electrode 24 normally attached to the lower left-hand portion of the patient's torso. Specifically, the sensor module 25 includes a connector 253 featuring an opening that receives the metal snap or rivet present on most disposable ECG electrodes. Connecting the connector 253 to the electrode's rivet holds the sensor module 25 in place. This configuration reduces the number of cables in the body-worn monitor, and additionally secures an accelerometer 12 to the patient's belly. This is typically the part of their torso that undergoes the greatest motion during respiration, and thus generates ACC waveforms with the highest possible signal-to-noise ratio. Also contained within the sensor module 25 are the ECG circuit 26, the IP circuit 27, microprocessor 33, and a temperature sensor 34.

[0157] To measure IP and ECG waveforms, the sensor module 25 connects through cables to electrodes 20, 22 attached, respectively, to the upper right-hand and left-hand portions of the patient's torso. This system measures RR using the peak counting, adaptive filtering, and FFT-based approaches described above, and has the additional advantage of measuring a relatively large ACC signals indicating respiration-induced motions of the patient's belly. As described above, these signals are typically generated by the z-axis of the accelerometer 12, which is normal to the patient's torso. ACC signals along the x and y-axes can be additionally processed to determine the patient's posture and activity level, as described above. Once RR and these motion-related properties are measured, a transceiver in the sensor module (not shown in the figure) transmits them in the form of a digital data stream through a cable to the wrist-worn transceiver for further processing.

[0158] Still other embodiments are within the scope of the following claims.

What is claimed is:

1. A system for measuring respiratory rate from a patient, comprising:

an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography sensor comprising a processing circuit configured to process signals from the at least two electrodes to measure an impedance pneumography signal from the patient;

a motion sensor connected to the patient and configured to measure at least one motion signal corresponding to motion of a portion of the patient's body to which it is attached; and

a processing system configured to receive the impedance pneumography signal and process it to determine a frequency-domain impedance pneumography spectrum, and to receive the motion signal and process it to determine a frequency-domain motion spectrum, the processing system further configured to collectively process both the impedance pneumography spectrum and motion spectrum to remove motion components from the impedance pneumography spectrum and then determine respiratory rate.

2. A system for measuring respiratory rate from a patient, comprising:

an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography sensor comprising a processing circuit configured to process signals from the at least two electrodes to measure an impedance pneumography signal from the patient;

a motion sensor connected to the patient and configured to measure at least one motion signal corresponding to motion of a portion of the patient's body to which it is attached; and

a processing system, worn on the patient's body and connected to the impedance pneumography sensor and the motion sensor, the processing system configured to: i)

receive the impedance pneumography signal from the impedance pneumography sensor and process it to determine a frequency-domain impedance pneumography spectrum; ii) receive the motion signal from the motion sensor and process it to determine a frequency-domain motion spectrum; iii) determine motion frequency components from the frequency-domain motion spectrum; iv) remove frequency components from the impedance pneumography spectrum corresponding to the motion frequency components to generate a processed frequency-domain impedance pneumography spectrum; and v) analyze the processed frequency-domain impedance pneumography spectrum to determine respiratory rate.

3. A system for determining respiratory rate values for a patient, comprising:

a first sensor, configured to worn on the patient's torso, comprising an impedance pneumography sensor;

a second sensor, configured to be worn on the patient's torso, comprising an accelerometer;

a processing system, configured to be worn on the patient's body and operably connect to both the first and second sensors, the processing system configured to determine a respiratory rate value by calculating a frequency-domain transform of signals from both the first and second sensors, and then removing motion components determined from the frequency-domain transform of one signal from the frequency-domain transform of the other signal.

4. A system for determining respiratory rate values for a patient, comprising:

a first sensor, configured to worn on the patient's torso, comprising an impedance pneumography sensor;

a second sensor, configured to be worn on the patient's torso, comprising an accelerometer;

a processing system, configured to be worn on the patient's wrist and operably connect to the first and second sensors, the processing system configured to determine a respiratory rate value by collectively processing frequency-domain spectra of signals from both the first and second sensors.

5. The system of claim 1, further comprising a sensor module that comprises both the impedance pneumography sensor and the motion sensor.

6. The system of claim 5, wherein the sensor module is configured to be worn on the patient's torso.

7. The system of claim 6, wherein the sensor module comprises at least one analog-to-digital converter configured to digitize the impedance pneumography signal.

8. The system of claim 7, wherein the sensor module comprises at least one analog-to-digital converter configured to digitize the motion signal.

9. The system of claim 8, further comprising a serial transceiver configured to transmit digitized versions of the impedance pneumography signal and motion signal to the processing system.

10. The system of claim 9, wherein the processing system is configured to be worn on the patient's wrist.

11. The system of claim 8, wherein the sensor module comprises the processing system.

12. The system of claim 8, further comprising a wireless transceiver.

13. The system of claim 12, wherein the processing system is remote from the patient, and the wireless transceiver is configured to wirelessly transmit digitized versions of the impedance pneumography signal and motion signal to the processing system.

14. The system of claim 13, wherein the processing system is further configured to wireless transmit a value describing respiratory rate to a second processor worn on the patient's body.

15. The system of claim 14, wherein the second processor is configured to display the value describing respiratory rate on the patient's body.

16. The system of claim 1, wherein the motion sensor is an accelerometer.

17. The system of claim 16, wherein the accelerometer is configured to generate a unique motion waveform for each axis of a coordinate system.

18. The system of claim 17, wherein the processing system is further configured to process each unique motion waveform to determine a posture corresponding to the patient.

19. The system of claim 5, wherein the sensor module further comprises a temperature sensor.

20. The system of claim 5, wherein the sensor module further comprises a sensor for measuring an electrocardiogram.

21. The system of claim 5, wherein the sensor module comprises a housing, the housing comprising a connector that connects directly to an electrode worn on the patient's torso.

22. A method for measuring respiratory rate from a patient, comprising the following steps:

(a) measuring a time-dependent impedance pneumography signal from the patient with an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography signal representing a time-dependent capacitance change in the patient's torso;

(b) measuring at least one time-dependent motion signal with a motion sensor connected to the patient, the at least one motion signal corresponding to motion of a portion of the patient's body to which the motion sensor is attached;

(c) transforming the time-dependent impedance pneumography signal into a frequency-dependent impedance pneumography spectrum;

(d) transforming the time-dependent motion signal into a frequency-dependent motion spectrum;

(e) determining motion components from the frequency-dependent motion spectrum that correspond to the patient's motion;

(f) removing the motion components, or components calculated therefrom, from the frequency-dependent impedance pneumography spectrum to generate a processed frequency-dependent impedance pneumography spectrum; and

(g) analyzing the processed frequency-dependent impedance pneumography spectrum to determine the patient's respiratory rate.

23. A method for determining a respiratory rate value from a patient, comprising the following steps:

(a) measuring a first time-dependent signal by detecting a modulated electrical current passing through the patient's torso;

(b) measuring a second time-dependent signal by detecting movements in the patient's torso with at least one motion sensor;

(c) transforming the first time-dependent signal into a first frequency-domain signal and the second time-dependent signal into a second frequency-domain signal;

(d) determining a motion-related event not related to the patient's respiratory rate value by analyzing the second frequency-domain signal; and

(e) collectively processing both the first and second frequency-domain signals to remove motion artifacts from the first frequency-domain signal to determine the respiratory rate value.

24. A method for determining a respiratory rate value from a patient, comprising the following steps:

(a) measuring at least one electrical signal affected by both respiratory rate and motion with a first sensor;

(b) measuring a motion signal affected by the patient's motion with a second sensor;

(c) transforming the motion signal into the frequency domain to determine frequency components corresponding to the patient's motion; and

(d) removing the frequency components corresponding to the patient's motion from a transform of the at least one electrical signal to determine a respiratory rate value for the patient.

25. The method of claim 22, wherein step (c) comprises taking a Fourier Transform of the time-dependent impedance pneumography signal.

26. The method of claim 25, wherein step (c) comprises calculating a power spectrum of the time-dependent impedance pneumography signal.

27. The method of claim 22, wherein step (d) comprises calculating a Fourier Transform of the time-dependent motion signal.

28. The method of claim 27, wherein step (d) comprises calculating a power spectrum of the time-dependent motion signal.

29. The method of claim 22, wherein step (e) comprises calculating a peak in the frequency-dependent motion spectrum, the peak corresponding to the motion components.

30. The method of claim 29, further comprising processing the peak in the frequency-dependent motion spectrum to determine a digital filter.

31. The method of claim 30, further comprising determining a passband for the digital filter by processing the peak in the frequency-dependent motion spectrum, the passband configured to pass frequency components lying therein.

32. The method of claim 31, wherein step (f) further comprising processing the frequency-dependent impedance pneumography spectrum with the digital filter to remove motion components and generate the processed frequency-dependent impedance pneumography spectrum.

33. The method of claim 29, wherein step (f) comprises subtracting the motion components from the frequency-dependent impedance pneumography spectrum to generate the processed frequency-dependent impedance pneumography spectrum.

34. The method of claim 29, wherein step (f) comprises dividing the motion components from the frequency-dependent impedance pneumography spectrum to generate the processed frequency-dependent impedance pneumography spectrum.

35. The method of claim 30, wherein step (f) further comprises processing the frequency-dependent impedance pneumography spectrum with a smoothing function after applying the digital filter to generate the processed frequency-dependent impedance pneumography spectrum.

36. The method of claim 30, wherein step (f) further comprises processing the frequency-dependent impedance pneumography spectrum with an averaging function after applying the digital filter to generate the processed frequency-dependent impedance pneumography spectrum.

37. The method of claim 30, wherein step (g) further comprises analyzing the processed frequency-dependent impedance pneumography spectrum to determine a spectral peak, the spectral peak corresponding to the patient's respiratory rate.

38. The method of claim 22, wherein the motion sensor is an accelerometer.

39. The method of claim 38, wherein the accelerometer is configured to generate a unique motion waveform for each axis of a coordinate system.

40. The method of claim 39, further comprising processing each unique motion waveform to determine a posture corresponding to the patient.

41. The method of claim 30, further comprising generating an alarm if the patient's respiratory rate is greater than a first pre-determined threshold, or less than a second pre-determined threshold.

42. The method of claim 41, further comprising processing the patient's respiratory rate and the posture corresponding to the patient to generate the alarm.

43. A method for measuring respiratory rate from a patient, comprising the following steps:

(a) measuring an impedance pneumography signal from the patient with an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography signal representing a time-dependent capacitance change in the patient's torso;

(b) measuring at least one motion signal with a motion sensor connected to the patient, the at least one motion signal corresponding to motion of a portion of the patient's body to which the motion sensor is attached;

(c) analyzing the motion signal to determine a motion parameter; and

(d) based on the motion parameter, selecting one of the following algorithms to process at least one of the motion and impedance pneumography signals to determine the patient's respiratory rate: i) a first algorithm comprising a step for counting breathing-induced pulses in the impedance pneumography signal to determine respiratory rate; and ii) a second algorithm comprising collectively processing both the motion signal and impedance pneumography signal to determine a digital filter, and then processing one of the motion signal and impedance pneumography signal with the digital filter to determine respiratory rate.

44. A method for measuring respiratory rate from a patient, comprising the following steps:

(a) measuring an impedance pneumography signal from the patient with an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography signal representing a time-dependent capacitance change in the patient's torso;

(b) measuring at least one motion signal with a motion sensor connected to the patient, the at least one motion signal corresponding to motion of a portion of the patient's body to which the motion sensor is attached;

(c) analyzing the motion signal to determine a motion parameter; and

(d) based on the motion parameter, selecting one of the following algorithms to process at least one of the motion and impedance pneumography signals to determine the patient's respiratory rate: i) a first algorithm comprising a step for counting breathing-induced pulses in the impedance pneumography signal to determine respiratory rate; and ii) a second algorithm comprising transforming both the motion signal and impedance pneumography signal into frequency-domain signals, and then collectively processing the frequency-domain signals to determine respiratory rate.

45. A method for measuring respiratory rate from a patient, comprising the following steps:

(a) measuring an impedance pneumography signal from the patient with an impedance pneumography sensor connected to at least two electrodes, the impedance pneumography signal representing a time-dependent capacitance change in the patient's torso;

(b) measuring at least one motion signal with a motion sensor connected to the patient, the at least one motion signal corresponding to motion of a portion of the patient's body to which the motion sensor is attached;

(c) analyzing the motion signal to determine a motion parameter; and

(d) based on the motion parameter, selecting one of the following algorithms to process both the motion and impedance pneumography signals to determine the patient's respiratory rate: i) a first algorithm comprising collectively processing both the motion signal and impedance pneumography signal to determine a digital filter, and then

processing one of the motion signal and impedance pneumography signal with the digital filter to determine respiratory rate; and ii) a second algorithm comprising transforming both the motion signal and impedance pneumography signal into frequency-domain signals, and then collectively processing the frequency-domain signals to determine respiratory rate.

46. A method for determining a respiratory rate value from a patient, comprising the following steps:

(a) measuring at least one electrical signal affected by at least one of respiratory rate and motion with a first sensor;

(b) measuring a motion signal affected by the patient's motion with a second sensor;

(c) analyzing the motion signal to determine a motion parameter;

(d) based on the motion parameter, selecting at least one of the following algorithms to determine the respiratory rate value: i) a first algorithm that counts breathing-induced pulses in the electrical signal; ii) a second algorithm that processes the electrical signal with an adaptive filter generated by collectively processing the electrical signal and the motion signal; and iii) a third algorithm that collectively processes frequency-dependent spectra of both the motion and electrical signals.

47. The method of claim 43, wherein the motion parameter is a degree of the patient's motion.

48. The method of claim 47, wherein step (c) further comprises selecting the first algorithm if the degree of the patient's motion is below a pre-determined threshold value.

49. The method of claim 47, wherein step (c) further comprises selecting the second algorithm if the degree of the patient's motion is above a pre-determined threshold value.

50. The method of claim 43, wherein the motion parameter is an activity level.

51. The method of claim 50, wherein step (c) further comprises selecting the first algorithm if the activity level is resting.

52. The method of claim 50, wherein step (c) further comprises selecting the second algorithm if the activity level is one of walking, moving, or running.

53. The method of claim 43, wherein the motion parameter is a posture.

54. The method of claim 53, wherein step (c) further comprises selecting the first algorithm if the posture is laying down.

55. The method of claim 53, wherein step (c) further comprises selecting the second algorithm if the posture is one of standing up.

56. The method of claim 44, wherein the motion parameter is a degree of the patient's motion.

57. The method of claim 56, wherein step (c) further comprises selecting the first algorithm if the degree of the patient's motion is below a pre-determined threshold value.

58. The method of claim 56, wherein step (c) further comprises selecting the second algorithm if the degree of the patient's motion is above a pre-determined threshold value.

59. The method of claim 44, wherein the motion parameter is an activity level.

60. The method of claim 59, wherein step (c) further comprises selecting the first algorithm if the activity level is resting.

61. The method of claim 59, wherein step (c) further comprises selecting the second algorithm if the activity level is one of walking, moving, or running.

62. The method of claim 44, wherein the motion parameter is a posture.

63. The method of claim 62, wherein step (c) further comprises selecting the first algorithm if the posture is laying down.

64. The method of claim 63, wherein step (c) further comprises selecting the second algorithm if the posture is one of standing up.

65. A system for measuring respiratory rate from a patient, comprising:

an impedance pneumography system comprising: i) a connecting portion configured to connect to a plurality of electrodes configured to be worn on the patient; ii) a differential amplifier configured to receive electrical signals from each of the plurality of electrodes and process them to generate an analog impedance pneumography signal; and iii) an analog-to-digital converter configured to convert the analog impedance pneumography signal into a digital impedance pneumography signal;

a motion-sensing system comprising: i) a motion detector configured to generate an analog motion signal; and ii) an analog-to-digital converter configured to convert the analog motion signal into a digital motion signal; and

a processing system, configured to be worn on the patient's body at a different location than the impedance pneumography system and the motion-sensing system, the processing system configured to receive a cable that transmits both the digital impedance pneumography signal and the digital motion signal, and comprising a processor in electrical communication with the cable and configured to receive the digital impedance pneumography and digital motion signals and collectively process them to determine the patient's respiratory rate.

66. A system for measuring respiratory rate from a patient, comprising:

an impedance pneumography system comprising: i) a connecting portion configured to connect to a plurality of electrodes configured to be worn on the patient; ii) a differential amplifier configured to receive electrical signals from each of the plurality of electrodes and process them to generate an analog impedance pneumography signal; and iii) an analog-to-digital converter configured to convert the analog impedance pneumography signal into a digital impedance pneumography signal;

a motion-sensing system comprising: i) a motion detector configured to generate an analog motion signal; and ii) an analog-to-digital converter configured to convert the analog motion signal into a digital motion signal;

a processing system, configured to be worn on the patient's body at a different location than the impedance pneumography system and the motion-sensing system, the processing system configured to receive a cable that transmits both the digital impedance pneumography signal and the digital motion signal, and comprising a processor in electrical communication with the cable and configured to receive the digital impedance pneumography and digital motion signals and transmit them to a remote computer; and

the remote computer, configured to receive the digital impedance pneumography and digital motion signals, or mathematical derivatives thereof, collectively process these signals with an algorithm to determine the patient's respiratory rate, and then transmit a value describing the respiratory rate back to the processing system for display on the patient's body.

67. A system for measuring respiratory rate from a patient, comprising:

an impedance pneumography system comprising: i) a connecting portion configured to connect to a plurality of electrodes configured to be worn on the patient; ii) a differential amplifier configured to receive electrical signals from each of the plurality of electrodes and process them to generate an analog impedance pneumography signal;

and iii) an analog-to-digital converter configured to convert the analog impedance pneumography signal into a digital impedance pneumography signal;

a motion-sensing system comprising: i) a motion detector configured to generate an analog motion signal; and ii) an analog-to-digital converter configured to convert the analog motion signal into a digital motion signal;

a processing system, configured to be worn on the patient's body at a different location than the impedance pneumography system and the motion-sensing system, the processing system configured to receive a cable that transmits both the digital impedance pneumography signal and the digital motion signal, and comprising a processor in electrical communication with the cable and configured to receive the digital impedance pneumography and digital motion signals and transmit them to a remote computer; and

the remote computer, configured to receive the digital impedance pneumography and digital motion signals, or mathematical derivatives thereof, collectively process these signals with an algorithm to determine the patient's respiratory rate.

68. A system for measuring respiratory rate from a patient, comprising:

a sensor module, configured to be worn on the patient's torso, comprising an impedance pneumography sensor configured to measure a digital impedance pneumography signal, a motion sensor configured to measure a digital motion signal, and a serial transceiver configured to transmit the digital signals through a cable configured to attach to the patient's arm; and

a processing system, configured to be worn on the patient's wrist, comprising a connector that receives the cable, and a processor that receives digital impedance pneumography and motion signals from the cable and processes them with an algorithm that includes at least three unique calculations for determining respiratory rate, with the calculation being selected depending on the patient's degree of motion.

69. A system for measuring respiratory rate from a patient, comprising:

a sensor module, configured to be worn on the patient's torso, comprising an impedance pneumography sensor configured to measure a digital impedance pneumography signal, a motion sensor configured to measure a digital motion signal, and a serial transceiver configured to transmit the digital signals through a cable; and

a processing system, configured to be worn on the patient's wrist, comprising a connector that receives the cable, and a processor that receives digital impedance pneumography and motion signals from the cable and collectively processes them with an algorithm for determining respiratory rate.

70. The system of claim 65, further comprising a sensor module that comprises both the impedance pneumography system and the motion sensing system.

71. The system of claim 70, wherein the sensor module further comprises a skin temperature sensor.

72. The system of claim 70, wherein the sensor module further comprises a sensor for measuring an electrocardiogram.

73. The system of claim 70, wherein the sensor module further comprises a microprocessor.

74. The system of claim 73, wherein the microprocessor is configured to process the digital impedance pneumography signal and digital motion signal before they are transmitted through the cable to the processing system.

75. The system of claim 74, wherein the microprocessor is configured to digitally filter the digital impedance pneumography signal and digital motion signal before they are transmitted through the cable to the processing system.

76. The system of claim 65, wherein the cable is configured to attach to the patient's arm.

77. The system of claim 76, wherein the cable further comprises an embedded accelerometer.

78. The system of claim 65, wherein the motion-sensing system comprises an accelerometer.

79. The system of claim 78, wherein the accelerometer is configured to generate at least three analog motion signals, each corresponding to a different axis on the patient, and the analog-to-digital converter is configured to convert each of the three analog motion signals into a unique digital motion signal.

80. The system of claim 79, wherein the processing system is further configured to receive a digital motion signal corresponding to each axis on the patient, and collectively process the digital motion signals to determine a posture corresponding to the patient.

81. The system of claim 80, wherein the processing system is further configured to generate an alarm based on both a posture and respiratory rate corresponding to the patient.

82. The system of claim 70, wherein the sensor module comprises a connector configured to connect directly to a first electrode.

83. The system of claim 82, wherein the sensor module is further configured to connect through a cable harness to a second and third electrode.

84. The system of claim 65, wherein the processing system further comprises a display configured to render a value of respiratory rate.

85. The system of claim 65, wherein the processing system further comprises a wireless transmitter configured to wirelessly transmit a value of respiratory rate.

(Subbe et al., 'Effect of introducing the Modified Early Warning score on clinical outcomes, cardio-pulmonary arrests and intensive care utilization in acute medical admissions', *Anaesthesia* 2003; 58: 797-802). Goldhill et al. reported that 21% of ward patients with a RR of 25–29 breaths/minute assessed by a critical care outreach service died in hospital (Goldhill et al., 'A physiologically-based early warning score for ward patients: the association between score and outcome', *Anaesthesia* 2005; 60: 547-553). Those with a higher RR had even higher mortality rates. In another study, just over half of all patients suffering a serious adverse event on the general wards (e.g. a cardiac arrest or ICU admission) had a RR greater than 24 breaths/minute. These patients could have been identified as high risk up to 24 hours before the event with a specificity of over 95% (Cretikos et al., 'The Objective Medical Emergency Team Activation Criteria: a case–control study', *Resuscitation* 2007; 73: 62-72). Medical references such as these clearly indicate that an accurate, easy-to-use device for measuring RR is an important component for patient monitoring within the hospital.

[0009] Despite its importance and the large number of available monitoring techniques, RR is notoriously difficult to measure, particularly when a patient is moving. During periods of motion, non-invasive techniques based on IP and PPG signals are usually overwhelmed by artifacts, and thus completely ineffective. This makes it difficult or impossible to measure RR from an ambulatory patient. Measurements based on et-CO2 are typically less susceptible to motion, but require a plastic tube inserted in the patient's mouth, which is uncomfortable and typically impractical for ambulatory patients.

SUMMARY OF THE INVENTION

[0009a] The invention is defined in the independent claim. Some optional features of the invention are defined in the dependent claims.

[0010] The techniques disclosed herein provide a technique for measuring RR using multiple input signals, including IP and accelerometer waveforms (ACC). After being measured with a

triggers a false alarm. Such a situation can be avoided with an independent measurement of motion, such as that described herein. Other heuristic rules based on analysis of ACC waveforms may also be deployed.

[0014] Sensors attached to the wrist and bicep each measure signals that are collectively analyzed to estimate the patient's arm height; this can be used to improve accuracy of a continuous blood pressure measurement (cNIBP), as described below, that measures systolic (SYS), diastolic (DIA), and mean (MAP) arterial blood pressures. And the sensor attached to the patient's chest measures signals that are analyzed to determine posture and activity level, which can affect measurements for RR, SpO2, cNIBP, and other vital signs. Algorithms for processing information from the accelerometers for these purposes are described in detail in the following patent applications, the contents of which are fully incorporated herein by reference: BODY-WORN MONITOR FEATURING ALARM SYSTEM THAT PROCESSES A PATIENT'S MOTION AND VITAL SIGNS (U.S.S.N 12/469,182; filed May 20, 2009) and BODY-WORN VITAL SIGN MONITOR WITH SYSTEM FOR DETECTING AND ANALYZING MOTION (U.S.S.N 12/469,094; filed May 20, 2009). As described therein, knowledge of a patient's motion, activity level, and posture can greatly enhance the accuracy of alarms/alerts generated by the body-worn monitor.

[0015] The body-worn monitor features systems for continuously monitoring patients in a hospital environment, and as the patient transfers from different areas in the hospital, and ultimately to the home. Both SpO2 and cNIBP rely on accurate measurement of PPG and ACC waveforms, along with an ECG, from patients that are both moving and at rest. cNIBP is typically measured with the 'Composite Technique', which is described in detail in the co-pending patent applications entitled: VITAL SIGN MONITOR FOR MEASURING BLOOD PRESSURE USING OPTICAL, ELECTRICAL, AND

applications, the contents of which have been previously incorporated herein by reference.

[0018] In one exemplary technique, there is provided a system for measuring RR from a patient. The system includes an IP sensor, connected to at least two electrodes, and a processing system that receives and processes signals from the electrodes to measure an IP signal. The electrodes can connect to the IP sensor through either wired or wireless means. A motion sensor (e.g. an accelerometer) measures at least one motion signal (e.g. an ACC waveform) describing movement of a portion of the patient's body to which it is attached. The processing system receives the IP and motion signals, and processes them to determine, respectfully, frequency-domain IP and motion spectra. Both spectra are then collectively processed to remove motion components from the IP spectrum and determine RR. For example, during the processing, an algorithm determines motion frequency components from the frequency-domain motion spectrum, and then using a digital filter removes these, or parameters calculated therefrom, from the IP spectrum.

[0019] In embodiments, a single sensor module, adapted to be worn on the patient's torso, encloses both the IP sensor and the motion sensor. The sensor module typically includes at least one analog-to-digital converter configured to digitize the IP signal; this component may be integrated directly into a single-chip circuit (e.g. an application-specific integrated circuit, or ASIC), or in a circuit consisting of a collection of discrete components (e.g. individual resistors and capacitors). The sensor module can also include at least one analog-to-digital converter configured to digitize the motion signal. Similarly, this component can be integrated directly into the accelerometer circuitry. Digitizing the IP and motion signals before transmitting them to the processing system has several advantages, as described in detail below.

[0020] In other embodiments, the sensor module includes a temperature sensor for measuring the patient's skin temperature, and an ECG circuit (corresponding to a three, five, or twelve-lead ECG) for measuring an ECG waveform. In embodiments, the sensor module simply rests on the patient's chest during a measurement, or can be connected with a small piece of medical tape. Alternatively, the housing features a connector that connects directly to an ECG electrode worn on the patient's torso.

[0021] The processing system is typically worn on the patient's wrist. Alternatively, this system can be within the sensor module, or within a remote computer server (located, e.g., in a hospital's IT system). Typically a wireless transceiver (e.g. a transceiver based on 802.11 or 802.15.4 transmission protocols) is included in the system, typically within the processing module. Such a transceiver, for example, can wirelessly transmit IP and ACC waveforms to a remote processing system for further analysis. In this case, the processing system is further configured to wireless transmit a RR value back to a second processor worn on the patient's body, where it can then be displayed (using, e.g., a conventional display).

[0022] Accelerometers used within the system typically generate a unique ACC waveform corresponding to each axis of a coordinate system. In embodiments the system can include three accelerometers, each worn on a different portion of the patient's body. Waveforms generated by the accelerometers can then be processed as described in detail below to determine the patient's posture.

[0023] In another exemplary technique, there is provided an algorithm, typically implemented using compiled computer code, a computer memory, and a microprocessor, that processes IP and ACC waveforms by calculating their power spectra by way of a Fourier transform (e.g. a fast Fourier transform, of FFT). The algorithm then determines motion components from the frequency-dependent ACC spectrum, and using a digital filter

removes these, or components calculated therefrom, from the frequency-dependent IP spectrum. This yields a processed, frequency-dependent IP spectrum which can then be analyzed as described in detail below to estimate RR, even when large amounts of motion-induced noise are evident on the IP signal.

[0024] In embodiments, power spectra for both the IP and ACC waveforms are calculated from a complex FFT that includes both real and imaginary components. In other embodiments, alternative mathematical transforms, such as a Laplace transform, can be used in place of the FFT.

[0025] To determine a digital filter from the ACC power spectrum, the algorithm typically includes a method for first finding a peak corresponding to one or more frequencies related to the patient's motion. A bandpass filter, characterized by a passband which filters out these (and related) frequencies, is then generated and used to process the IP spectrum. Alternatively, these frequencies can simply be divided or subtracted from the IP spectrum. In all cases, this yields a processed IP spectrum which is then further analyzed to determine a frequency corresponding to RR. Analysis can include smoothing, averaging, or related methodologies uses to extract a single frequency, corresponding to RR, from a collection of frequencies. In embodiments, the algorithm can also include a component that generates an alarm if the patient's RR is greater than a first pre-determined threshold, or less than a second pre-determined threshold. The alarm can be generated by considering both the patient's RR and posture.

[0026] In another exemplary technique, there is provided a multi-component algorithm for determining RR. The multi-component algorithm first determines a motion parameter from the ACC waveform. The motion parameter indicates the patient's degree of motion, activity level, or posture. Based on the motion parameter, the multi-component algorithm then selects one of the following algorithms to process one or both of the ACC and IP

waveforms to determine RR: i) a first algorithm featuring counting breathing-induced pulses in the IP waveform; and ii) a second algorithm featuring collectively processing both the ACC and IP waveform to determine a digital adaptive filter, and then processing one of these waveforms with the adaptive filter to determine RR; and iii) a third algorithm featuring mathematically transforming both the ACC and IP waveforms into frequency-domain spectra, and then collectively processing the spectra to determine RR. Typically the first, second, and third algorithms are deployed, respectively, when the motion parameter indicates the patient's motion is non-existent, minimal, or large. For example, the first algorithm is typically deployed when the patient is resting; the second algorithm deployed when the patient is moving about somewhat; and the third algorithm deployed when the patient is standing up, and possibly walking or even running.

[0027] In another exemplary technique, the multi-component algorithm is deployed on one or more microprocessors associated with the system. For example, to conserve battery life of the body-worn monitor, numerically intensive calculations (such as the FFT or those used to generate the digital filter) can be performed on a remote server; intermediate or final parameters associated with these calculations can then be wirelessly transmitted back to the body-worn monitor for further processing or display. In another embodiment, portions of the multi-component algorithm can be carried out by microprocessors located in both the wrist-worn transceiver and chest-worn sensor module. The microprocessors can communicate through serial or wireless interfaces. This latter approach will have little impact on battery life, but can reduce processing time by simultaneously performing different portions of the calculation.

[0028] In another exemplary technique, there is provided a method for measuring RR from a patient using an algorithm based on a digital adaptive filter. In this approach, the body-worn monitor measures both IP and ACC waveforms as described above. The waveforms

are then collectively processed to determine a set of coefficients associated with the adaptive filter. Once calculated, the coefficients are stored in a computer memory. At a later point in time, the monitor measures a second set of IP and ACC waveforms, and analyzes these to determine a motion parameter. When the motion parameter exceeds a pre-determined threshold, the algorithm processes the set of coefficients and the latest IP waveform to determine a processed IP waveform, and then analyzes this to determine RR.

[0029] In embodiments, the digital adaptive filter is calculated from an impulse response function, which in turn is calculated from either a FIR function or an autoregressive moving average model. The order of the adaptive filter calculated from the impulse response function is typically between 20 and 30, while the order of the filter calculated from the autoregressive moving average model is typically between 1 and 5. A specific mathematic approach for calculating the digital adaptive filter is described below with reference to Eqs. 1-16. As described above, the coefficients can be calculated using a microprocessor located on the wrist-worn transceiver, sensor module, or a remote server.

[0030] In yet another exemplary technique, there is provided a system for measuring RR featuring a sensor module configured to be worn on the patient's torso. The sensor module includes sensors for measuring both IP and ACC waveforms, and a serial transceiver configured to transmit the digital signals through a cable to a wrist-worn processing system. This system features a connector that receives the cable, and a processor that receives digital signals from the cable and collectively processes them with a multi-component algorithm to determine RR. In embodiments, the sensor module digitally filters the IP and ACC waveforms before they pass through the cable. The cable can also include one or more embedded accelerometers, and is configured to attach to the patient's arm.

[0031] In all embodiments, the wrist-worn transceiver can include a display configured to render the patient's RR and other vital signs, along with a touchpanel interface. A wireless transceiver within the wrist-worn transceiver can transmit information to a remote computer using conventional protocols such as 802.11, 802.15.4, and cellular (e.g. CDMA or GSM). The remote computer, for example, can be connected to a hospital network. It can also be a portable computer, such as a tablet computer, personal digital assistant, or cellular phone.

[0032] Many advantages are associated with the implementation of the disclosed exemplary techniques. In general, the techniques disclosed herein may provide an accurate measurement of RR, along with an independent measurement of a patient's posture, activity level, and motion. These parameters can be collectively analyzed to monitor a hospitalized patient and improve true positive alarms while reducing the occurrence of false positive alarms. Additionally, the measurement of RR may be performed with a body-worn monitor that is comfortable, lightweight, and low-profile, making it particularly well suited for ambulatory patients. Such a monitor could continuously monitor a patient as, for example, they transition from the emergency department to the ICU, and ultimately to the home after hospitalization.

[0033] Still other embodiments are found in the following detailed description of the invention and in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0034] Fig. 1 shows a schematic view of a patient wearing a sensor module on their chest that connects to three electrodes arranged in an Einthoven's triangle configuration and measures both ACC and IP waveforms;

[0035] Fig. 2 shows a schematic view of a patient wearing a sensor module on their belly that connects to three electrodes arranged in an Einthoven's triangle configuration and measures both ACC and IP waveforms;

[0036] Fig. 3A is a schematic view of a patient wearing an alternate arrangement featuring a sensor module for measuring IP and ACC waveforms that connects directly through an electrode to the patient's belly;

[0037] Fig. 3B is a schematic, cross-sectional view of the sensor module of Fig. 3A connected to the patient's belly with the electrode;

[0038] Figs. 4A and 4B show, respectively, a three-dimensional image of the body-worn monitor attached to a patient during and after an initial indexing measurement;

[0039] Fig. 5 shows a three-dimensional image of the wrist-worn transceiver used with the body-worn monitor from Figs. 4A and 4B;

[0040] Fig. 6 shows a schematic view of a multi-component algorithm used to collectively process ACC and IP waveforms to measure RR;

[0041] Fig. 7 shows a schematic drawing of Algorithm 1 used in the multi-component algorithm of Fig. 6;

[0042] Fig. 8 shows a schematic drawing of computation steps used in Algorithm 1 to calculate RR;

[0043] Fig. 9 shows a series of time-dependent IP waveforms (left-hand side) and their corresponding mathematical derivatives (right-hand side) measured from a slowly breathing patient and processed with digital filters featuring gradually decreasing passbands;

[0044] Fig. 10 shows a series of time-dependent IP waveforms (left-hand side) and their corresponding mathematical derivatives (right-hand side) measured from a rapidly breathing patient and processed with digital filters featuring gradually decreasing passbands;

simultaneously measures acceleration (e.g. motion) along x, y, and z axes of a local coordinate system, such as that shown in Fig. 29. As shown in this figure, and described in more detail below, the accelerometer 12 is preferably aligned so the z axis points into the patient's torso. Within the accelerometer 12 is an internal analog-to-digital converter that generates a digital ACC waveform corresponding to each axis.

[0074] Also within the sensor module 25 is a microprocessor 33 and analog-to-digital converter (not shown in the figure) that digitize the IP and ACC waveforms, and sends them through a serial protocol (e.g. the control area network, or CAN protocol) to the wrist-worn transceiver for further processing. There, IP and ACC waveforms are processed with the multi-component algorithm to determine the patient's RR. Alternatively, the algorithms can be performed in part with a remote server, or with the microprocessor 33 mounted within the sensor module. Additional properties such as the patient's posture, degree of motion, and activity level are determined from these same digital ACC waveforms. The axis within the accelerometer's coordinate system that is aligned along the patient's torso (and thus orthogonal to their respiration-induced torso movement) is typically more sensitive to events not related to respiration, e.g. walking and falling.

[0075] In a preferred configuration, digital accelerometers manufactured by Analog Devices (e.g. the ADXL345 component) are used in the configuration shown in Fig. 1. These sensors detect acceleration over a range of +/-2 g (or, alternatively, up to +/-8 g) with a small-scale, low-power circuit.

[0076] Many patient's are classified as 'belly breathers', meaning during respiration their belly undergoes larger movements than their chest. A relative minority of patients are 'chest breathers', indicating that it is the chest that undergoes the larger movements. For this reason it is preferred that RR is determined using an ACC waveform detected

generated by different sensors. This includes multiple ECG waveforms (corresponding, e.g., to vectors associated with three, five, and twelve-lead ECG systems) from the ECG circuit 26, the IP waveform from the IP circuit 27, and ACC waveforms associated with the x, y, and z axes of accelerometers 10, 12 attached to the patient's chest. Limiting the transmission line to a single cable reduces the number of wires attached to the patient, thereby decreasing the weight and cable-related clutter of the body-worn monitor. Second, cable motion induced by an ambulatory patient can change the electrical properties (e.g. electrical impendence) of its internal wires. This, in turn, can add noise to an analog signal and ultimately the vital sign calculated from it. A digital signal, in contrast, is relatively immune to such motion-induced artifacts. More sophisticated ECG circuits can plug into the wrist-worn transceiver to replace the three-lead system shown in Figs. 1 and 2. These ECG circuits, for example, can include, e.g., five and twelve leads.

[0080] Digital data streams are typically transmitted to the wrist-worn transceiver using a serial protocol, such as the CAN protocol, USB protocol, or RS-232 protocol. CAN is the preferred protocol for the body-worn monitor described in Figs. 4A, 4B.

[0081] Multi-Component Algorithm for Determining RR

[0082] Fig. 6 shows an overview of a multi-component algorithm 149, implemented with the body-worn monitor shown in Figs. 4A, 4B, and 5 and an accompanying server, which determines a patient's RR. The algorithm features the following components for determining RR from a hospitalized patient undergoing different levels of motion:

> **Algorithm 1** – simple peak-counting calculation implemented on the wrist-worn transceiver; used when patient motion is minimal or non-existent
>
> **Algorithm 2** – adaptive filtering calculation with filtering parameters calculated on the wrist-worn transceiver; used when some patient motion is evident

sampled at the same rate. If the IP waveform is sampled at a higher frequency than that used for the ACC waveform (e.g. 50 Hz), then this waveform may be converted into a 50 Hz waveform using conventional mathematical techniques, such as decimation or a numerical 'mapping' operation.

[0101] At this point zero mean input and output signals for u[i] and y[i] are constructed by subtracting the ensemble signal mean from each signal. This operation, shown below in Eqs. 2 and 3, effectively removes any DC offset (step 252).

$$u[i] = u[i] - \left(\frac{1}{N}\right)\sum_{k=1}^{N} u[k] \tag{2}$$

$$y[i] = y[i] - \left(\frac{1}{N}\right)\sum_{k=1}^{N} y[k] \tag{3}$$

[0102] A mathematical model used to define the impulse response function of the adaptive filter may be chosen, with the two primary options being filters based on FIR (finite impulse response) or ARMA (autoregressive moving average) models. Both models are indicated below in Eqs. 4 and 5, but only one should be chosen and implemented during the algorithm (step 254):

FIR Model

$$H[z] = b_0 + b_1 z^{-1} + \cdots + b_L z^{-L} \tag{4}$$

ARMA Model

$$H[z] = \frac{b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-p}} \tag{5}$$

At this point the order of the filter is determined. For the FIR model, the order is L; for the ARMA model, the order is m and p. In a preferred embodiment, the orders for L, m, and p are, respectively, 25, 2, and 2; these values may vary depending on the degree of motion and the computational capabilities on the wrist-worn transceiver. A column

[0122] Fig. 26 shows an alternate arrangement wherein a rolling average is used in place of the smoothing filter described above with reference to Fig. 25. Here, the rolling average is gradually increased from 0 points (Fig. 26A, at the top of the page) to 100 points. When the average is increased above about 20 points the features in the frequency spectrum begin to blend together to form a well-defined peak that can be easily analyzed using the peak-finding algorithm referenced above.

[0123] Referring to Figs. 27 and 28, the number of time-domain samples used to calculate an associated Fourier Transform and power spectrum will have a significant influence on the resolution of the power spectrum. In general, increasing the number of time-domain samples will increase resolution in the power spectrum. In this configuration, the frequency-domain resolution can be arbitrarily increased by adding constant values to the time-domain ACC and IP waveform. In this technique, typically called 'zero padding', the constant values are typically 0, or alternatively a constant value.

[0124] Both Fig. 27 and 28 show a time-domain IP waveform (Figs. 27A and 28A, shown at the top of the page) along with associated power spectra calculated, respectively, using 1000 points (Figs. 27B, 28B), 500 points (Fig. 27C, 28C), and 250 points (Fig. 27D, 28D). The IP waveform for this figure was sampled at 25 Hz, and thus the time-domain markers that correspond to the above-mentioned points are indicated by a light gray circle (1000 points), a dark gray circle (500 points), and a black circle (250 points). As shown in Figs. 27B, 28B, 27C, 28C, power spectra determined with both 1000-point and 500-point Fourier Transforms feature roughly the same frequency profile, with, as expected, the 1000-point spectra showing relatively greater resolution. Power spectra calculated from the 250-point Fourier Transform show one or more very broad peaks, and, importantly, undergo a frequency shift which trends toward higher frequencies for the dominant peak. Such a frequency shift will result in an erroneous

determined using DC signals from the accelerometers 413, 414 disposed, respectively, on the patient's bicep and wrist. Posture, in contrast, can be exclusively determined by the accelerometer 412 worn on the patient's chest. An algorithm operating on the wrist-worn transceiver extracts DC values from waveforms measured from this accelerometer and processes them with an algorithm described below to determine posture.

[0127] Specifically, torso posture is determined for a patient 410 using angles determined between the measured gravitational vector and the axes of a torso coordinate space 411. The axes of this space 411 are defined in a three-dimensional Euclidean space where $\vec{R}_{CV}$ is the vertical axis, $\vec{R}_{CH}$ is the horizontal axis, and $\vec{R}_{CN}$ is the normal axis. These axes may be identified relative to a 'chest accelerometer coordinate space' before the patient's posture can be determined.

[0128] The first step in determining a patient's posture is to identify alignment of $\vec{R}_{CV}$ in the chest accelerometer coordinate space. This can be determined in either of two approaches. In the first approach, $\vec{R}_{CV}$ is assumed based on a typical alignment of the body-worn monitor relative to the patient. During a manufacturing process, these parameters are then preprogrammed into firmware operating on the wrist-worn transceiver. In this procedure it is assumed that accelerometers within the body-worn monitor are applied to each patient with essentially the same configuration. In the second approach, $\vec{R}_{CV}$ is identified on a patient-specific basis. Here, an algorithm operating on the wrist-worn transceiver prompts the patient (using, e.g., video instruction operating on the wrist-worn transceiver, or audio instructions transmitted through a speaker) to assume a known position with respect to gravity (e.g., standing upright with arms pointed straight down). The algorithm then calculates $\vec{R}_{CV}$ from DC values corresponding to the x, y, and z axes of the chest accelerometer while the patient is in this position. This case, however, still requires knowledge of which arm (left or right) the monitor is worn on, as the chest

[0156] Figs. 3A, 3B show yet another alternate arrangement wherein a sensor module 25 attaches to the belly of a patient 10 using an electrode 24 normally attached to the lower left-hand portion of the patient's torso. Specifically, the sensor module 25 includes a connector 253 featuring an opening that receives the metal snap or rivet present on most disposable ECG electrodes. Connecting the connector 253 to the electrode's rivet holds the sensor module 25 in place. This configuration reduces the number of cables in the body-worn monitor, and additionally secures an accelerometer 12 to the patient's belly. This is typically the part of their torso that undergoes the greatest motion during respiration, and thus generates ACC waveforms with the highest possible signal-to-noise ratio. Also contained within the sensor module 25 are the ECG circuit 26, the IP circuit 27, microprocessor 33, and a temperature sensor 34.

[0157] To measure IP and ECG waveforms, the sensor module 25 connects through cables to electrodes 20, 22 attached, respectively, to the upper right-hand and left-hand portions of the patient's torso. This system measures RR using the peak counting, adaptive filtering, and FFT-based approaches described above, and has the additional advantage of measuring a relatively large ACC signals indicating respiration-induced motions of the patient's belly. As described above, these signals are typically generated by the z-axis of the accelerometer 12, which is normal to the patient's torso. ACC signals along the x and y-axes can be additionally processed to determine the patient's posture and activity level, as described above. Once RR and these motion-related properties are measured, a transceiver in the sensor module (not shown in the figure) transmits them in the form of a digital data stream through a cable to the wrist-worn transceiver for further processing.

[0158] Still other embodiments are within the scope of the following claims.

What is claimed is:

1. A system for non-invasively measuring respiratory rate from a patient, comprising:

an impedance pneumography sensor comprising:

at least two electrodes configured to be positioned on the patient's torso and to detect respiration-induced impedance changes indicative of respiration, and

a sensor module configured to be worn on the patient's torso and operably connected to the at least two electrodes, the sensor module comprising a processing circuit configured to process signals from the at least two electrodes to measure an impedance pneumography signal from the patient and a motion sensor configured to measure at least one motion signal corresponding to motion of a portion of the patient's body to which it is attached; and

a processing system configured to receive the impedance pneumography signal and process it to determine a frequency-domain impedance pneumography spectrum, and to receive the motion signal and process it to determine a frequency-domain motion spectrum, the processing system further configured to collectively process both the impedance pneumography spectrum and motion spectrum to remove motion components from the impedance pneumography spectrum and then determine respiratory rate.

2. The system of claim 1, wherein the sensor module comprises at least one analog-to-digital converter configured to digitize the impedance pneumography signal.

3. The system of claim 2, wherein the sensor module comprises at least one analog-to-digital converter configured to digitize the motion signal.

4. The system of claim 1, further comprising a serial transceiver configured to transmit digitized versions of the impedance pneumography signal and motion signal to the processing system.

5. The system of claim 1, wherein the processing system is configured to be worn on the patient's wrist.

6. The system of claim 1, wherein the sensor module comprises the processing system.

7. The system of claim 1, further comprising a wireless transceiver.

8. The system of claim 7, wherein the processing system is remote from the patient, and the wireless transceiver is configured to wirelessly transmit digitized versions of the impedance pneumography signal and motion signal to the processing system.

9. The system of claim 8, wherein the processing system is further configured to wirelessly transmit a value describing respiratory rate to a second processor worn on the patient's body.

10. The system of claim 9, wherein the second processor is configured to display the value describing respiratory rate on the patient's body.

11. The system of claim 1, wherein the motion sensor is an accelerometer.

12. The system of claim 11, wherein the accelerometer is configured to generate a unique motion waveform for each axis of a coordinate system.

13. The system of claim 12, wherein the processing system is further configured to process each unique motion waveform to determine a posture corresponding to the patient.

14. The system of claim 1, wherein the sensor module further comprises a temperature sensor.

15. The system of claim 1, wherein the sensor module further comprises a sensor for measuring an electrocardiogram.

16. The system of claim 1, wherein the sensor module comprises a housing, the housing comprising a connector that connects directly to an electrode worn on the patient's torso.