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(71) Applicant(s)
Baxter International Inc.;Baxter Healthcare SA

(72) Inventor(s)
DHILLON, Marshal;DHILLON, Mark;TANG, Erik;HAYWARD, Lauren Nicole Miller;BANET, Matthew;MCCANNA, James

(74) Agent / Attorney
K&L Gates, Level 25 South Tower 525 Collins Street, Melbourne, VIC, 3000, AU

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(71) Applicants: **BAXTER INTERNATIONAL INC.** [US/US]; One Baxter Parkway, Deerfield, Illinois 60015 (US). **BAXTER HEALTHCARE SA** [CH/CH]; 130 Thurgauerstrasse, CH-8152 Glattpark (Opfikon) (CH).

(72) Inventors: **DHILLON, Marshal**; 15909 Kennicott Lane, San Diego, California 92127 (US). **DHILLON, Mark**; 3788 10th Avenue, San Diego, California 92103 (US). **TANG, Erik**; 13349 Sparren Avenue, San Diego, California 92129 (US). **HAYWARD, Lauren Nicole Miller**; 3280 Caminito Ameca, La Jolla, California 92037 (US). **BANET, Matthew**; 1050 Island Avenue, Suite 710, San Diego, California 92121 (US). **MCCANNA, James**; 881 Montevino Drive, Pleasanton, California 94566 (US).

(74) Agent: **DICKE, Matthew S.** et al.; K&L Gates LLP, c/o Foreign Patents, P.O. Box 1135, Chicago, Illinois 60690-1135 (US).

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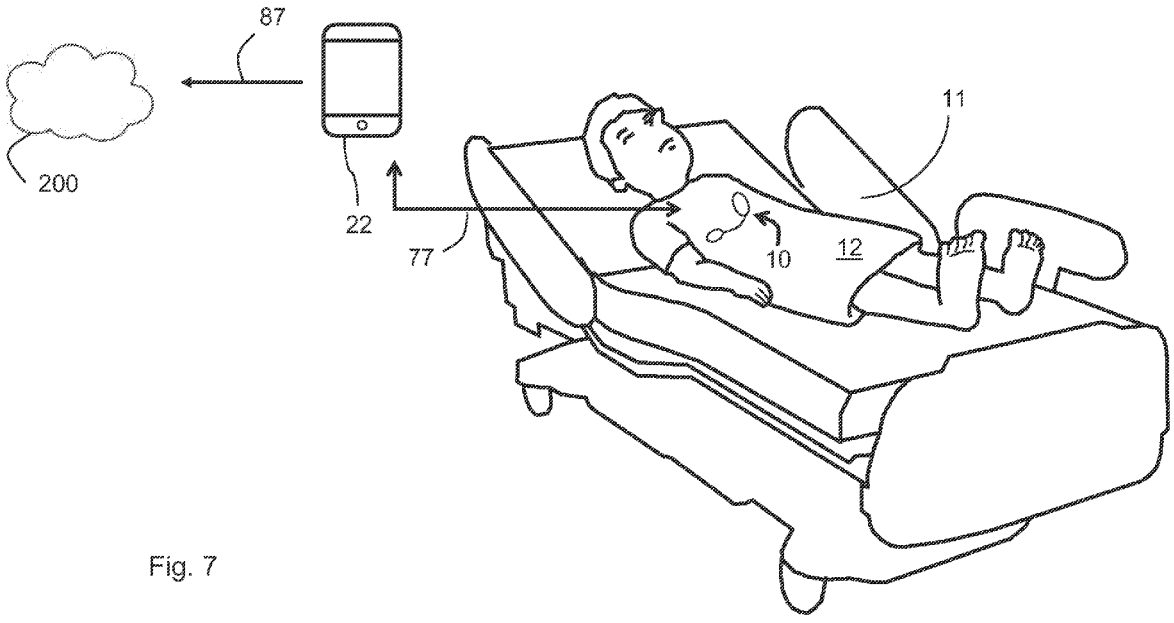


Fig. 7

(57) Abstract: A body-worn patch sensor for simultaneously measuring a blood pressure (BP), pulse oximetry (SpO2), and other vital signs and hemodynamic parameters from a patient featuring a sensing portion having a flexible housing that is worn entirely on the patient's chest and encloses a battery, wireless transmitter, and all the sensor's sensing and electronic components. It measures electrocardiogram (ECG), impedance plethysmogram (IPG), photoplethysmogram (PPG), and phonocardiogram (PCG) waveforms, and collectively processes these to determine the vital signs and hemodynamic parameters. The sensor that measures PPG waveforms also includes a heating element to increase perfusion of tissue on the chest.

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PATCH-BASED PHYSIOLOGICAL SENSOR

PRIORITY CLAIM

[0001] This application claims priority to and the benefit of U.S. Provisional Patent Application No. 62/845,097 entitled PATCH-BASED PHYSIOLOGICAL SENSOR, filed on May 8, 2019, the entire contents of which are incorporated by reference and relied upon.

FIELD OF THE INVENTION

[0002] The invention relates to the use of systems that measure physiological parameters from patients located, e.g., in hospitals, clinics, and the home.

BACKGROUND

[0003] There are a number of physiological parameters that can be assessed by measuring biometric signals from a patient. Some signals, such as electrocardiogram (ECG), impedance plethysmogram (IPG), photoplethysmogram (PPG), and phonocardiogram (PCG) waveforms, are measured with sensors (e.g., electrodes, optics, microphones) that connect or attach directly to the patient's skin. Processing of these waveforms yields parameters such as heart rate (HR), heart rate variability (HRV), respiration rate (RR), pulse oximetry (SpO2), blood pressure (BP), stroke volume (SV), cardiac output (CO), and parameters related to thoracic impedance, such as thoracic fluid content (FLUIDS). Many physiological conditions can be identified from these parameters when they are obtained at a single point in time; others may require continuous assessment over long or short periods of time to identify trends in the parameters. In both instances, it is important to obtain the parameters consistently and with high repeatability and accuracy.

[0004] Some devices that measure ECG waveforms are worn entirely on the patient's body. These devices often feature simple, patch-type systems that include both analog and digital electronics connected directly to underlying electrodes. Typically, these systems measure HR, HRV, RR, and, in some cases, posture, motion, and falls. Such devices are typically prescribed for relatively short periods of time, such as for a time period ranging from a few days to several weeks. They are typically wireless, and usually include technologies such as Bluetooth® transceivers to transmit information over a short range to a second device, which typically includes a cellular radio to transmit the information to a web-based system.

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[0005] Bioimpedance medical devices measure SV, CO, and FLUIDS by sensing and processing time-dependent ECG and IPG waveforms. Typically, these devices connect to patients through disposable electrodes adhered at various locations on a patient's body. Disposable electrodes that measure ECG and IPG waveforms are typically worn on the patient's chest or legs and include: i) a conductive hydrogel that contacts the patient; ii) a Ag/AgCl-coated eyelet that contacts the hydrogel; iii) a conductive metal post that connects the eyelet to a lead wire or cable extending from the device; and iv) an adhesive backing that adheres the electrode to the patient. Medical devices that measure BP, including systolic (SYS), diastolic (DIA), and mean (MAP) BP, typically use cuff-based techniques called oscillometry or auscultation, or pressure-sensitive catheters than are inserted in a patient's arterial system. Medical devices that measure SpO2 are typically optical sensors that clip onto a patient's finger or earlobes, or attach through an adhesive component to the patient's forehead.

SUMMARY OF THE INVENTION

[0006] The present invention relates to methods and systems to improve the monitoring of patients in hospitals, clinics, and the home. As described herein, patch sensors are provided that non-invasively measure vital signs such as HR, HRV, RR, SpO2, TEMP, and BP, along with complex hemodynamic parameters such as SV, CO, and FLUIDS. The patch sensor adheres to a patient's chest and continuously and non-invasively measures the above-mentioned parameters without cuffs and wires. In this way, it simplifies traditional protocols for taking such measurements, which typically involve multiple machines and can take several minutes to accomplish. The patch sensor wirelessly transmits information to an external gateway (e.g., tablet, smartphone, or non-mobile, plug-in system) which can integrate with existing hospital infrastructure and notification systems, such as a hospital electronic medical records (EMR) system. With such a system, caregivers can be alerted to changes in vital signs, and in response can quickly intervene to help deteriorating patients. The patch sensor can additionally monitor patients from locations outside the hospital.

[0007] More particularly, the invention features a chest-worn patch sensor that measures the following parameters from a patient: HR, PR, SpO2, RR, BP, TEMP, FLUIDS, SV, CO, and a set of parameters sensitive to blood pressure and systemic vascular resistance called pulse arrival time (PAT) and vascular transit time (VTT).

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[0008] The patch sensor also includes a motion-detecting accelerometer, from which it can determine motion-related parameters such as posture, degree of motion, activity level, respiratory-induced heaving of the chest, and falls. Such parameters could determine, for example, a patient's posture or movement during a hospital stay. The patch sensor can operate additional algorithms to process the motion-related parameters to measure vital signs and hemodynamic parameters when motion is minimized and below a predetermined threshold, thereby reducing artifacts. Moreover, the patch sensor estimates motion-related parameters such as posture to improve the accuracy of calculations for vital signs and hemodynamic parameters.

[0009] Disposable electrodes on a bottom surface of the patch sensor secure it to the patient's body without requiring bothersome cables. The electrodes measure ECG and IPG waveforms. They easily connect (and disconnect) to circuit boards contained within the sensor by means of magnets that are electrically connected to the circuit boards to provide signal-conducting electrical couplings. Prior to use, the electrodes are simply held near the circuit boards, and magnetic attraction causes the electrode patches to snap into proper position, thereby ensuring proper positioning of the electrodes on the patient's body.

[00010] Using light-emitting diodes (LEDs) operating in the red (e.g., 660 nm) and infrared (e.g., 900 nm) spectral regions, the patch sensor measures SpO2 by pressing lightly against capillary beds in the patient's chest. A heating element on the bottom surface of the patch sensor contacts the patient's chest and gently warms the underlying skin, thereby increasing perfusion of the tissue. Operating with reflection-mode optics, the patch sensor measures PPG waveforms with both red and infrared wavelengths. SpO2 is processed from alternating and static components of these waveforms, as is described in more detail below.

[00011] The patch sensor measures all of the above-mentioned properties while featuring a comfortable, easy-to-wear form factor. It is lightweight (e.g., about 20 grams) and powered with a rechargeable battery. During use, it rests on the patient's chest, where the disposable electrodes hold it in place, as described in more detail below. The patient's chest is a location that is unobtrusive, comfortable, removed from the hands, and able to hold the sensor without being noticeable to the patient. It is also relatively free of motion compared to appendages such as the hands and fingers, and thus a sensor affixed to the chest region minimizes motion-related artifacts. Such artifacts are compensated for, to some degree, by the accelerometer within the sensor. And because the patch sensor is a small and therefore considerably less noticeable or obtrusive than

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various other physiological sensor devices, emotional discomfort over wearing a medical device over an extended period of time is reduced, thereby fostering long-term patient compliance for use of this device within a monitoring regimen.

[00012] Given the above, in one aspect, the invention provides a patch sensor for simultaneously measuring BP and SpO2 from a patient. The patch sensor features a sensing portion having a flexible housing that is worn entirely on the patient's chest and encloses a battery, wireless transmitter, and all the sensor's sensing and electronic components. The sensor measures ECG, IPG, PPG, and PCG waveforms, and collectively processes these determine BP and SpO2. The sensor that measures PPG waveforms includes a heating element to increase perfusion of tissue on the chest.

[00013] On its bottom surface, the flexible housing includes an analog optical system, located proximal to one pair of the electrode contact points, that features a light source that generates radiation in both the red and infrared spectral ranges. This radiation separately irradiates a portion of the patient's chest disposed underneath the flexible housing. A photodetector detects the reflected radiation in the different spectral ranges to generate analog red-PPG and infrared-PPG waveforms.

[00014] A digital processing system disposed within the flexible housing includes a microprocessor and an analog-to-digital converter, and is configured to: 1) digitize the analog ECG waveform to generate a digital ECG waveform, 2) digitize the analog impedance waveform to generate a digital impedance waveform, 3) digitize the analog red-PPG waveform to generate a digital red-PPG waveform, 4) digitize the analog infrared-PPG waveform to generate a digital infrared-PPG waveform, and 5) digitize the analog PCG waveform to generate a digital PCG waveform. Once these waveforms are digitized, numerical algorithms operating in embedded computer code called 'firmware' process them to determine the parameters described herein.

[00015] In another aspect, the invention provides a patch sensor for measuring a PPG waveform from a patient. The patch sensor includes a housing worn entirely on the patient's chest, and a heating element attached to the bottom surface of the housing so that, during use, it contacts and heats an area of the patient's chest. An optical system is located on a bottom surface of the housing and proximal to the heating element, and includes a light source that generates optical radiation that irradiates the area of the patient's chest during a measurement. The sensor also features a temperature sensor in direct contact with the heating element, and a closed-loop temperature

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controller within the housing and in electrical contact with the heating element and the temperature sensor. During a measurement, the closed-loop temperature controller receives a signal from the temperature sensor and, in response, controls an amount of heat generated by the heating element. A photodetector within the optical system generates the PPG waveform by detecting radiation that reflects off the area of the patient's chest after it is heated by the heating element.

[00016] Heating tissue that yields the PPG waveform typically increases blood flow (i.e., perfusion) to the tissue, thereby increasing the amplitude and signal-to-noise ratio of the waveform. This is particularly important for measurements made at the chest, where signals are typically significantly weaker than those measured from more conventional locations, such as the fingers, earlobes, and forehead.

[00017] In embodiments, the heating element features a resistive heater, such as a flexible film, metallic material, or polymeric material (e.g., Kapton®) that may include a set of embedded electrical traces that increase in temperature when electrical current passes through them. For example, the electrical traces may be disposed in a serpentine pattern to maximize and evenly distribute the amount of heat generated during a measurement. In other embodiments, the closed-loop temperature controller includes an electrical circuit that applies an adjustable potential difference to the resistive heater that is controlled by a microprocessor. Preferably, the microcontroller adjusts the potential difference it applies to the resistive heater so that its temperature is between 40 and 45°C.

[00018] In embodiments, the flexible-film heating element features an opening that transmits optical radiation generated by the light source so that it irradiates an area of the patient's chest disposed underneath the housing. In similar embodiments, the flexible film features a similar opening or set of openings that transmit optical radiation reflected from the area of the patient's chest so that it is received by the photodetector.

[00019] In still other embodiments, the housing further includes an ECG sensor that features a set of electrode leads, each configured to receive an electrode, that connect to the housing and electrically connect to the ECG sensor. For example, in embodiments, a first electrode lead is connected to one side of the housing, and a second electrode lead is connected to an opposing side of the housing. During a measurement, the ECG sensor receives ECG signals from both the first and second electrodes leads, and, in response, processes the ECG signals to determine an ECG waveform.

[00020] In another aspect, the invention provides a sensor for measuring PPG and ECG waveforms from a patient that is also worn entirely on the patient's chest. The sensor features an optical sensor, heating element, and temperature sensor similar to that described above. The sensor also includes a closed-loop temperature controller within the housing and in electrical contact with the heating element, the temperature sensor, and the processing system. The closed-loop temperature controller is configured to: 1) receive a first signal from the temperature sensor; 2) receive a second signal from the processing system corresponding to the second fiducial marker; 3) collectively process the first and second signals to generate a control parameter; and 4) control an amount of heat generated by the heating element based on the control parameter.

[00021] In embodiments, a software system included in the processing system determines a first fiducial marker within the ECG waveform that is one of a QRS amplitude, a Q-point, a R-point, an S-point, and a T-wave. Similarly, the software system determines a second fiducial marker that is one of an amplitude of a portion of the PPG waveform, a foot of a portion of the PPG waveform, and a maximum amplitude of a mathematical derivative of the PPG waveform.

[00022] In embodiments, the closed-loop temperature controller features an adjustable voltage source, and is configured to control an amount of heat generated by the heating element by adjusting the voltage source, such as the amplitude or frequency of a voltage generated by the voltage source.

[00023] In another aspect, the invention provides a similar chest-worn sensor that measures PPG waveforms from the patient, and from these SpO2 values. The sensor features a similar heating element, temperature, closed-loop temperature controller, and optical system as described above. Here, the optical system generates optical radiation in both the red and infrared spectral regions. The sensor also includes an ECG sensor with at least two electrode leads and an ECG circuit that generates an ECG waveform. During a measurement, a processing system featuring a software system analyzes the ECG waveform to identify a first fiducial marker, and based on the first fiducial marker, identifies a first set of fiducial markers within the red PPG waveform, and a second set of fiducial markers within the infrared PPG waveform. The processing system then collectively processes the first and second set of fiducial markers to generate the SpO2 value.

[00024] In embodiments, for example, the first set of fiducials identified by the software system features an amplitude of a baseline of the red PPG waveform (RED(DC)) and an amplitude of a heartbeat-induced pulse within the red PPG waveform (RED(AC)), and the second set of fiducials

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identified by the software system features an amplitude of a baseline of the infrared PPG waveform (IR(DC)) and an amplitude of a heartbeat-induced pulse within the infrared PPG waveform (IR(AC)). The software system can be further configured to generate the SpO2 value from a ratio of ratios (R) by analyzing the RED(DC), RED(AC), IR(DC), and IR(AC) using the following equations, or mathematical equivalents thereof:

$$R = \frac{RED(AC)/RED(DC)}{IR(AC)/IR(DC)}$$

$$SpO2 = \frac{k_1 - k_2 \times R}{k_3 - k_4 \times R}$$

where k_1, k_2, k_3, and k_4 are pre-determined constants. Typically, these constants are determined during a clinical study called a 'breathe-down study' using a group of patients. During the study, the concentration of oxygen supplied to the patients is gradually lowered in sequential 'plateaus' so that their SpO2 values changes from normal values (near 98 to 100%) to hypoxic values (near 70%). As the concentration of oxygen is lowered, reference SpO2 values are typically measured at each plateau with a calibrated oximeter or a machine that measures oxygen content from aspirated blood. These are the 'true' SpO2 values. R values are also determined at each plateau from PPG waveforms measured by the patch sensor. The pre-determined constants k_1, k_2, k_3, and k_4 can then be determined by fitting these data using equations shown above.

[00025] In other aspects, the invention provides a chest-worn sensor similar to that described above, that also includes an acoustic sensor for measuring PCG waveforms. Here, the sensor is mated with a single-use component that temporarily attaches to the sensor's housing and features a first electrode region positioned to connect to the first electrode contact point, a second electrode region positioned to connect to the second electrode contact point, and an impedance-matching region positioned to attach to the acoustic sensor.

[00026] In embodiments, the impedance-matching region comprises a gel or plastic material, and has an impedance at 100 kHz of about 220 Ω. The acoustic sensor can be a single microphone or a pair of microphones. Typically, the sensor includes an ECG sensor that yields a signal that is then processed to determine a first fiducial point (e.g., a Q-point, R-point, S-point, or T-wave of a heartbeat-induced pulse in the ECG waveform). A processing system within the sensor processes the PCG waveform to determine the second fiducial point, which is either the S1 heart sound or S2 heart sound associated with a heartbeat-induced pulse in the PCG waveform. The processing system then determines a time difference separating the first fiducial point and the second fiducial

point, and uses this time difference to determine the patient's blood pressure. Typically a calibration measurement made by a cuff-based system is used along with the time difference to determine blood pressure.

[00027] In embodiments, the processor is further conjured to determine a frequency spectrum of the second fiducial point (using, e.g., a Fourier Transform), and then uses this to determine the patient's blood pressure.

[00028] In yet another aspect, the invention provides a chest-worn sensor similar to that described above. Here, the sensor features an optical system, located on a bottom surface of the sensor's housing, that includes: 1) a light source that generates optical radiation that irradiates an area of the patient's chest disposed underneath the housing; and 2) a circular array of photodetectors that surround the light source and detect optical radiation that reflects off the area of the patient's chest. As before, the area is heated with a heating element prior to a measurement.

[00029] In light of the disclosure herein, disclosure herein, and without limiting the scope of the invention in any way, in a first aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, a sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's chest includes a housing configured to be located on the patient's chest. The sensor includes a reflective optical sensor for measuring the PPG waveform. The sensor includes a digital microphone for measuring the PCG waveform. The sensor includes a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform. The set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform. The IPG sensor is configured to inject current into the patient's chest, and further configured to measure the current to determine the IPG waveform.

[00030] In a second aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG sensor is configured to inject current at multiple frequencies into the patient's chest, and further configured to measure the current at multiple frequencies to determine the IPG waveform at multiple frequencies.

[00031] In a third aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG sensor is configured to inject current at a single

frequency into the patient's chest, and further configured to measure the current at the single frequency to determine the IPG waveform at the single frequency.

[00032] In a fourth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the reflective optical sensor further includes a heating element.

[00033] In a fifth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the heating element comprises a resistive heater.

[00034] In a sixth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the resistive heater is a flexible film.

[00035] In a seventh aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the housing is of solid, unitary construction.

[00036] In an eighth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the set of electrodes is a single electrode patch.

[00037] In a ninth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, a sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's chest includes a housing configured to be located on the patient's chest. The sensor includes a reflective optical sensor for measuring the PPG waveform. The sensor includes a digital microphone for measuring the PCG waveform. The sensor includes a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform. The set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform. The IPG waveform and the PCG waveform are used to determine a respiratory event.

[00038] In a tenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG waveform is one of time-domain bioimpedance waveform and a time-domain bioreactance waveform.

[00039] In an eleventh aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the PCG waveform is a time-domain acoustic waveform.

[00040] In a twelfth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the respiratory event is one of a cough and a wheeze.

[00041] In a thirteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG sensor is configured to inject current into the patient's chest, and further configured to measure the current to determine the IPG waveform.

[00042] In a fourteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG sensor is configured to inject current at multiple frequencies into the patient's chest, and further configured to measure the current at multiple frequencies to determine the IPG waveform at multiple frequencies.

[00043] In a fifteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the IPG sensor is configured to inject current at a single frequency into the patient's chest, and further configured to measure the current at the single frequency to determine the IPG waveform at the single frequency.

[00044] In a sixteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the reflective optical sensor further includes a heating element.

[00045] In a seventeenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the heating element comprises a resistive heater.

[00046] In an eighteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the resistive heater is a flexible film.

[00047] In a nineteenth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the housing is of solid, unitary construction.

[00048] In a twentieth aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, the set of electrodes is a single electrode patch.

[00049] In a twenty-first aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, a sensor for measuring a bio-reactance waveform from a patient's chest includes an electrical circuit for performing a bio-reactance measurement, a housing, and a set of electrodes. The electrical circuit is configured to inject current into the patient's chest and measure a time-dependent phase change of the injected current to determine the bio-reactance waveform. The housing is configured to be located on the patient's chest and includes the electrical circuit. The set of electrodes is in electrical contact with the electrical circuit and configured to attach the housing to the patient's chest.

[00050] In a twenty-second aspect of the present disclosure, which may be combined with any other aspect listed herein unless specified otherwise, a sensor for determining a coughing action by a patient includes an electrical circuit for performing a time-dependent impedance measurement, a housing, a set of electrodes, and a computer code. The electrical circuit is configured to inject current into the patient's chest and measure a time-dependent change in the injected current to determine an impedance waveform. The housing is configured to be located on the patient's chest and includes the electrical circuit board and a microprocessor. The set of electrodes is in electrical contact with the electrical circuit and configured to attach the housing to the patient's chest. The computer code operates on the microprocessor and is configured to analyze the impedance waveform to determine the coughing action.

[00051] Additional features and advantages of the disclosed devices, systems, and methods are described in, and will be apparent from, the following Detailed Description and the Figures. The features and advantages described herein are not all-inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the figures and description. Also, any particular embodiment does not have to have all of the advantages listed herein. Moreover, it should be noted that the language used in the specification has been selected for readability and instructional purposes, and not to limit the scope of the inventive subject matter.

[00052] In yet another aspect of the present disclosure, there is provided sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's

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chest, the sensor comprising: a housing configured to be located on the patient's chest; a reflective optical sensor for measuring the PPG waveform; a digital microphone for measuring the PCG waveform; a buzzer disposed in the housing adjacent to the digital microphone, the buzzer configured to generate an acoustic sound at a known amplitude and frequency; a processor disposed within the housing; and a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform, wherein the set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform, wherein the IPG sensor is configured to inject current at multiple frequencies into the patient's chest, and further configured to measure the current at multiple frequencies to determine the IPG waveform at multiple frequencies, wherein the digital microphone is configured to compare the acoustic sound generated by the buzzer with the PCG waveform to determine a quality of patient-sensor adhesion between the sensor and a surface of the patient's chest, and wherein the processor uses time-domain analysis and frequency-domain analysis of the IPG waveform and uses time-domain analysis and frequency-domain analysis of the PCG waveform to collectively determine one of a coughing event, a wheezing event, and an apnea event by identifying amplitude modulation in the IPG waveform.

[00053] In yet another aspect of the present invention, there is provided a sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's chest, the sensor comprising: a housing configured to be located on the patient's chest; a reflective optical sensor for measuring the PPG waveform; a digital microphone for measuring the PCG waveform; a buzzer disposed in the housing adjacent to the digital microphone, the buzzer configured to generate an acoustic sound at a known amplitude and frequency; a processor disposed within the housing; and a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform, wherein the set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform at multiple frequencies, and wherein the IPG waveform at multiple frequencies, wherein the IPG waveform at multiple frequencies and the PCG waveform are used to determine a respiratory event, wherein the digital microphone is configured to compare the acoustic sound generated by the buzzer with the PCG waveform to determine a quality of patient-sensor adhesion between the sensor and a surface of the patient's

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chest, and wherein the processor uses time-domain analysis and frequency-domain analysis of the IPG waveform and uses time-domain analysis and frequency-domain analysis of the PCG waveform to collectively determine one of a coughing event, a wheezing event, and an apnea event by identifying amplitude modulation in the IPG waveform.

BRIEF DESCRIPTION OF THE DRAWINGS

[00054] Understanding that figures depict only typical embodiments of the invention and are not to be considered to be limiting the scope of the present disclosure, the present disclosure is described and explained with additional specificity and detail through the use of the accompanying figures. The figures are listed below.

[00055] Fig. 1 is a perspective view of a patient wearing a patch sensor according to the invention;

[00056] Fig. 2 is a perspective view of a back surface of the patch sensor shown in Fig. 1;

[00057] Fig. 3 is a cross-sectional view of the acoustic sensor used in the patch sensor;

[00058] Fig. 4 is an exploded drawing of the optical sensor used in the patch sensor;

[00059] Fig. 5 is a drawing of the bottom surface of the optical sensor shown in Fig. 4.

[00060] Figs. 6A-C are drawing of different embodiments of the disposable electrode that adheres the patch sensor to the patient's chest;

[00061] Fig. 7 is drawing of a patient lying in a hospital bed and wearing the patch sensor according to the invention, with the patch sensor transmitting information through a gateway to a cloud-based system;

[00062] Fig. 8A is a time-dependent plot of an ECG waveform collected from a patient;

[00063] Fig. 8B is a time-dependent plot of a PPG waveform collected simultaneously and from the same patient as the ECG waveform shown in Fig. 8A;

[00064] Fig. 8C is a time-dependent plot of a IPG waveform collected simultaneously and from the same patient as the ECG waveform shown in Fig. 8A;

[00065] Fig. 8D is a time-dependent plot of a PCG waveform collected simultaneously and from the same patient as the ECG waveform shown in Fig. 8A;

[00066] Fig. 8E is a motion waveform collected simultaneously and from the same patient as the ECG waveform shown in Fig. 8A;

[00067] 9A is a time-dependent plot of ECG and PCG waveforms generated with the patch sensor from a single heartbeat from a patient, along with circular symbols marking fiducial points in these waveforms and indicating a time interval related to S2;

[00068] 9B is a time-dependent plot of an ECG waveform and the mathematical derivative of an IPG waveform generated with the patch sensor from a single heartbeat from a patient, along with circular symbols marking fiducial points in these waveforms and indicating a time interval related to B;

[00069] 9C is a time-dependent plot of an ECG waveform and the mathematical derivative of an IPG waveform generated with the patch sensor from a single heartbeat from a patient, along with an arrow symbol marking a amplitude related to $(dZ/dt)_{max}$;

[00070] Fig. 9D is a time-dependent plot of ECG and PPG waveforms generated with the patch sensor from a single heartbeat from a patch patient, along with circular symbols marking fiducial points in these waveforms and indicating a time interval related to PAT;

[00071] Fig. 9E is a time-dependent plot of an ECG waveform and the mathematical derivative of an IPG waveform generated with the patch sensor from a single heartbeat from a patient, along with circular symbols marking fiducial points in these waveforms and indicating a time interval related to C;

[00072] 9F is a time-dependent plot of ECG and IPG waveforms generated with the patch sensor from a single heartbeat from a patient, along with an arrow symbol marking an amplitude related to Z_0;

[00073] Fig. 10A is a time-dependent plot of a PPG waveform measured with the optical sensor of Fig. 3B before heat is applied to an underlying surface of a patient's skin;

[00074] Fig. 10B is a time-dependent plot of a PPG waveform measured with the optical sensor of Fig. 3B after heat is applied to an underlying surface of a patient's skin;

[00075] Fig. 11A is an alternate embodiment of the patch sensor of the invention;

[00076] Fig. 11B is an image of a patient wearing the patch sensor of Fig. 11A on their chest;

[00077] Fig. 12 is a plot resistance and reactance, as measured at multiple frequencies using the impedance sensor within the patch sensor of the invention;

[00078] Fig. 13 is a plot of PPG waveforms measured from a patient's wrist and IPG waveforms measured simultaneously from the patient's chest during different respiratory events; and

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[00079] Fig. 14 are plots of IPG and PCG waveforms, measured in the time and frequency domains, during coughing and wheezing events.

DETAILED DESCRIPTION

[00080] It is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The invention is capable of embodiments in addition to those described and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein, as well as the abstract, are for the purpose of description and should not be regarded as limiting.

[00081] As such, those skilled in the art will appreciate that the conception upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, methods and systems for carrying out the several purposes of the present invention. It is important, therefore, that the claims be regarded as including such equivalent constructions insofar as they do not depart from the spirit and scope of the present invention.

Patch Sensor

[00082] As shown in Figs. 1 and 2, a patch sensor 10 according to the invention measures ECG, PPG, PCG, and IPG waveforms from a patient 12, and from these calculates vital signs (HR, HRV, SpO2, RR, BP, TEMP) and hemodynamic parameters (FLUIDS, SV, and CO) as described in detail below. The IPG waveform may be a bio-impedance waveform or a bio-reactance waveform, as described in more detail below. Once this information is determined, the patch sensor 10 wirelessly transmits it to an external gateway, which then forwards it to a cloud-based system. In this way, a clinician can continuously and non-invasively monitor the patient 12, who may be located in either the hospital or home.

[00083] The patch sensor 10 features two primary components: a central sensing/electronics module 30 worn near the center of the patient's chest, and secondary battery 57 worn near the patient's left shoulder. A flexible, wire-containing cable 34 connects the central sensing/electronics module 30 and the battery 57. The central sensing/electronics module 30 includes an optical sensor 36 and an acoustic sensor 46 on its patient-contacting surface, and includes four electrode leads 41, 42, 43, 45 that connect to adhesive electrodes and help secure the

patch sensor 10 (and particularly the optical sensor 36 and acoustic sensor 46) to the patient 12. An additional two electrode leads 47, 48 connect the secondary battery to the patient's chest. The central sensing/electronics module 30 features two 'halves' 39A, 39B, each housing sensing and electronic components described in more detail below, that are separated by a first flexible rubber gasket 38. Flexible circuits (not shown in the figure) typically made of a Kapton® with embedded electrical traces connect fiberglass circuit boards (also not shown in the figure) within the acoustic module 32 and the two halves 39A, 39B of the central sensing/electronics module 30. A first adhesive, disposable electrode 49 connects the central sensing/electronics module 30 to the patient's chest. A second disposable electrode 69 connects the secondary battery 57 to the patient's chest.

[00084] Referring more specifically to Fig. 2, the patch sensor 10 includes a back surface that, during use, contacts the patient's chest through a set of single-use, adhesive electrodes 49, 69. One half 39B of the central sensing/electronics module 30 includes two electrode leads 41, 42. These, coupled with the electrode leads 47, 48 connected to the optical sensor 36, attach through a magnetic interface to the set of single-use electrodes. The electrode leads 41, 42, 47, 48 form two 'pairs' of leads, wherein one of the leads 41, 47 in each pair injects electrical current to measure IPG waveforms, and the other leads 42, 48 in each pair sense bio-electrical signals that are then processed by electronics in the central sensing/electronics module 30 to determine the ECG and IPG waveforms. The opposing half 39A of the central sensing/electronics module 30 includes another electrode contact 43 that, like electrode leads 41, 42, 47, 48, connects to a single-use electrode (also not shown in the figure) to help secure the patch sensor 10 to the patient 12.

[00085] The IPG measurement is made when the current-injecting electrodes 41, 47 inject high-frequency (e.g., 100 kHz), low-amperage (e.g., 4mA) current into the patient's chest. Current may be injected at other frequencies, or, additionally or alternatively, sequentially injected at different frequencies. The electrodes 42, 48 sense a voltage that will vary with the resistance encountered by the injected current. This, in turn, will impact both the amplitude and the phase of the injected current. The voltage passes through a series of electrical circuits featuring analog filters and differential amplifiers to, respectively, filter out and amplify signal components related to the two different waveforms. One of the signal components indicates the ECG waveform; another indicates the IPG waveform. Depending on the circuit used to measure it, the IPG waveform can indicate time-dependent changes in either the amplitude or the phase of the injected current. In both cases,

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the IPG waveform has low-frequency (DC) and high-frequency (AC) components that are further filtered out and processed, as described in more detail below, to determine different impedance waveforms.

[00086] Use of a cable 34 to connect the central sensing/electronics module 30 and the optical sensor 36 means the electrode leads (41, 42 in the central sensing/electronics module 30; 47, 48 in the optical sensor 36) can be separated by a relatively large distance when the patch sensor 10 is attached to a patient's chest. For example, the optical sensor 36 can be attached near the patient's left shoulder, as shown in Fig. 1. Such separation between the electrode leads 41, 42, 47, 48 typically improves the signal-to-noise ratios of the ECG and IPG waveforms measured by the patch sensor 10, as these waveforms are determined from difference of bio-electrical signals collected by the single-use electrodes, which typically increases with electrode separation. Ultimately this improves the accuracy of any physiological parameter detected from these waveforms, such as HR, HRV, RR, BP, SV, CO, and FLUIDS.

[00087] Referring to Fig. 3, the acoustic module 46 features a solid-state acoustic microphone that is a thin, piezoelectric disk 109 surrounded by foam substrates 111, 112. Another foam substrate 113 contacts the patient's chest during the measurement, and couples sounds from the patient's heart through the first foam substrate 111, and into the piezoelectric disk 109, which then measures heart sounds from the patient 12. A plastic enclosure 115 encloses the entire acoustic module 46. It should be appreciated that other related types of microphones, such one featuring an acoustic bell and underlying pressure sensor, can also be used.

[00088] The heart sounds are the 'lub' and 'dub' sounds typically heard from the heart with a stethoscope; they indicate when the underlying mitral and tricuspid (S1, or 'lub' sound) and aortic and pulmonary (S2, or 'dub' sound) valves close (no detectable sounds are generated when the valves open). With signal processing, the heart sounds yield a PCG waveform that is used along with other signals to determine BP, as is described in more detail below. In other embodiments, two solid-state acoustic microphones 45, 46 are used to provide redundancy and better detect the sounds. The acoustic module 32, like the half 39A of the central sensing/electronics module 30, includes an electrical contact 43 that connects to a single-use electrode (also not shown in the figure) to help secure the patch sensor 10 to the patient 12.

[00089] The optical sensor 36 features an optical system 60 that includes an array of photodetectors 62, arranged in a circular pattern, that surround a LED 61 that emits radiation in

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the red and infrared spectral regions. During a measurement, sequentially emitted red and infrared radiation from the LED 61 irradiates and reflects off underlying tissue in the patient's chest, and is detected by the array of photodetectors 62. The detected radiation is modulated by blood flowing through capillary beds in the underlying tissue. Processing the reflected radiation with electronics in the central sensing/electronics module 30 results in PPG waveforms corresponding to the red and infrared radiation, which as described below are used to determine BP and SpO2.

[00090] The patch sensor 10 also typically includes a three-axis digital accelerometer and a temperature sensor (not specifically identified in the figure) to measure, respectively, three time-dependent motion waveforms (along x, y, and z-axes) and TEMP values.

[00091] Figs. 4 and 5 show the optical sensor 36 in more detail. As described above, the sensor 36 features an optical system 60 with a circular array of photodetectors 62 (six unique detectors are shown in the figure, although this number can be between three and nine photodetectors) that surround a dual-wavelength LED 61 that emits red and infrared radiation. A heating element featuring a thin Kapton® film 65 with embedded electrical conductors arranged in a serpentine pattern is adhered to the bottom surface of the optical sensor 36. Other patterns of electrical conductors can also be used. The Kapton® film 65 features cut-out portions that pass radiation emitted by the LED 61 and detected by the photodetectors 62 after it reflects off the patient's skin. A tab portion 67 on the thin Kapton® film 65 folds over so it can plug into a connector 74 on a fiberglass circuit board 80. The fiberglass circuit board 80 supports and provides electrical connections to the array of photodetectors 62 and the LED 61. During use, software operating on the patch sensor 10 controls power-management circuitry on the fiberglass circuit board 80 to apply a voltage to the embedded conductors within the thin Kapton® film 65, thereby passing electrical current through them. Resistance of the embedded conductors causes the film 65 to gradually heat up and warm the underlying tissue. The applied heat increases perfusion (i.e., blood flow) to the tissue, which in turn improves the signal-to-noise ratio of the PPG waveform. This is shown in Fig. 10A, which shows a PPG waveform measured before heat is applied, and Fig. 10B, which shows a PPG waveform measured after heat is applied with the Kapton® film 65. As is clear from the figures, heat increases the perfusion underneath the optical sensor 36. This, in turn, dramatically improves the signal-to-noise ratio of heartbeat-induced pulses in the PPG waveform. This is important for the patch sensor's optical measurements, as PPG waveforms measured from the chest typically have a signal-to-noise ratio that is 10X to 100X weaker than similar waveforms

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measured from typical locations used by pulse oximeters, such as the fingers, earlobes, and forehead. PPG waveforms with improved signal-to-noise ratios typically improve the accuracy of BP and SpO2 measurements made by the patch sensor 10. The fiberglass circuit board 80 also includes a temperature sensor 76 that integrates with the power-management circuitry, allowing the software to operate in a closed-loop manner to carefully control and adjust the applied temperature. Here, 'closed-loop manner' means that the software analyzes amplitudes of heartbeat-induced pulses the PPG waveforms, and, if necessary, increases the voltage applied to the Kapton® film 65 to increase its temperature and maximize the heartbeat-induced pulses in the PPG waveforms. Typically, the temperature is regulated at a level of between 41°C and 42°C, which has been shown to not damage the underlying tissue, and is also considered safe by the U.S. Food and Drug Administration (FDA).

[00092] A plastic housing 44 featuring a top portion 53 and a bottom portion 70 enclose the fiberglass circuit board 80. The bottom portion 70 also supports the Kapton® film 65, has cut-out portions 86 that passes optical radiation, and includes a pair of snaps 84, 85 that connect to mated components on the top portion 53. The top portion also includes a pair of 'wings' that enclose the electrode leads 47, 48 which, during use, connect to the single-use, adhesive electrodes (not shown in the figure) that secure the optical sensor 36 to the patient. These electrode leads 47, 48 also measure electrical signals that are used for the ECG and IPG measurements. The top portion 53 also includes a mechanical strain relief 68 that supports the cable 34 connecting the optical sensor 36 to the central sensing/electronics module 30.

[00093] The patch sensor 10 typically measures waveforms at relatively high frequencies (e.g., 250 Hz). Multiple frequencies, typically spanning from 5KHz to 1000KHz, can be used to measure impedance waveforms. In other embodiments, single or multiple frequencies are used to measure bio-reactance waveforms, which are based on the phase difference between the injected and measurement current. Both impedance and bio-reactance measurement can be measured at multiple frequencies, as described above.

[00094] An internal microprocessor running firmware processes the waveforms with computational algorithms to generate vital signs and hemodynamic parameters with a frequency of about once every minute. Examples of algorithms are described in the following co-pending and issued patents, the contents of which are incorporated herein by reference: "NECK-WORN PHYSIOLOGICAL MONITOR," U.S.S.N. 14/975,646, filed December 18, 2015; "NECKLACE-

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SHAPED PHYSIOLOGICAL MONITOR," U.S.S.N 14/184,616, filed 8/21/2014; and "BODY-WORN SENSOR FOR CHARACTERIZING PATIENTS WITH HEART FAILURE," U.S.S.N 14/145,253, filed July 3, 2014.

[00095] Referring to Figs. 6A-6C show different configurations of the disposable electrodes 49A-I that surround the optical sensor 36 and acoustic sensor 45, and connect the central sensing/electronics module 30 to the patient's chest.

[00096] The patch sensor 10 shown in Figs. 1 to 6 is designed to maximize comfort and reduce 'cable clutter' when deployed on a patient, while at the same time optimizing the ECG, IPG, PPG, and PCG waveforms it measures to determine physiological parameters such as HR, HRV, BP, SpO2, RR, TEMP, FLUIDS, SV, and CO. The first 38 and second 51 flexible rubber gaskets allow the sensor 10 to flex on a patient's chest, thereby improving comfort. The central sensing/electronics module 30 positions the first pair of electrode leads 41, 42 above the heart, where bio-electrical signals are typically strong, while the cable-connected optical sensor 36 positions the second pair of electrode leads 47, 48 near the shoulder, where they have large separation from the first pair. As described above, this configuration results in ideal ECG and IPG waveforms. The acoustic module 32 is positioned directly above the patient's heart, and includes multiple acoustic sensors 45, 46 to optimize PCG waveforms and the heart sounds indicated therein. And the optical sensor is positioned near the shoulder, wherein underlying capillary beds typically result in PPG waveforms having good signal-to-noise ratios, especially when perfusion is increased by the sensor's heating element.

[00097] This patch sensor's design also allows it to comfortably fit both male and female patients. An additional benefit of its chest-worn configuration is reduction of motion artifacts, which can distort waveforms and cause erroneous values of vital signs and hemodynamic parameters to be reported. This is due, in part, to the fact that during everyday activities, the chest typically moves less than the hands and fingers, and subsequent artifact reduction ultimately improves the accuracy of parameters measured from the patient.

Use Cases

[00098] As shown in Fig. 7, in a preferred embodiment, a patch sensor 10 according to the invention is designed to monitor a patient 12 during a hospital stay. Typically, the patient 12 is situated in a hospital bed 11. As indicated above, in a typical use case, the patch sensor 10

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continuously measures numerical and waveform data, and then sends this information wirelessly (as indicated by arrow 77) to a gateway 22, which can be a number of different devices. For example, the gateway 22 can be any device operating a short-range wireless (e.g., Bluetooth®) wireless transmitter, such as a mobile telephone, tablet computer, vital sign monitor, central station (e.g., nursing station in a hospital), hospital bed, 'smart' television set, single-board computer, infusion pump, syringe pump, or a simple plug-in unit. The gateway 22 wirelessly forwards information (as indicated by arrow 87) from the patch sensor 10 to a cloud-based software system 200. Typically, this is done with a wireless cellular radio, or one based on an 802.11a-g protocol. There, it can be consumed and processed by a variety of different software systems, such as an EMR, a third-party software system, or a data-analytics engine.

[00099] In another embodiment, the sensor collects data and then stores it in internal memory. The data can then be sent wirelessly (e.g., to the cloud-based system, EMR, or central station) at a later time. For example, in this case, the gateway 22 can include an internal Bluetooth® transceiver that sequentially and automatically pairs with each sensor attached to a charging station. Once all the data collected during use are uploaded, the gateway then pairs with another sensor attached to the charging station and repeats the process. This continues until data from each sensor is downloaded.

[000100] In other embodiments, the patch sensor can be used to measure ambulatory patients, patients undergoing dialysis in either the hospital, clinic, or at home, or patients waiting to see a doctor in a medical clinic. Here, the patch sensor can transmit information in real time, or store it in memory for transmission at a later time.

Determining Cuffless Blood Pressure

[000101] The patch sensor determines BP by collectively processing time-dependent ECG, IPG, PPG, and PCG waveforms, as shown in Figs. 6A-E. Each waveform is typically characterized by a heartbeat-induced 'pulse' that is affected in some way by BP. More specifically, embedded firmware operating on the patch sensor processes pulses in these waveforms with 'beatpicking' algorithms to determine fiducial makers corresponding to features of each pulse; these markers are then processed with algorithms, described below, to determine BP. In Figs. 6A-E, the fiducial makers for pulses within the ECG, IPG, PPG, and PCG waveforms are indicated with '×' symbols.

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[000102] An ECG waveform measured by the patch sensor is shown in Fig. 8A. It includes a heartbeat-induced QRS complex that informally marks the beginning of each cardiac cycle. Fig. 8D shows a PCG waveform, which is measured with the acoustic module and features the S1 and S2 heart sounds. Fig. 8B shows a PPG waveform, which is measured by the optical sensor, and indicates volumetric changes in underlying capillaries caused by heartbeat-induced blood flow. The IPG waveform includes both DC (Z_0) and AC (dZ(t)) components: Z_0 indicates the amount of fluid in the chest by measuring underlying electrical impedance, and represents the baseline of the IPG waveform; dZ(t), which is shown in Fig. 8C, tracks blood flow in the thoracic vasculature and represents the pulsatile components of the IPG waveform. The time-dependent derivative of dZ(t) –dZ(t)/dt– includes a well-defined peak that indicates the maximum rate of blood flow in the thoracic vasculature. A motion waveform measured by the accelerometer is shown in Fig. 8E.

[000103] Each pulse in the ECG waveform (Fig. 8A) features a QRS complex that delineates a single heartbeat. Feature-detection algorithms operating in firmware on the patch sensor calculate time intervals between the QRS complex and fiducial markers on each of the other waveforms. For example, the time separating a 'foot' of a pulse in the PPG waveform (Fig. 8B) and the QRS complex is referred to as PAT. PAT relates to BP and systemic vascular resistance. During a measurement, the patch sensor calculates PAT and VTT which is a time difference between fiducial markers in waveforms other than ECG, such as the S1 or S2 points in a pulse in the PCG waveform (Fig. 8D) and the foot of the PPG waveform (Fig. 8B). Or the peak of a pulse in the dZ(t)/dt waveform and the foot of the PPG waveform (Fig. 8B). In general, any set of time-dependent fiducials determined from waveforms other than ECG can be used to determine VTT. Collectively, PAT, VTT, and other time-dependent parameters extracted from pulses in the four physiologic waveforms are referred to herein as 'INT' values. Additionally, firmware in the patch sensor calculates information about the amplitudes of heartbeat-induced pulses in some of the waveforms; these are referred to herein as 'AMP' values. For example, the amplitude of the pulse in the derivative of the AC component of the IPG waveform ((dZ(t)/dt)max) indicates the volumetric expansion and forward blood flow of the thoracic arteries, and is related to SYS and the contractility of the heart.

[000104] The general model for calculating SYS and DIA involves extracting a collection of INT and AMP values from the four physiologic waveforms measured by the patch sensor, and then using algorithms based in machine learning and artificial intelligence to process these values

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to determine blood pressure. Figs. 9A-F, for example, show different INT and AMP values that may correlate to BP. INT values include the time separating R and S2 from a pulse in the PCG waveform (RS2, shown in Fig. 9A); the time separating R and the base of a derivative of a pulse from the AC component of the IPG waveform (RB, Fig. 9B); the time separating R and the foot of a pulse in the PPG waveform (PAT, Fig. 9D); and the time separating R and the maximum of a derivative of a pulse from the AC component of the IPG waveform (RC, Fig. 9E). AMP values include the maximum value of a derivative of a pulse from the AC component of the IPG waveform ((dZ(t)/dt)max, Fig. 9C); and the maximum value of the DC component of the IPG waveform (Z_0, Fig. 9F). Any of these parameters may be used, in combination with a calibration defined below, to determine blood pressure. All of these fiducial values can serve as input into the blood pressure model based on machine learning and artificial intelligence.

[000105] The method for determining BP according to the invention involves first calibrating the BP measurement during a short initial period, and then using the resulting calibration for subsequent measurements. The calibration process typically lasts for about 5 days. It involves measuring the patient multiple (e.g., 2 to 4) times with a cuff-based BP monitor employing oscillometry, while simultaneously collecting the INT and AMP values like those shown in Figs. 9A-F. Each cuff-based measurement results in separate values of SYS, DIA, and MAP. In embodiments, one of the cuff-based BP measurements is coincident with a 'challenge event' that alters the patient's BP, such as squeezing a handgrip, changing posture, or raising their legs. The challenge events typically impart variation in the calibration measurements; this can help improve the ability of the calibration to track BP swings. Typically, the patch sensor and cuff-based BP monitor are in wireless communication with each other; this allows the calibration process to be fully automated, such as information between the two systems can be automatically shared without any user input. Processing the INT and AMP values, such as using the method shown in Fig. 9 and described in more detail below, results in a 'BP calibration'. This includes initial values of SYS and DIA, which are typically averaged from the multiple measurements made with the cuff-based BP monitor, along with a patient-specific model that is used in combination with selected INT and AMP values to cufflessly determine the patient's blood pressure. The calibration period (about 5 days), is consistent with a conventional hospital stay; after this, the patch sensor typically requires a new calibration to ensure accurate BP measurements.

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Alternate Embodiments

[000106] The patch sensor described herein can have a form factor that differs from that shown in Fig. 1. Fig. 11A, for example, shows such an alternate embodiment. Like the preferred embodiment described above, the patch sensor 210 in Fig. 11A features two primary components: a central sensing/electronics module 230 worn near the center of the patient's chest, and an optical sensor 236 worn near the patient's left shoulder. Electrode leads 241, 242 measure bio-electrical signals for the ECG and IPG waveforms and secure the central sensing/electronics module 230 to the patient 12, similar to the manner as described above. A flexible, wire-containing cable 234 connects the central sensing/electronics module 230 and the optical sensor 236. In this case, the central sensing/electronics module 230 features a substantially rectangular shape, as opposed to a substantially circular shape shown in Fig. 1. The optical sensor 236 includes two electrode leads 247, 248 that connect to adhesive electrodes and help secure the patch sensor 210 (and particularly the optical sensor 236) to the patient 12. The distal electrode lead 248 connects to the optical sensor through an articulating arm 245 that allows it to extend further out near the patient's shoulder, thereby increasing its separation from the central sensing/electronics module 230. Fig. 11B shows the patch sensor 210 worn on the chest of a patient 12.

[000107] The electrode leads 241, 242, 247, 248 form two 'pairs' of leads, wherein one of the leads 241, 247 injects electrical current to measure IPG waveforms, and the other leads 242, 248 sense bio-electrical signals that are then processed by electronics in the central sensing/electronics module 230 to determine the ECG and IPG waveforms. The IPG waveform measured by the patch sensor can be measured at multiple frequencies and is defined by an impedance magnitude and phase angle, both of which vary as a function of time and can be measured using different frequencies of injected current. Fig. 12, for example, shows resistance (which represents the impedance magnitude) and reactance (which represents the impedance phase angle) measured at different frequencies. Typically, time-dependent reactance waveforms yield more accurate values of SV and CO compared to conventional IPG waveforms. At low frequencies, current injected from the IPG measurement is unable to penetrate cells that it encounters because of the capacitance of the cellular walls, and thus samples mostly extra-cellular fluids; for this reason, it may be desirable to make low-frequency measurements to characterize parameters such as extra-cellular fluids. At high frequencies, current injected from the IPG measurement passes through the cellular walls, and thus samples both intra-cellular and extra-

cellular fluids. The patch sensor described herein can include IPG, resistance, and/or reactance measurements made at one or more frequency.

[000108] The acoustic module 232 includes one or more solid-state acoustic microphones (not shown in the figure, but similar to that shown in Fig. 1) that measure heart sounds from the patient 12. The optical sensor 236 attaches to the central sensing/electronics module 30 through the flexible cable 234, and features an optical system (also not shown in the figure, but similar to that shown in Fig. 1) that includes an array of photodetectors, arranged in a circular pattern, that surround a LED that emits radiation in the red and infrared spectral regions. During a measurement, sequentially emitted red and infrared radiation emitted from the LED irradiates and reflects off underlying tissue in the patient's chest, and is detected by the array of photodetectors.

[000109] In other embodiments, an amplitude of either the first or second (or both) heart sound is used to predict blood pressure. Blood pressure typically increases in a linear manner with the amplitude of the heart sound. In embodiments, a universal calibration describing this linear relationship may be used to convert the heart sound amplitude into a value of blood pressure. Such a calibration, for example, may be determined from data collected in a clinical trial conducted with a large number of subjects. Here, numerical coefficients describing the relationship between blood pressure and heart sound amplitude are determined by fitting data determined during the trial. These coefficients and a linear algorithm are coded into the sensor for use during an actual measurement. Alternatively, a patient-specific calibration can be determined by measuring reference blood pressure values and corresponding heart sound amplitudes during a calibration measurement, which proceeds an actual measurement. Data from the calibration measurement can then be fit as described above to determine the patient-specific calibration, which is then used going forward to convert heart sounds into blood pressure values.

[000110] In embodiments, the IPG and PCG sensors can be used in a patch to detect respiratory conditions. For example, in a study conducted with the patch, N = 11 subjects (9M, 2F) underwent: 1) normal breathing (initially and between all respiratory events); 2) coughing (5 times; 2 events); 3) wheezing (5 times; 2 events); and 4) apnea (1 event). Subjects were measured using the patch, which was applied to each subject's chest to collect the following time-dependent waveforms: 1) electrocardiogram (ECG); 2) optical photoplethysmogram (PPG); 3) impedance plethysmogram (IPG); 4) accelerometer signal (ACC); and 5) acoustic phonocardiogram (PCG). For this analysis, PCG waveforms were processed to determine a 'Shannon Envelogram', which

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simplifies analysis by rendering an envelope essentially representing the underlying high-frequency signals. During a three-minute measurement period, each subject underwent the 4 respiratory events listed above (normal breathing took place for the first 60 seconds; respiratory events followed, as indicated by the dashed lines in Fig. 13) while the Patch measured the time-dependent waveforms. Fig. 13 shows sample waveforms collected from a single subject participating in the study. Once measured, each waveform was analyzed by a subject-matter expert and ranked for its ability to accurately characterize the different respiratory events, with a '0' ranking indicating no ability, and a '3' ranking indicating excellent ability. This is an informal analysis, and will be performed in a more rigorous manner (e.g., one that includes both true positive/negative and false positive/negative rankings) at a later time. These results are summarized as follows:

- Best waveform for characterizing normal breathing: IPG
- Best waveform for characterizing apnea: IPG
- Best waveforms for characterizing coughing: IPG, ACC, PPG, PCG
- Best waveforms for characterizing wheezing: IPG, ACC, PPG

[000111] The above-described results indicate that the patch's IPG waveform is ideal for characterizing common respiratory events, such as normal breathing, coughing, wheezing, and apnea. A novel impedance sensor measures this waveform. It features an impedance-measuring circuit that injects high-frequency (100 kHz), low-amperage (~4 mA) current into a patient's chest. Respiratory events change air flow within the chest and thus modify its impedance, allowing the impedance-measuring circuit and associated embedded code to easily detect them, as shown in Fig. 13.

[000112] As a follow-on experiment, as shown in Fig. 13, a single subject experiencing the above-described respiratory events was simultaneously measured with an impedance sensor placed on the chest (for IPG waveforms) and an optical sensor placed on the wrist (for PPG waveforms). This allowed direct comparison of the patch's measurements to those made with a conventional wrist-worn activity/heart rate monitor. Fig. 13 shows the resulting waveforms, with the colored dashed lines indicating coughing, wheezing, and apnea as described above, and the gray dashed lines indicating normal breaths.

[000113] Both the IPG and PPG waveforms clearly show heartbeat-induced pulses. Processing the pulses in the IPG waveform yields heart rate, stroke volume and cardiac output,

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while processing them in the PPG waveform yields heart rate and pulse oximetry. However only the chest-measured IPG waveform shows clear amplitude modulation due to normal breathing, coughing, wheezing, and apnea, as described above; the wrist-measured PPG waveform lacks any obvious features that indicate these respiratory events. The data indicate that a chest-worn IPG sensor is superior to a wrist-worn PPG sensor for detecting respiration events.

[000114] Time and frequency-domain analyses of IPG and PCG waveforms collected during coughing and wheezing indicate that these two respiratory events have different 'breath morphologies', meaning a sensor can likely delineate between them using conventional signal-processing techniques. Fig. 14, for example, shows time and frequency-domain plots of IPG and PCG waveforms measured while a single subject was coughing (top left and right, respectively) and wheezing (bottom left and right). The PCG waveform appears particularly sensitive to the different respiratory events. Coughing is characterized by a short, time-dependent 'burst' in the waveform that features relatively high-frequency components; wheezing, in contrast, features a more drawn out profile composed of relatively low-frequency components. Based on these preliminary results, it appears that IPG and PCG waveforms processed with standard signal-processing techniques—used alone or combined with more sophisticated machine-learning algorithms—may be able to categorize different respiratory events.

[000115] Both the first and second heart sounds are typically composed of a collection, or 'packet' of acoustic frequencies. Thus, when measured in the time domain, the heart sounds typically feature a number of closely packed oscillations within to the packet. This can make it complicated to measure the amplitude of the heart sound, as no well-defined peak is present. To better characterize the amplitude, a signal-processing technique can be used to draw an envelope around the heart sound, and then measure the amplitude of the envelope. One well-known technique for doing this involves using a Shannon Energy Envelogram (E(t)), where each data point within E(t) is calculated as shown below:

$$E_{average} = -\frac{1}{N}\sum_{t=1}^{N}[PCG^2(t) \times \log(PCG^2(t))]$$

where N is the window size of E(t). In embodiments, other techniques for determining the envelope of the heart sound can also be used.

[000116] Once the envelope is calculated, its amplitude can be determined using standard techniques, such as taking a time-dependent derivative and evaluating a zero-point crossing.

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Typically, before using it to calculate blood pressure, the amplitude is converted into a normalized amplitude by dividing it by an initial amplitude value measured from an earlier heart sound (e.g., one measured during calibration). A normalized amplitude means the relative changes in amplitude are used to calculate blood pressure; this typically leads to a more accurate measurement.

[000117] In other embodiments, an external device may be used to determine how well the acoustic sensor is coupled to the patient. Such an external device, for example, may be a piezoelectric 'buzzer', or something similar, that generates an acoustic sound and is incorporated into the patch-based sensor, proximal to the acoustic sensor. Before a measurement, the buzzer generates an acoustic sound at a known amplitude and frequency. The acoustic sensor measures the sound, and then compares its amplitude (or frequency) to other historical measurements to determine how well the acoustic sensor is coupled to the patient. An amplitude that is relatively low, for example, indicates that the sensor is poorly coupled. This scenario may result in an alarm alerting the user that the sensor should be reapplied.

[000118] In other alternative embodiments, the invention may use variation of algorithms for finding INT and AMP values, and then processing these to determine BP and other physiological parameters. For example, to improve the signal-to-noise ratio of pulses within the IPG, PCG, and PPG waveforms, embedded firmware operating on the patch sensor can operate a signal-processing technique called 'beatstacking'. With beatstacking, for example, an average pulse (e.g., Z(t)) is calculated from multiple (e.g., seven) consecutive pulses from the IPG waveform, which are delineated by an analysis of the corresponding QRS complexes in the ECG waveform, and then averaged together. The derivative of Z(t) —dZ(t)/dt— is then calculated over an seven-sample window. The maximum value of Z(t) is calculated, and used as a boundary point for the location of $[dZ(t)/dt]_{max}$. This parameter is used as described above. In general, beatstacking can be used to determine the signal-to-noise ratio of any of the INT/AMP values described above.

[000119] In other embodiments, the BP calibration process indicated by the flow chart shown in Fig. 9 can be modified. For example, it may select more than two INT/AMP values to use for the multi-parameter linear fitting process. And the BP calibration data may be calculated with less than or more than four cuff-based BP measurements. In still other embodiments, a non-linear model (e.g., one using a polynomial or exponential function) may be used to fit the calibration data.

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[000120] In still other embodiments, a sensitive accelerometer can be used in place of the acoustic sensor to measure small-scale, seismic motions of the chest driven by the patient's underlying beating heart. Such waveforms are referred to as seismocardiogram (SCG) and can be used in place of (or in concert with) PCG waveforms.

[000121] While the invention has been described and exemplified in sufficient detail for those skilled in this art to make and use it, various alternatives, modifications, and improvements should be apparent without departing from the spirit and scope of the invention. The examples provided herein are representative of preferred embodiments, are exemplary, and are not intended as limitations on the scope of the invention. Modifications therein and other uses will occur to those skilled in the art. These modifications are encompassed within the spirit of the invention and are defined by the scope of the claims.

[000122] It will be readily apparent to a person skilled in the art that varying substitutions and modifications may be made to the invention disclosed herein without departing from the scope and spirit of the invention.

[000123] All patent applications, patents, publications and other references mentioned in the specification are indicative of the levels of those of ordinary skill in the art to which the invention pertains and are each incorporated herein by reference. The references cited herein are not admitted to be prior art to the claimed invention.

[000124] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. In the case of conflict, the present specification, including definitions, will control.

[000125] The use of the articles "a", "an", and "the" in both the description and claims are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising", "having", "being of" as in "being of a chemical formula", "including", and "containing" are to be construed as open terms (i.e.,
meaning "including but not limited to") unless otherwise noted. Additionally whenever "comprising" or another open-ended term is used in an embodiment, it is to be understood that the same embodiment can be more narrowly claimed using the intermediate term "consisting essentially of" or the closed term "consisting of".

[000126] The term "about", "approximately", or "approximate", when used in connection with a numerical value, means that a collection or range of values is included. For example, "about X"

includes a range of values that are ±20%, ±10%, ±5%, ±2%, ±1%, ±0.5%, ±0.2%, or ±0.1% of X, where X is a numerical value. In one embodiment, the term "about" refers to a range of values which are 10% more or less than the specified value. In another embodiment, the term "about" refers to a range of values which are 5% more or less than the specified value. In another embodiment, the term "about" refers to a range of values which are 1% more or less than the specified value.

[000127] Recitation of ranges of values are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. A range used herein, unless otherwise specified, includes the two limits of the range. For example, the terms "between X and Y" and "range from X to Y, are inclusive of X and Y and the integers there between. On the other hand, when a series of individual values are referred to in the disclosure, any range including any of the two individual values as the two end points is also conceived in this disclosure. For example, the expression "a dose of about 100 mg, 200 mg, or 400 mg" can also mean "a dose ranging from 100 to 200 mg", "a dose ranging from 200 to 400 mg", or "a dose ranging from 100 to 400 mg".

[000128] The invention illustratively described herein suitably may be practiced in the absence of any element or elements, limitation or limitations which is not specifically disclosed herein. Thus, for example, in each instance herein any of the terms "comprising", "consisting essentially of" and "consisting of" may be replaced with either of the other two terms. The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention that in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred

embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the appended claims.

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CLAIMS

What is claimed is:

1. A sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's chest, the sensor comprising:

a housing configured to be located on the patient's chest;

a reflective optical sensor for measuring the PPG waveform;

a digital microphone for measuring the PCG waveform;

a buzzer disposed in the housing adjacent to the digital microphone, the buzzer configured to generate an acoustic sound at a known amplitude and frequency;

a processor disposed within the housing; and

a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform,

wherein the set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform,

wherein the IPG sensor is configured to inject current at multiple frequencies into the patient's chest, and further configured to measure the current at multiple frequencies to determine the IPG waveform at multiple frequencies,

wherein the digital microphone is configured to compare the acoustic sound generated by the buzzer with the PCG waveform to determine a quality of patient-sensor adhesion between the sensor and a surface of the patient's chest, and

wherein the processor uses time-domain analysis and frequency-domain analysis of the IPG waveform and uses time-domain analysis and frequency-domain analysis of the PCG waveform to collectively determine one of a coughing event, a wheezing event, and an apnea event by identifying amplitude modulation in the IPG waveform.

2. The sensor of Claim 1, wherein the IPG sensor is configured to inject current at a single frequency into the patient's chest, and further configured to measure the current at the single frequency to determine the IPG waveform at the single frequency.

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3. The sensor of Claim 1 or claim 2, wherein the reflective optical sensor further includes a heating element.

4. The sensor of Claim 3, wherein the heating element comprises a resistive heater.

5. The sensor of Claim 4, wherein the resistive heater is a flexible film.

6. The sensor of any one of Claims 1-5, wherein the housing is of solid, unitary construction.

7. The sensor of any one of Claims 1-6, wherein the set of electrodes is a single electrode patch.

8. A sensor for measuring a photoplethysmogram (PPG) waveform, a phonocardiogram (PCG) waveform, an impedance plethysmogram (IPG) waveform, and an electrocardiogram (ECG) waveform from a patient's chest, the sensor comprising:

a housing configured to be located on the patient's chest;

a reflective optical sensor for measuring the PPG waveform;

a digital microphone for measuring the PCG waveform;

a buzzer disposed in the housing adjacent to the digital microphone, the buzzer configured to generate an acoustic sound at a known amplitude and frequency;

a processor disposed within the housing; and

a set of electrodes that attach the optical sensor and the digital microphone to the patient's chest, with the set of electrodes connected to an ECG sensor configured to measure the ECG waveform,

wherein the set of electrodes is further attached to an IPG sensor, the IPG sensor configured to measure the IPG waveform at multiple frequencies,

wherein the IPG waveform at multiple frequencies and the PCG waveform are used to determine a respiratory event,

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wherein the digital microphone is configured to compare the acoustic sound generated by the buzzer with the PCG waveform to determine a quality of patient-sensor adhesion between the sensor and a surface of the patient's chest, and

wherein the processor uses time-domain analysis and frequency-domain analysis of the IPG waveform and uses time-domain analysis and frequency-domain analysis of the PCG waveform to collectively determine one of a coughing event, a wheezing event, and an apnea event by identifying amplitude modulation in the IPG waveform.

9. The sensor of Claim 8, wherein the IPG waveform is one of time-domain bioimpedance waveform and a time-domain bioreactance waveform.

10. The sensor of Claim 8 or claim 9, wherein the PCG waveform is a time-domain acoustic waveform.

11. The sensor of any one of Claims 8-10, wherein the respiratory event is one of a cough and a wheeze.

12. The sensor of any one of Claims 8-11, wherein the IPG sensor is configured to inject current into the patient's chest, and further configured to measure the current to determine the IPG waveform.

13. The sensor of any one of Claims 8-12, wherein the IPG sensor is configured to inject current at a single frequency into the patient's chest, and further configured to measure the current at the single frequency to determine the IPG waveform at the single frequency.

14. The sensor of any one of Claims 8-13, wherein the reflective optical sensor further includes a heating element.

15. The sensor of Claim 14, wherein the heating element comprises a resistive heater.

16. The sensor of Claim 15, wherein the resistive heater is a flexible film.

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17. The sensor of any one of Claims 8-16, wherein the housing is of solid, unitary construction.

18. The sensor of any one of Claims 8-17, wherein the set of electrodes is a single electrode patch.

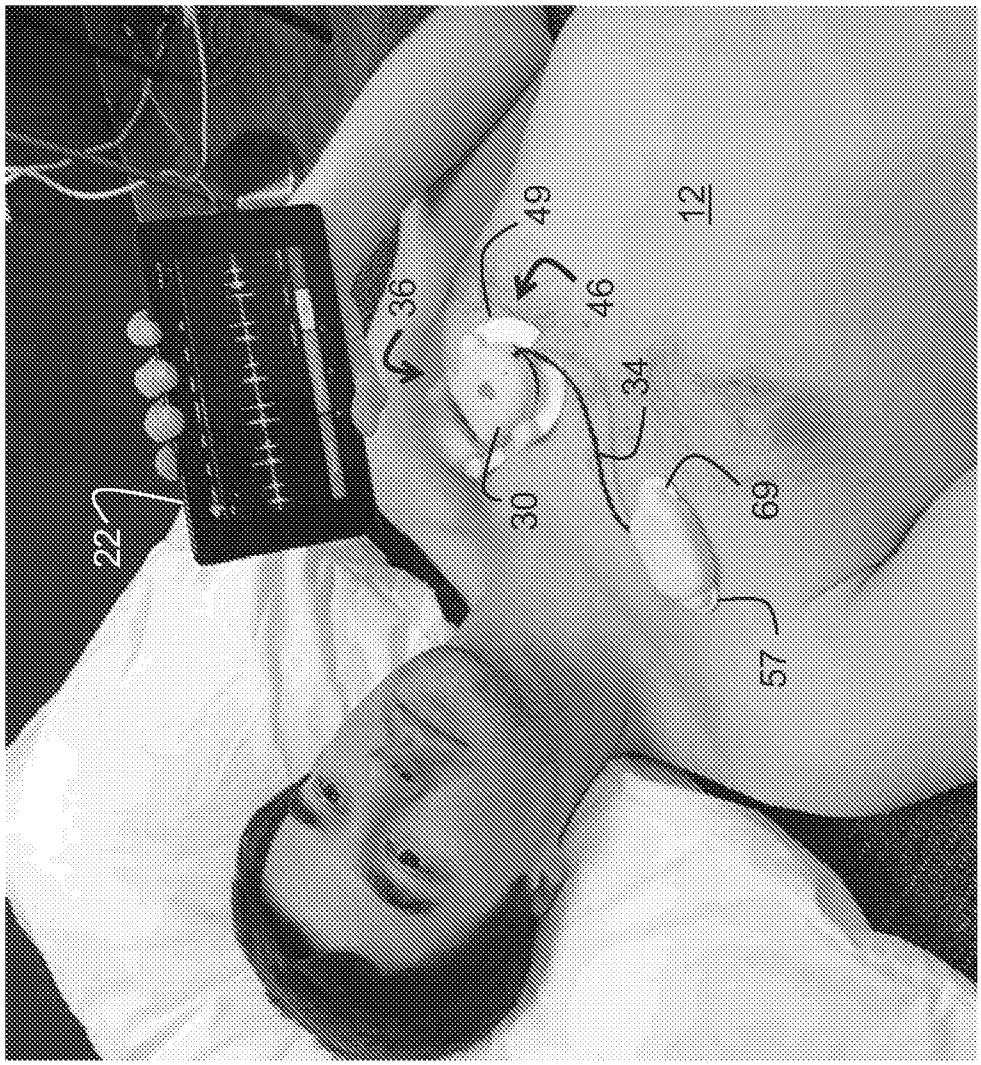


Fig. 1

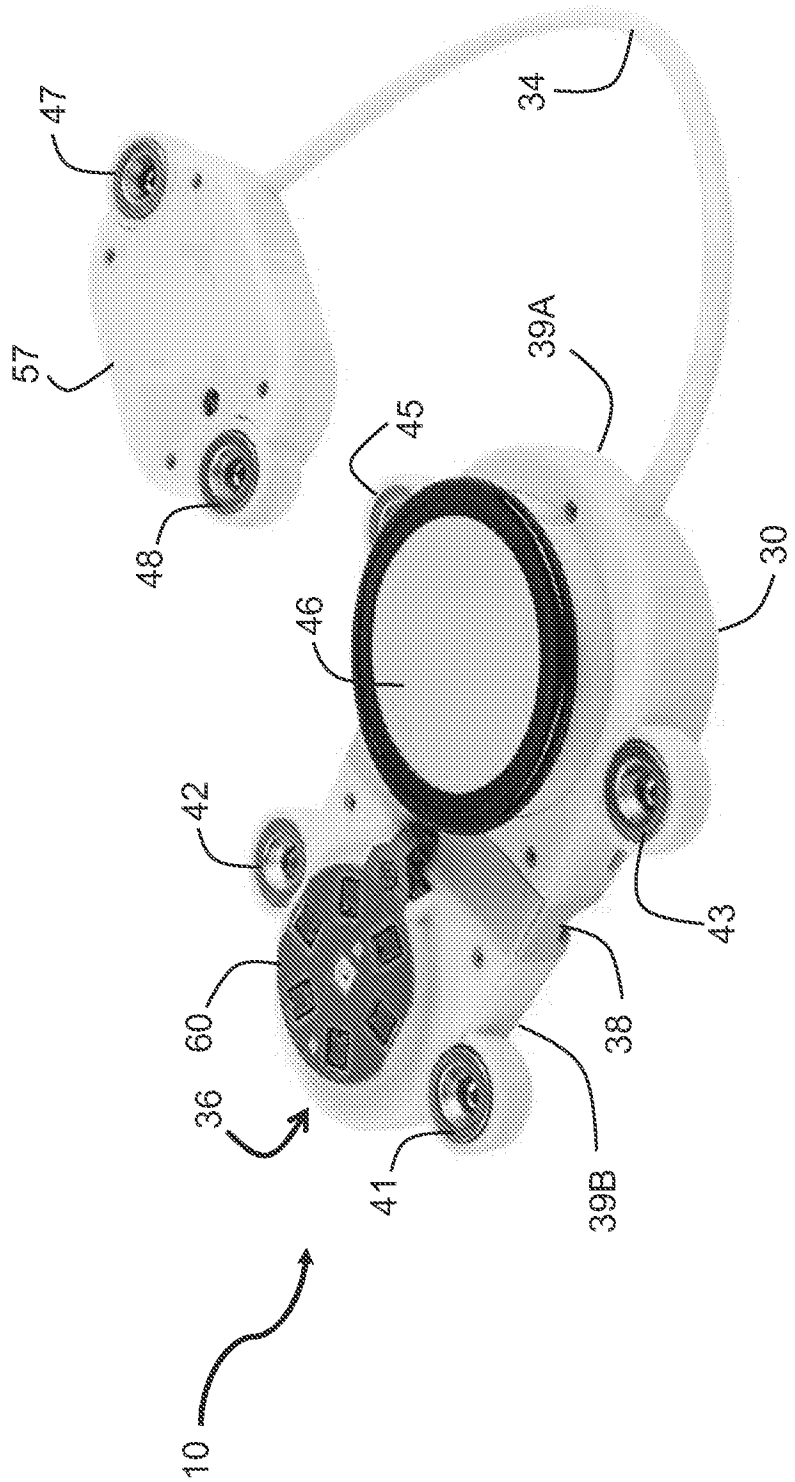


Fig. 2

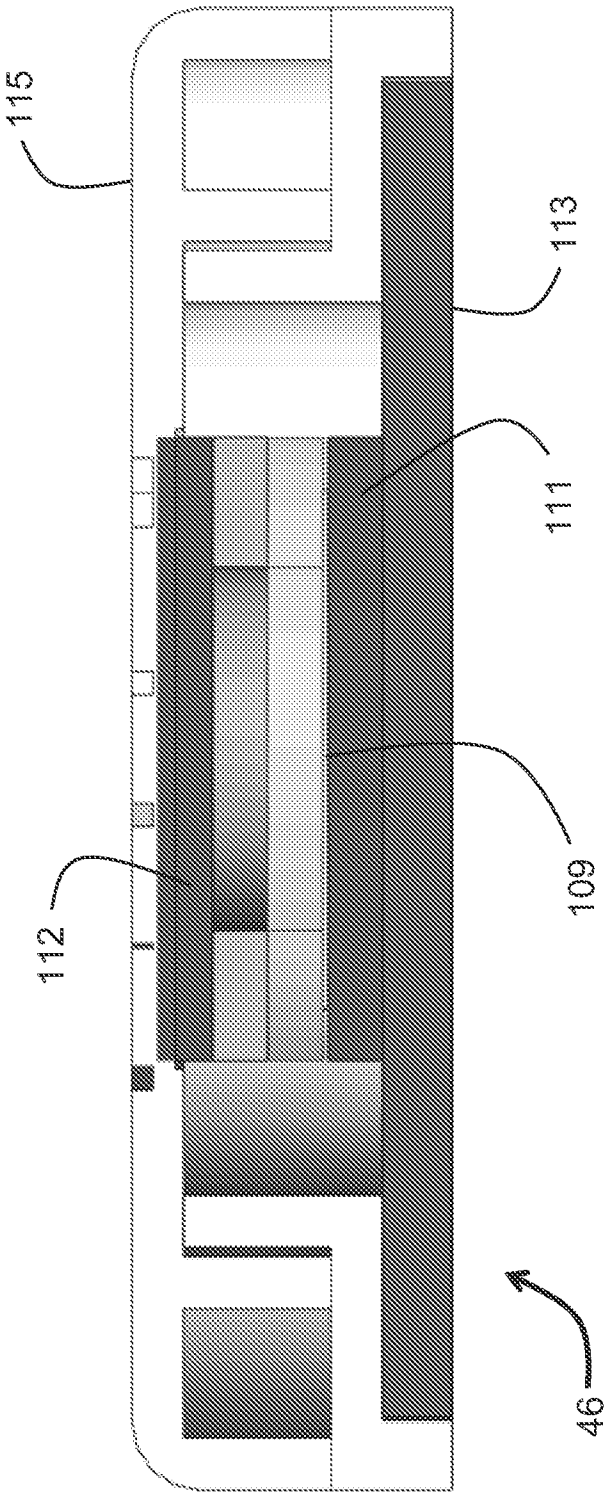


Fig. 3

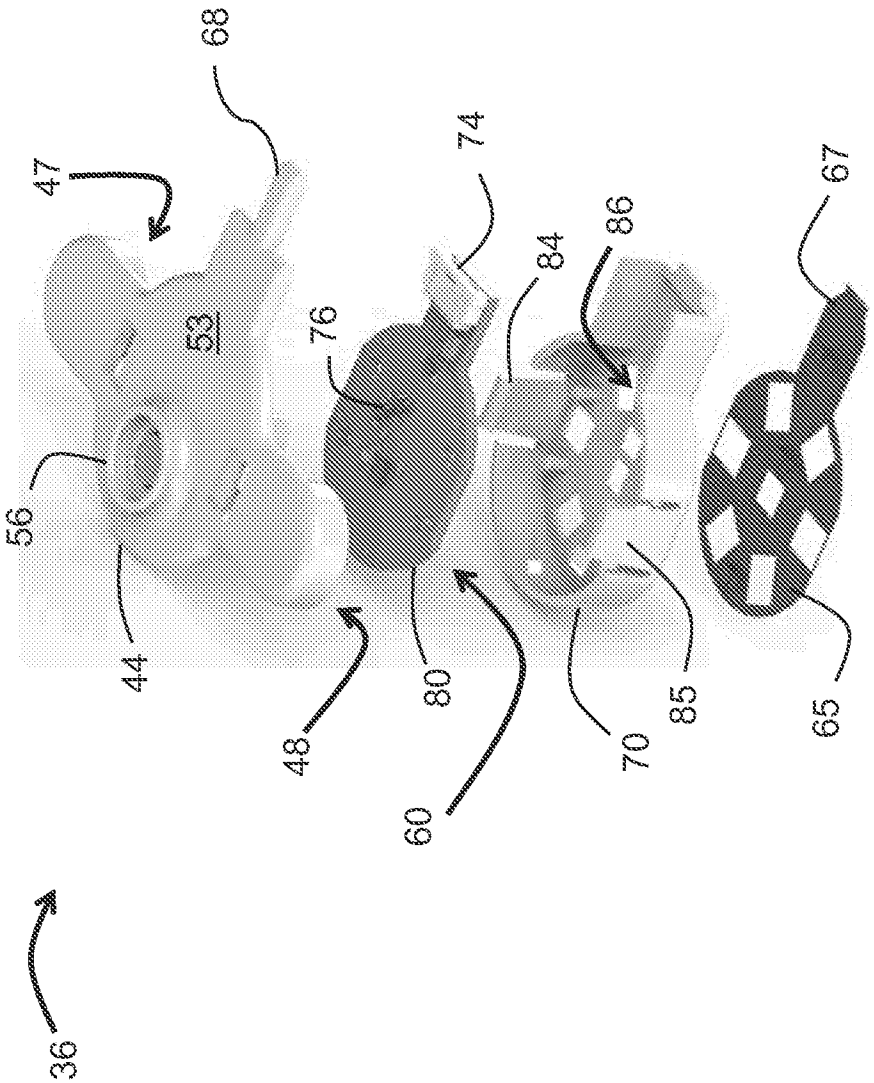


Fig. 4

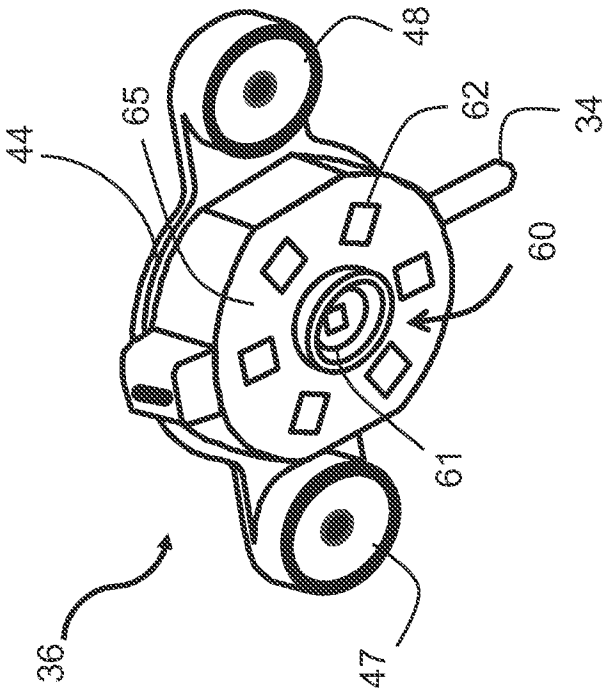


Fig. 5

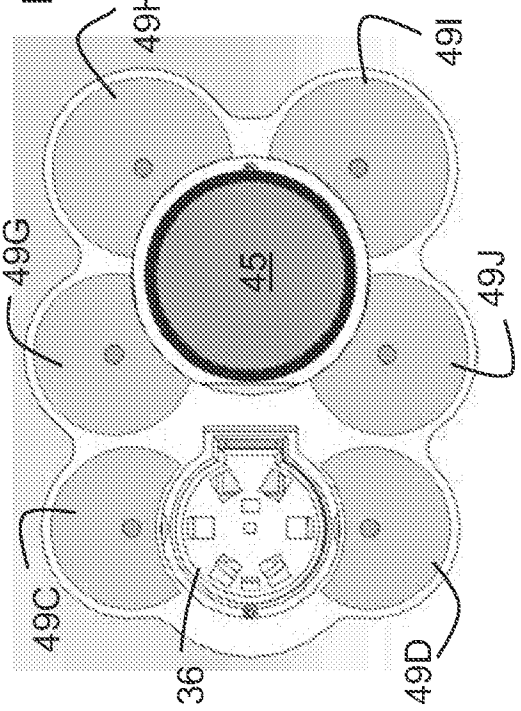


Fig. 6C

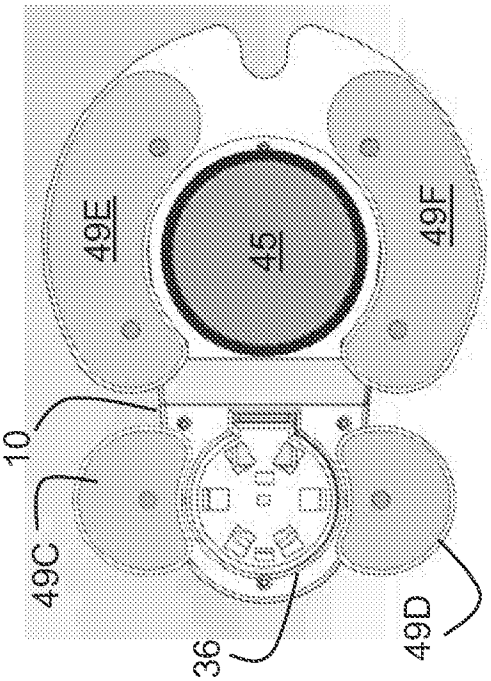


Fig. 6B

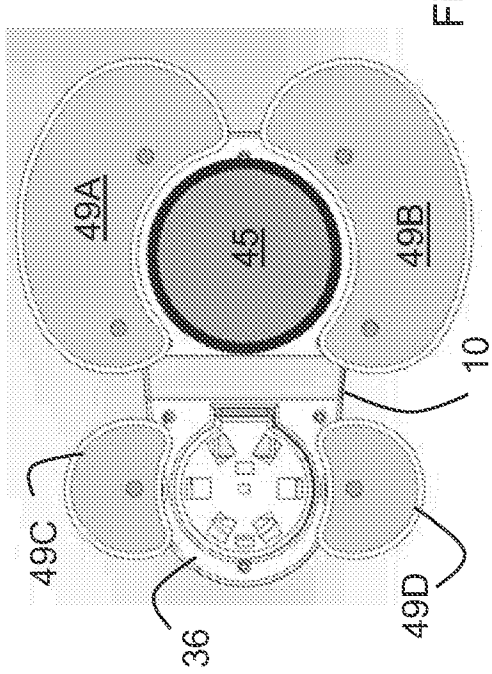


Fig. 6A

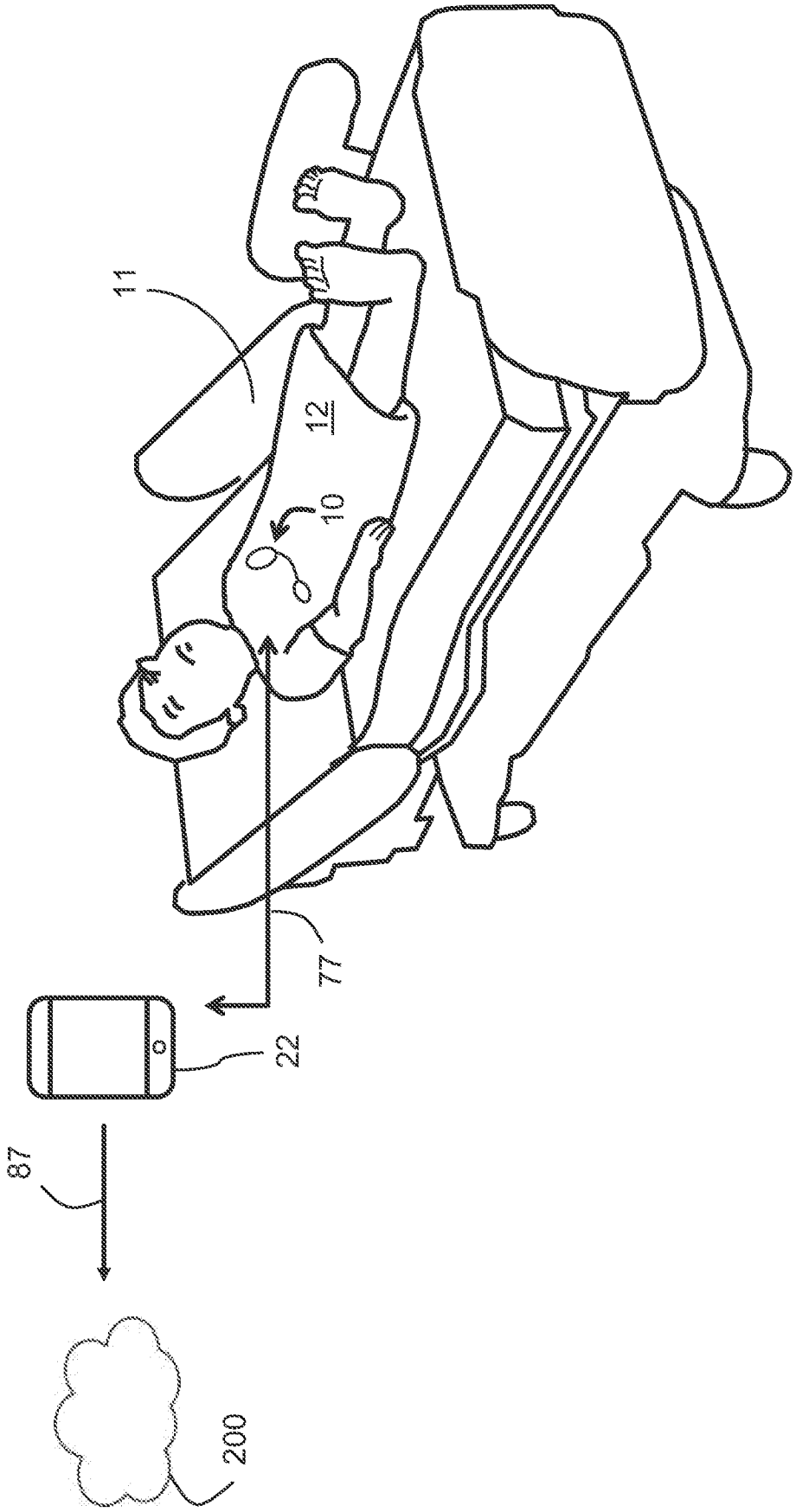


Fig. 7

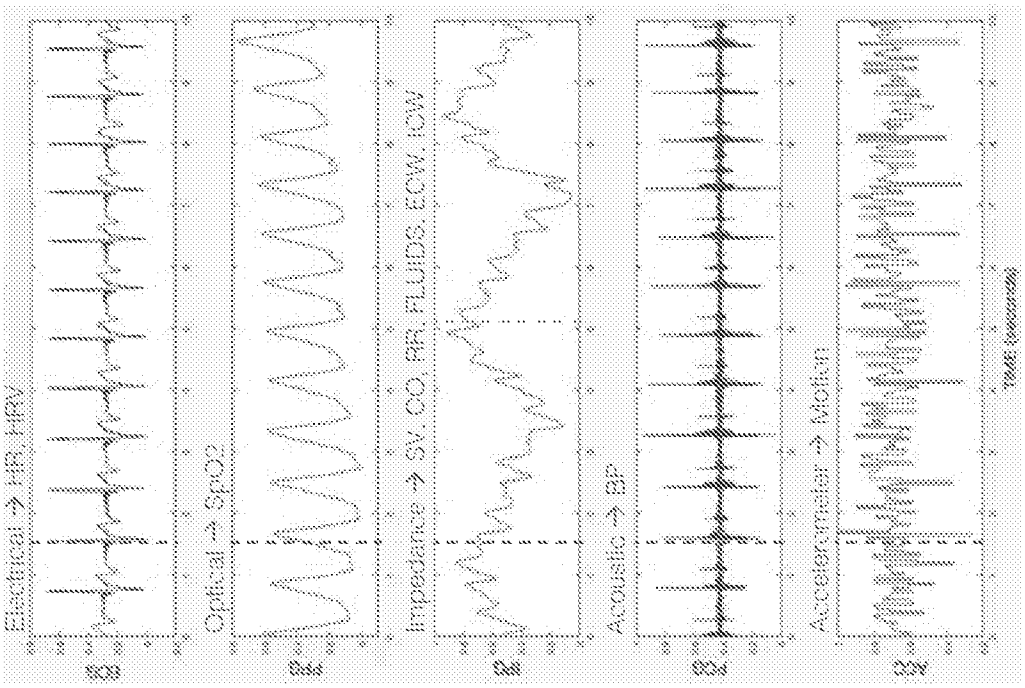


Fig. 8A

Fig. 8B

Fig. 8C

Fig. 8D

Fig. 8E

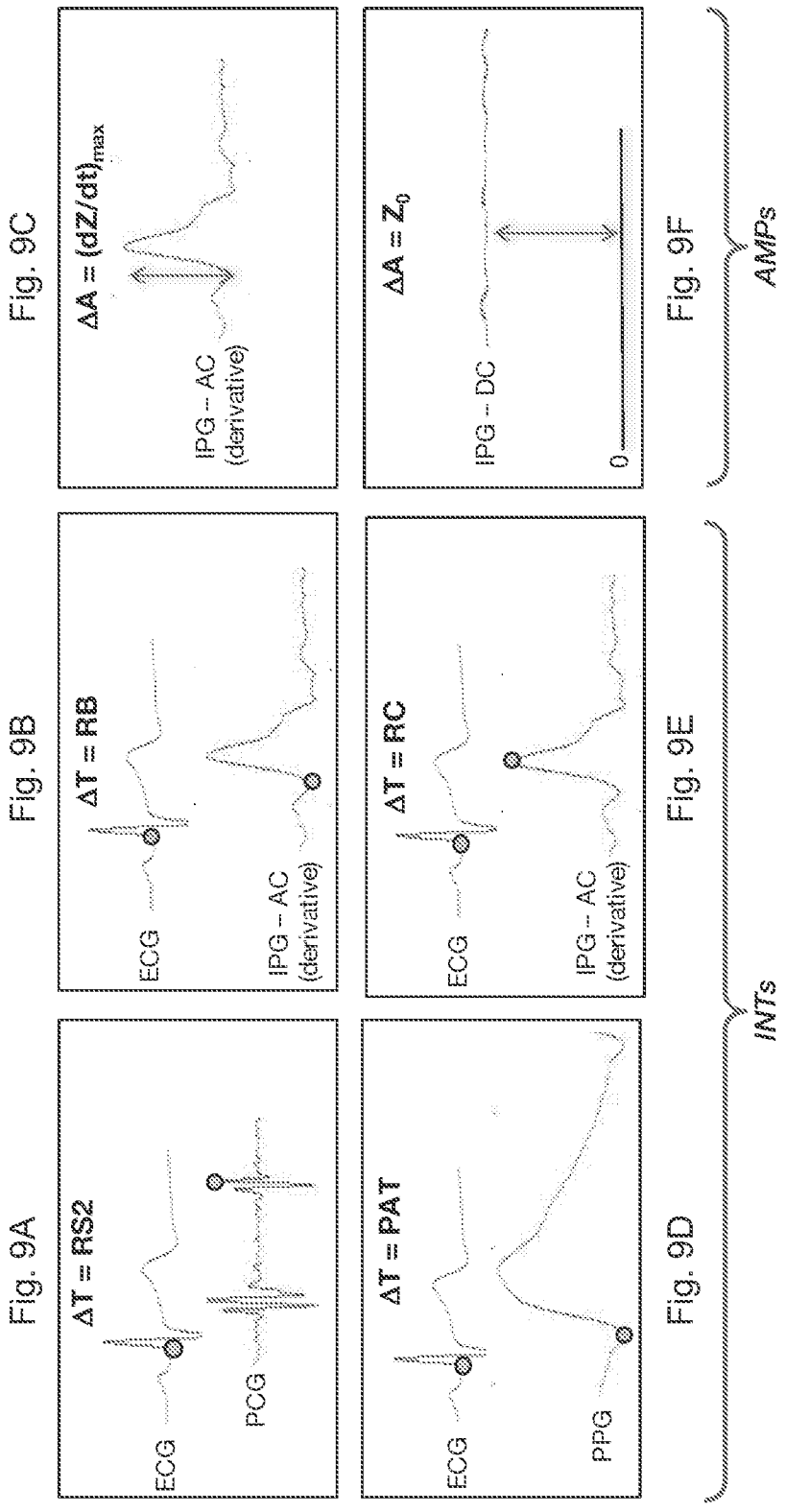

Fig. 9A
ΔT = RS2
ECG
PCG
Fig. 9B
ΔT = RB
ECG
IPG – AC (derivative)
Fig. 9C
ΔA = (dZ/dt)max
IPG – AC (derivative)
Fig. 9D
ΔT = PAT
ECG
PPG
Fig. 9E
ΔT = RC
ECG
IPG – AC (derivative)
Fig. 9F
ΔA = Z0
IPG – DC
0
INTs
AMPs

Fig. 10A

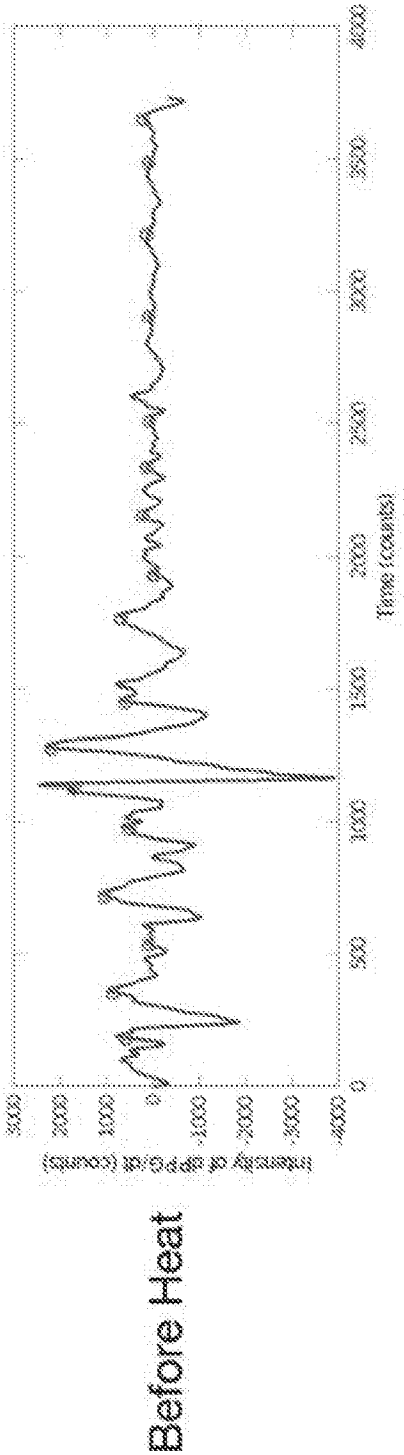
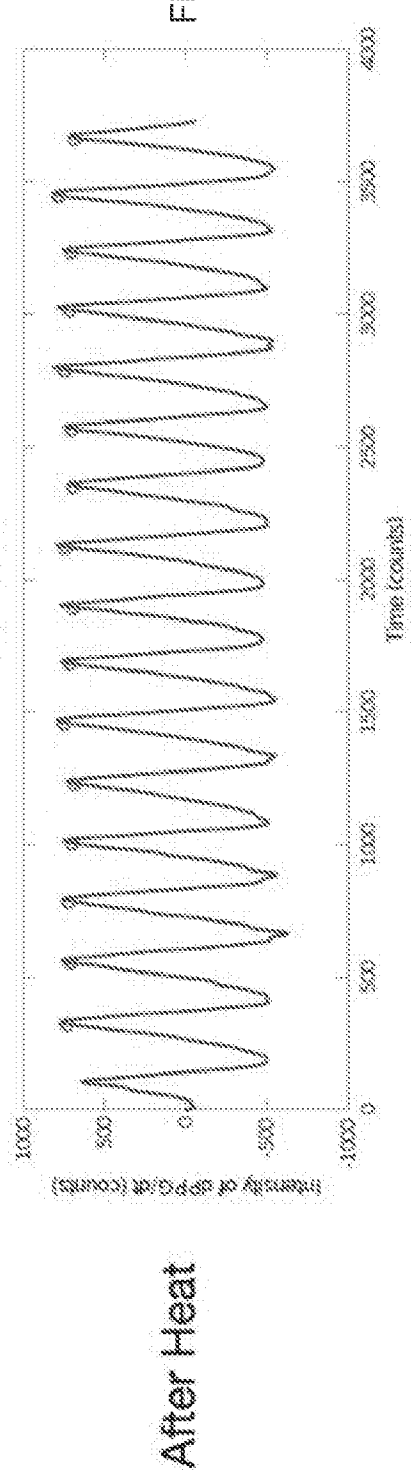


Fig. 10B



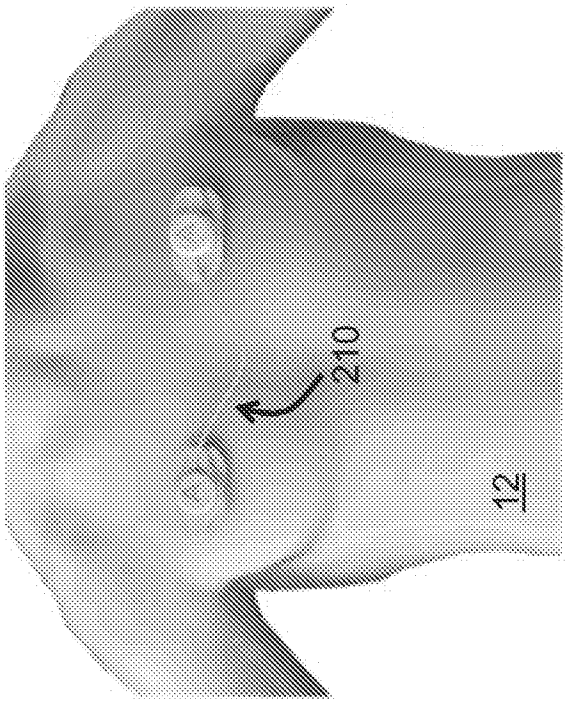


Fig. 11B

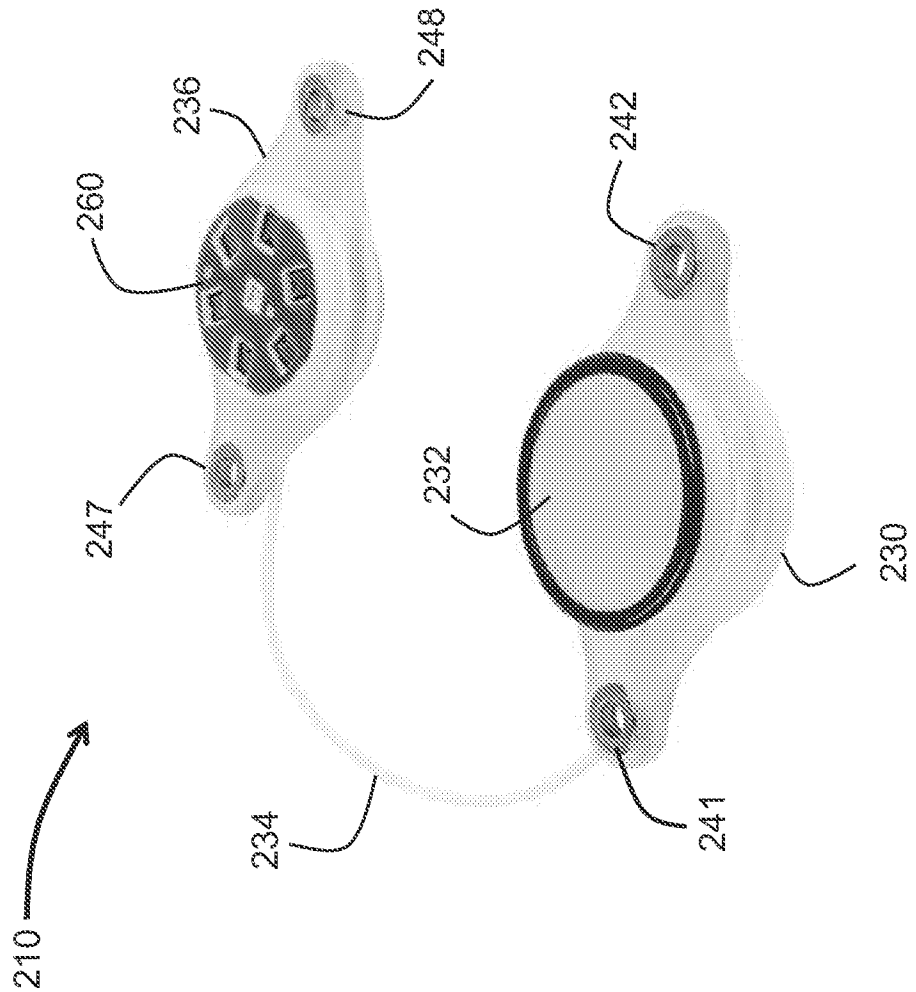


Fig. 11A

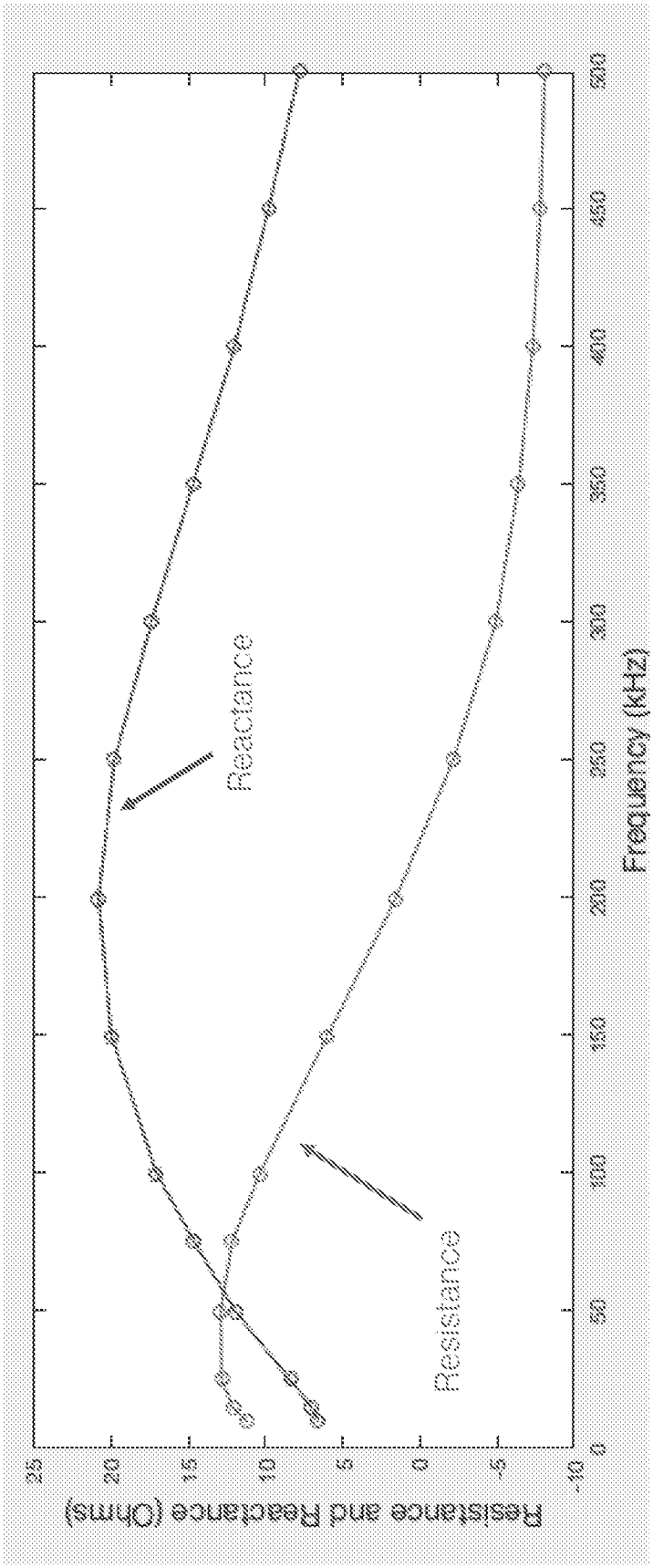

Resistance and Reactance (Ohms)
Frequency (kHz)
Reactance
Resistance
25
20
15
10
5
0
-5
-10
0
50
100
150
200
250
300
350
400
450
500

Fig. 12

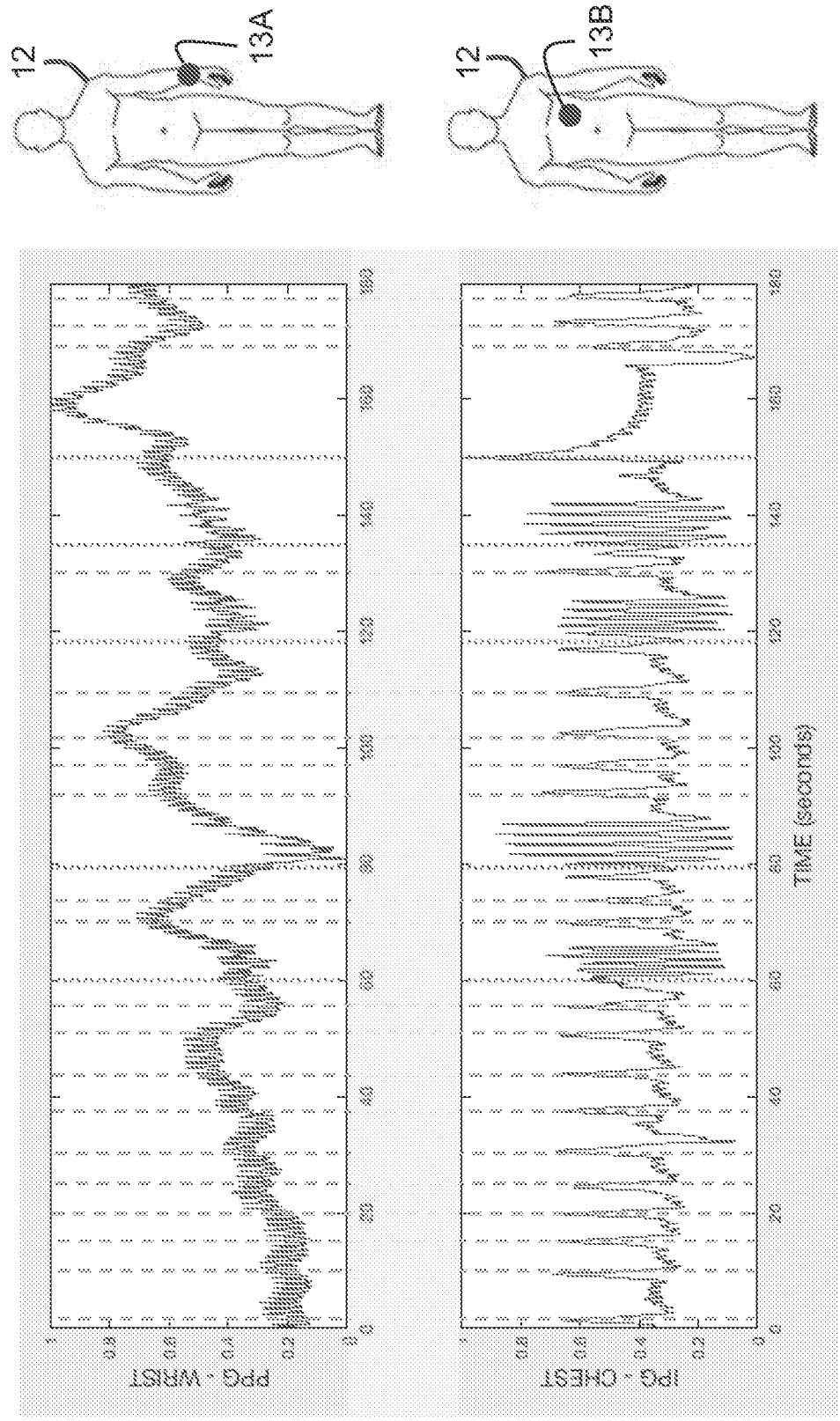

12
13A
12
13B
PPG - WRIST
IPG - CHEST
TIME (seconds)
normal breath
cough
wheeze
apnea

Fig. 13

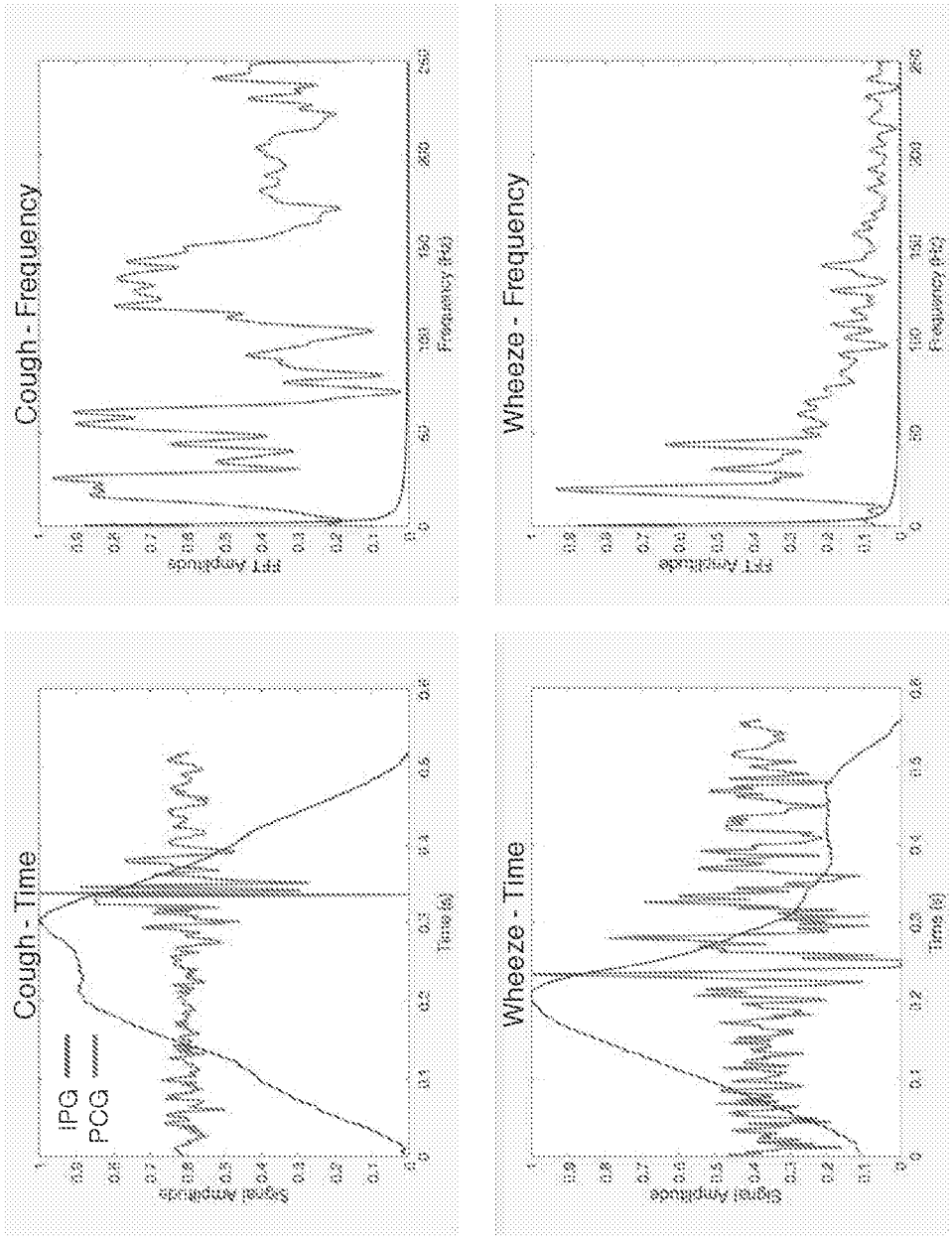

Cough - Frequency
FFT Amplitude
Frequency (Hz)
Wheeze - Frequency
FFT Amplitude
Frequency (Hz)
Cough - Time
IPG
PCG
Signal Amplitude
Time (s)
Wheeze - Time
Signal Amplitude
Time (s)

Fig. 14