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(54) **GENERATIVE MODEL-DRIVEN RESOURCE-EFFICIENT MONITORING IN BODY SENSOR NETWORKS**

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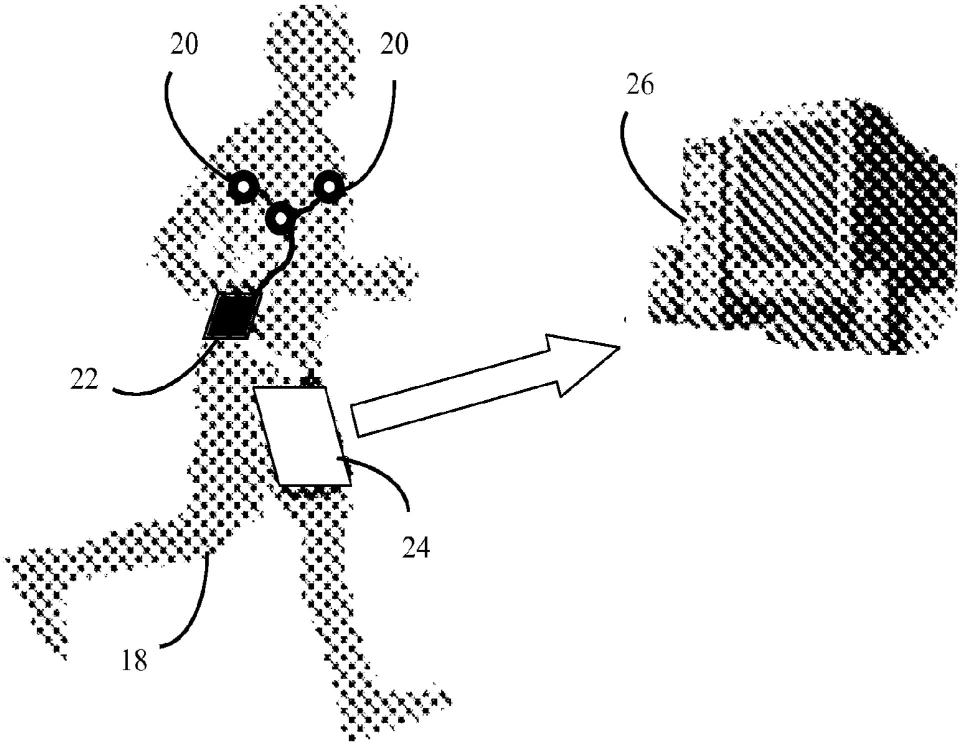
USPC **600/515**

(57) **ABSTRACT**

Body sensor networks (BSNs) and methods for monitoring an electrocardiogram using such BSNs include a base station that generates an ECG model and an output ECG signal for displaying on a display device, and a sensor platform in electrical communication with the base station. The sensor platform may be configured to receive a sensed ECG signal from one or more sensors, receive an instance of the ECG model, and produce a model ECG signal from the instance. The sensor platform compares the sensed ECG signal to the model ECG signal and, if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmits deviation data describing the deviation to the base station module. The sensor platform module does not transmit any data to the base station if there is no such deviation.



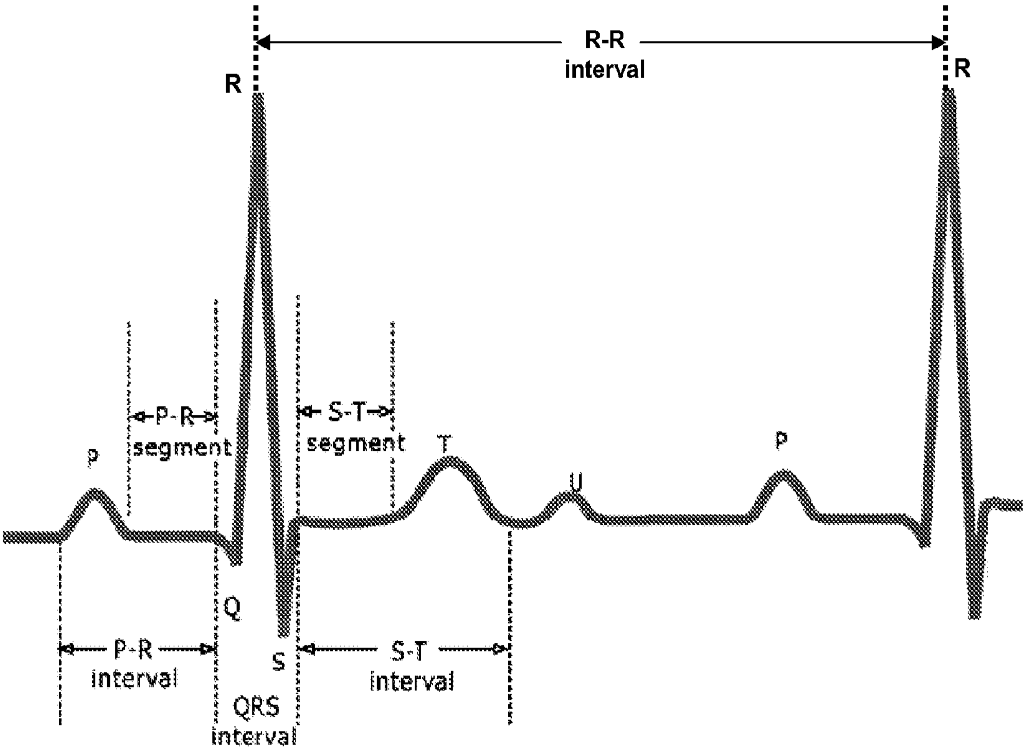

R-R interval
R
R
P
P-R segment
S-T segment
T
U
P
Q
S
P-R interval
QRS interval
S-T interval

FIG. 1

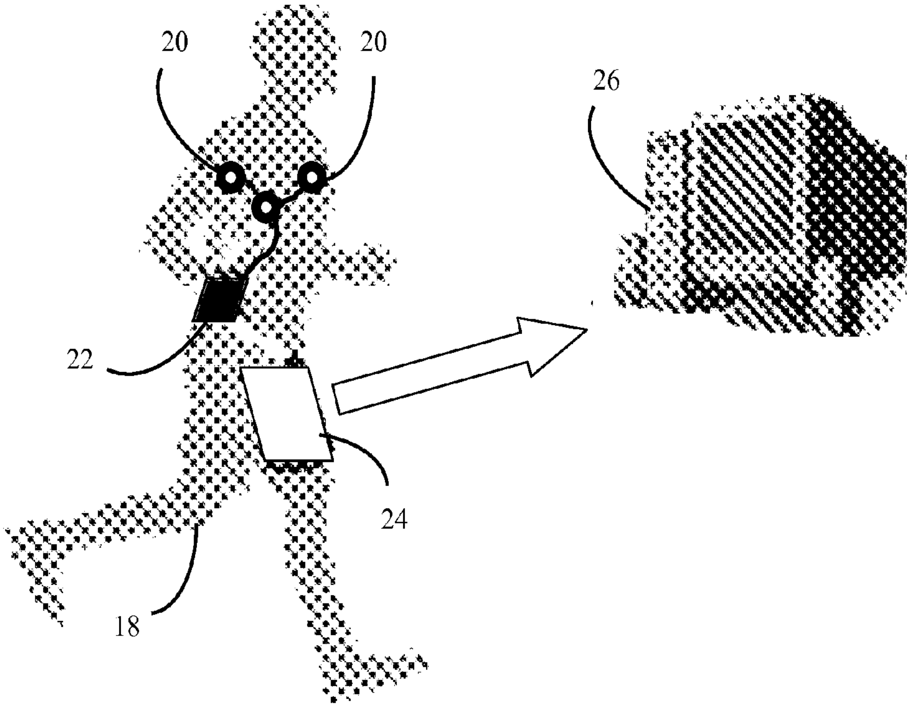

20
20
26
22
24
18

FIG. 2

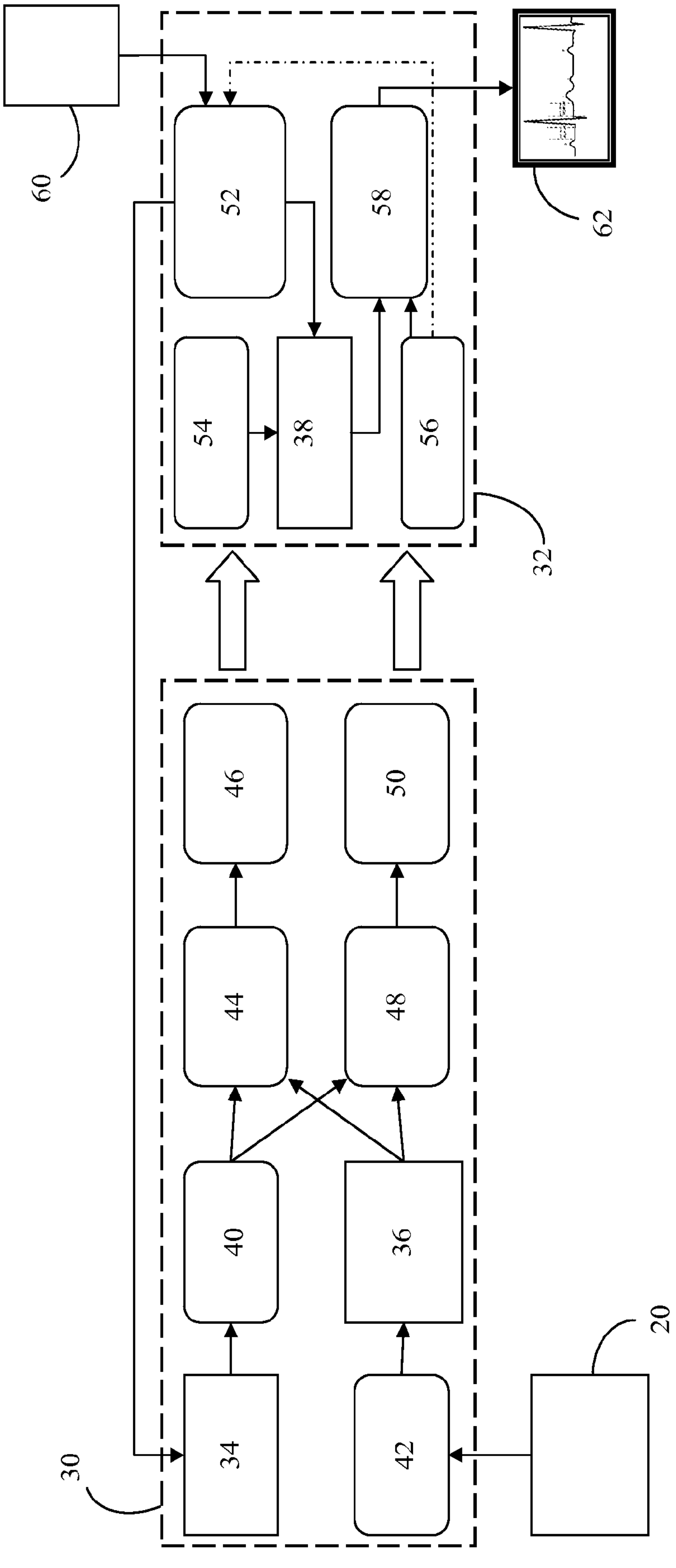


FIG. 3

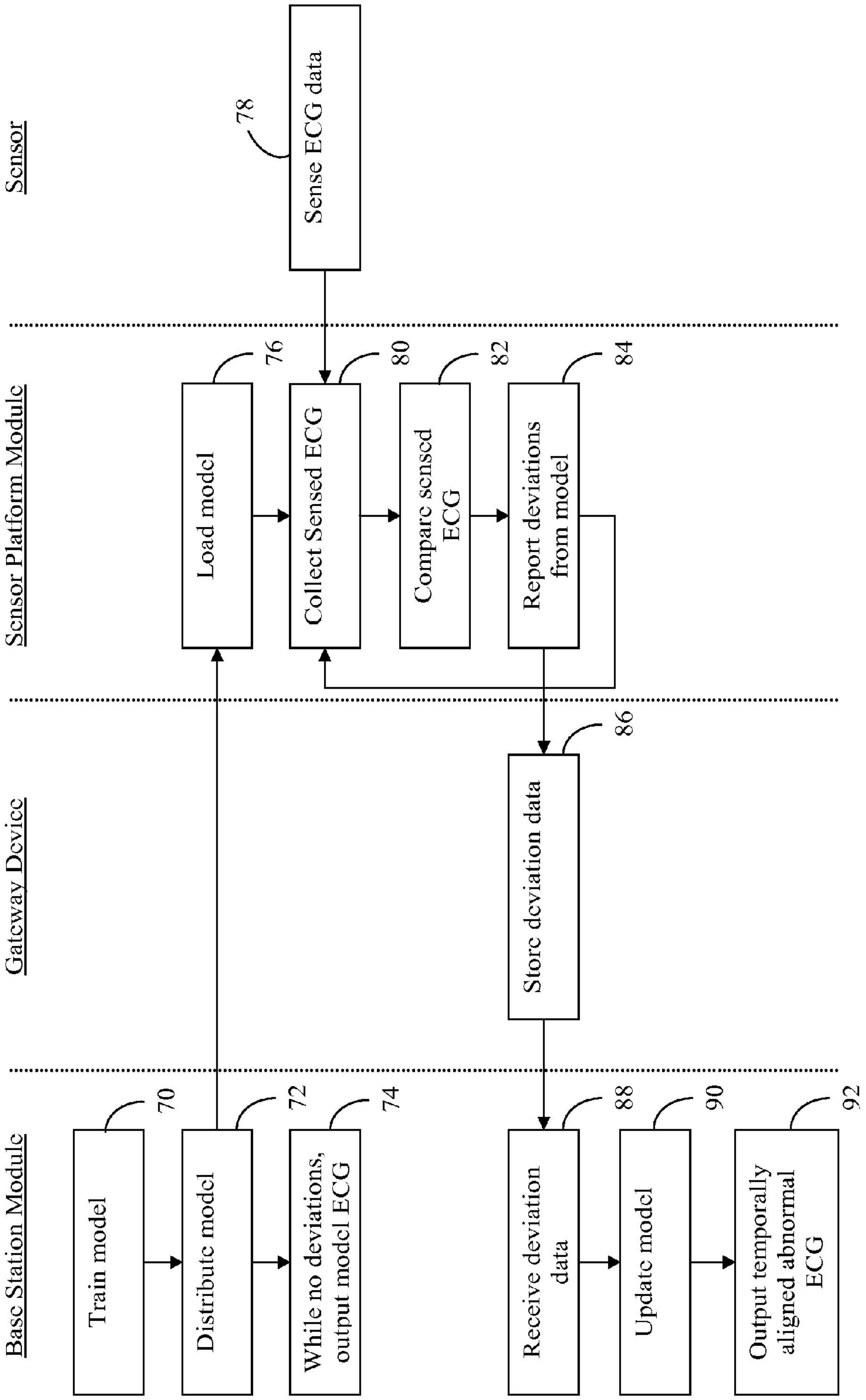

Base Station Module
Gateway Device
Sensor Platform Module
Sensor
Train model
70
Distribute model
72
While no deviations, output model ECG
74
Receive deviation data
88
Update model
90
Output temporally aligned abnormal ECG
92
Store deviation data
86
Load model
76
Collect Sensed ECG
80
Compare sensed ECG
82
Report deviations from model
84
Sense ECG data
78

FIG. 4

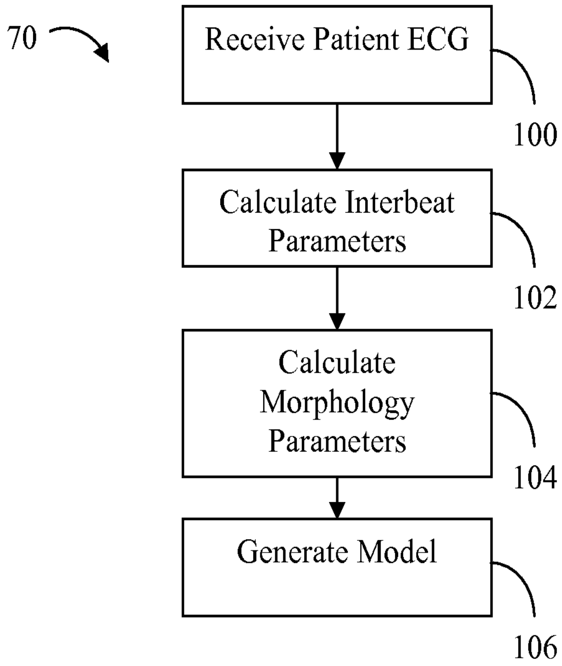

70
Receive Patient ECG
100
Calculate Interbeat Parameters
102
Calculate Morphology Parameters
104
Generate Model
106

FIG. 5

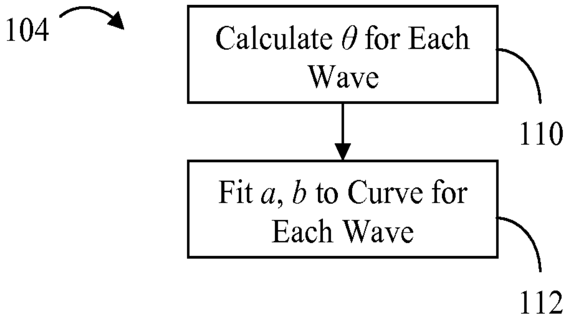

104
Calculate θ for Each Wave
110
Fit a, b to Curve for Each Wave
112

FIG. 6

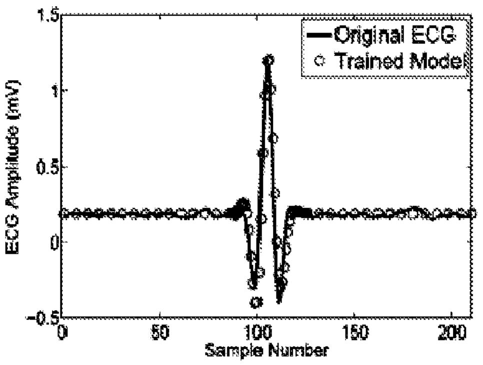


FIG. 7A

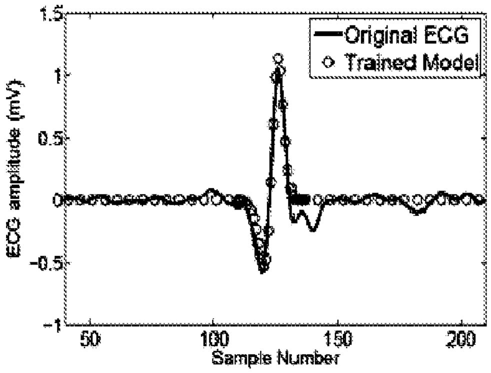


FIG. 7B

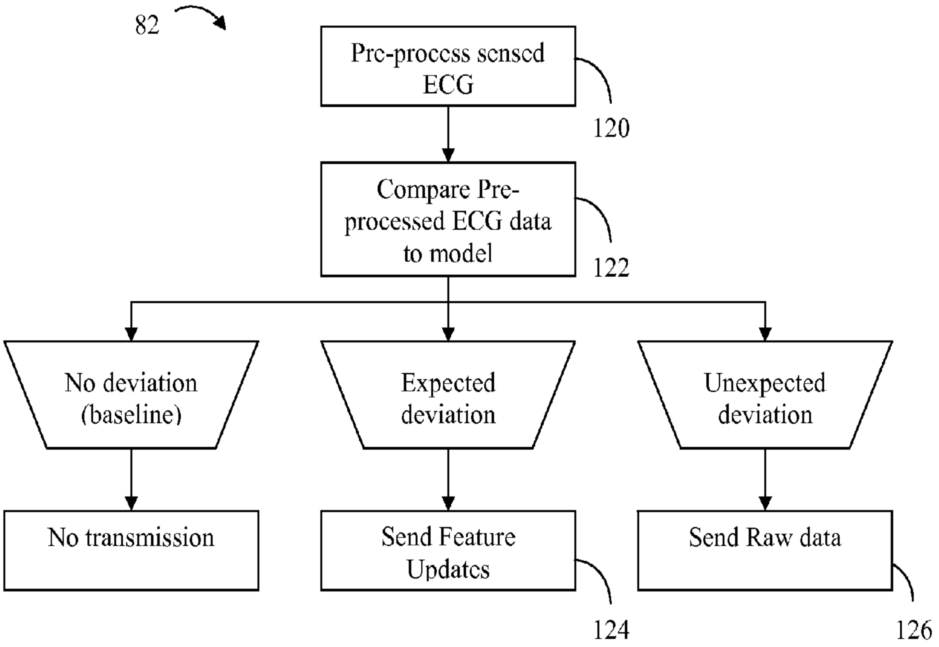


FIG. 8

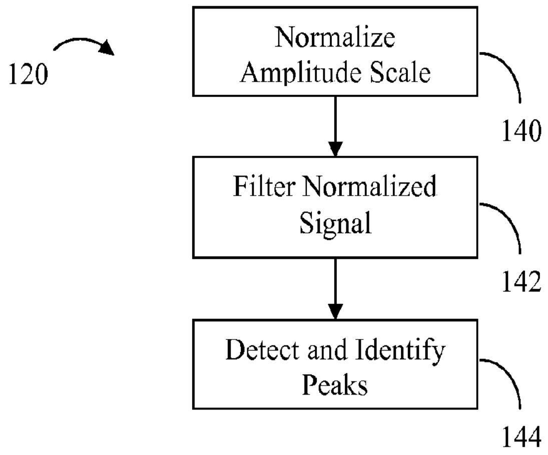


FIG. 9

144

QRS PEAK DETECTION IN THE SENSOR MODULE

```
For each incoming data sample x[i]
        if (x[i] > MAX) Set MAX = x[i]
        if (x[i] < MIN) Set MIN = x[i]

        if      // Looking for upward peak
                if (x[i] < MAX) Mark x[i-1] as PossiblePeak
                if (x[i] < (MAX- thresholdUp))
                        Mark latest PossiblePeak as RealPeak
                        if (magnitude(RealPeak) > thresholdR)
                                Mark peak as R peak
                        Start Looking for downward peak

        else    // Looking for downward peak
                if (x[i] > MIN) Mark x[i-1] as PossiblePeak
                if (x[i] > (MIN + thresholdDown))
                        Mark latest PossiblePeak as RealPeak
                        if ((magnitude(RealPeak) > thresholdQ)
                                AND (PreviousPeak is S peak))
                                Mark peak as Q peak
                        if ((magnitude(RealPeak) > thresholdS)
                                AND (PreviousPeak is R peak))
                                Mark peak as S peak
                        Start Looking for upward peak
```

FIG. 10

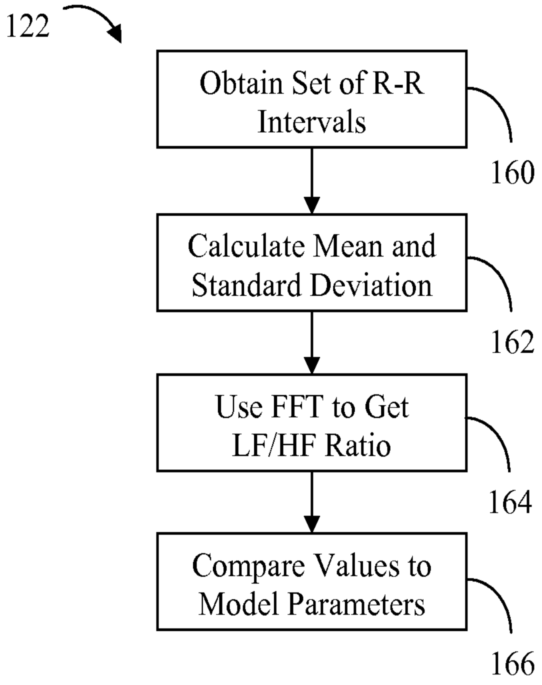

122
Obtain Set of R-R Intervals
160
Calculate Mean and Standard Deviation
162
Use FFT to Get LF/HF Ratio
164
Compare Values to Model Parameters
166

FIG. 11

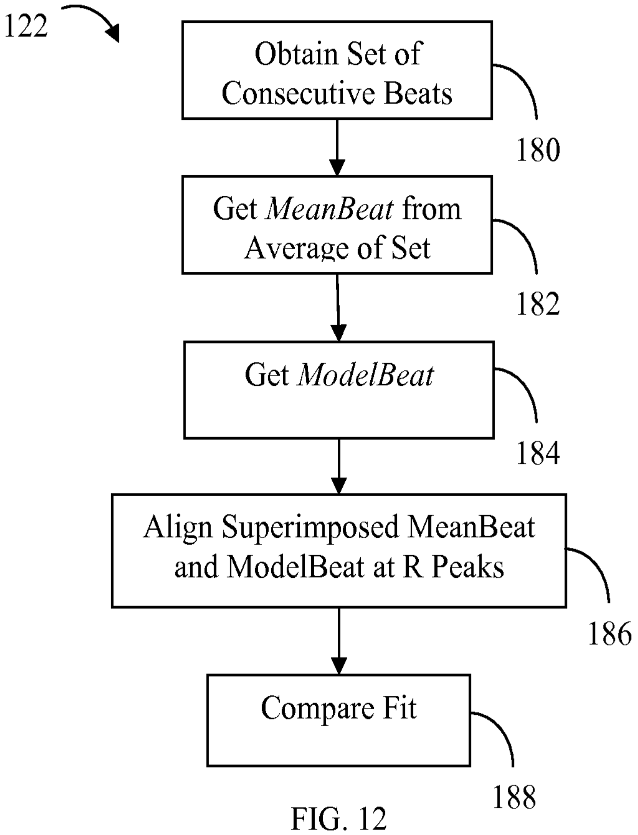

122
Obtain Set of Consecutive Beats
180
Get *MeanBeat* from Average of Set
182
Get *ModelBeat*
184
Align Superimposed MeanBeat and ModelBeat at R Peaks
186
Compare Fit
188

FIG. 12

GENERATIVE MODEL-DRIVEN RESOURCE-EFFICIENT MONITORING IN BODY SENSOR NETWORKS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This Application claims priority to U.S. Provisional Patent Application Ser. No. 61/650,560 filed May 23, 2012, incorporated by reference herein in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] Research described in this application was partially funded by ARO MURI Grant Number W911NF0710287 and NSF grant CT-0831544. The government has certain rights in this invention.

FIELD OF INVENTION

[0003] This invention relates to electrocardiogram monitoring. In particular, this invention relates to body sensor networks that record and transmit an electrocardiogram with reduced data storage and energy consumption requirements.

BACKGROUND OF THE INVENTION

[0004] An electrocardiogram (ECG) is a time-varying signal representing the electrical activity of the heart, and is an effective, non-invasive diagnostic tool for cardiac monitoring. Recently, several systems have been developed for continuous, remote ECG monitoring using Body Sensor Networks (BSNs). Such systems typically consist of a wireless, battery-operated, body-worn sensor that collects ECG data and transmits it to a gateway device such as a smartphone. The gateway reports this data over the internet to a remote base station, which is typically a hospital server or caregiver's computer. Such remote monitoring allows collection of data during a person's daily routine and enables early detection of conditions such as tachycardia or angina. Further, the availability of continuous long-term data can help identify gradual, long-term trends in the cardiac health of at-risk patients.

[0005] A key challenge in BSN-based ECG monitoring is the large volume of data collected by the sensor in a short time interval. For example, at a clinically-recommended sampling rate of 250 Hz and resolution of 12 bits/sample, more than 2 KB of data is collected within 6 seconds. Local storage of this data on the sensor or the gateway device is impractical due to storage limitations. Further, wireless transmission of this data consumes significant power at the energy-constrained sensor. At the same time, the quality and continuity of the reported ECG signal must be maintained at the base station to allow effective investigation and diagnosis by a physician.

[0006] Most current attempts to address these key challenges are based on data compression, where the sensed ECG data is compressed before transmission. Several techniques based on wavelets, Huffman coding and priority-based encoding have been proposed in literature. Unfortunately, known compression schemes need to continuously transmit data, thus limiting their energy savings. In one alternative approach, a set of features is extracted from the sensed ECG and used for classification. The preprocessing and pattern recognition workload is transferred to local nodes close to the ECG leads to reduce transmission energy consumption. This scheme, however, does not provide a complete sensed ECG signal at the base station and thus its value for diagnosis is limited. Another compressive sensing approach has been proposed for ECG monitoring, which uses the sparsity of the ECG signal in specific wavelet transformations to reduce sampling rate. However, reconstruction of the received signal is complex and strongly depends on error-free transmission of all coefficients.

SUMMARY OF THE INVENTION

[0007] The present invention provides methods for monitoring an electrocardiogram. In one embodiment, the methods include receiving a sensed ECG signal from one or more sensors configured to collect the sensed ECG signal from the patient, comparing the sensed ECG signal to a model ECG signal, and, if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmitting deviation data describing the deviation to a base station.

[0008] In another embodiment, the methods include receiving, at a sensor platform, a sensed ECG signal from one or more sensors configured to collect the sensed ECG signal from the patient and comparing, at the sensor platform, the sensed ECG signal to a model ECG signal. If a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, the methods may further include transmitting, from the sensor platform, deviation data describing the deviation to a base station. The methods may further include generating, at the base station, an output ECG signal to be displayed on a display device, wherein the output ECG signal comprises the model ECG signal and, when deviation data is received, further comprises a modification to the model ECG signal.

[0009] The present invention further provides systems for monitoring an ECG. In one embodiment, the system is a body sensor network for monitoring an electrocardiogram of a patient. The body sensor network may include a base station comprising a base station module configured to generate an ECG model and to generate an output ECG signal for displaying on a display device, and a sensor platform in electrical communication with the base station. The sensor platform may have a sensor platform module configured to: receive a sensed ECG signal from one or more sensors attached to the patient and collecting the patient's ECG embodied in the sensed ECG signal; receive an instance of the ECG model and produce a model ECG signal from the instance; compare the sensed ECG signal to the model ECG signal; and, if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmit deviation data describing the deviation to the base station module. The sensor platform module does not transmit the sensed ECG signal if there is no deviation of the sensed ECG signal from the model ECG signal exceeding the threshold.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. **1** is a diagram of an ECG beat.

[0011] FIG. **2** is a diagram of an ECG body sensor network in accordance with the present disclosure.

[0012] FIG. **3** is a schematic diagram of a data reporting implementation within a sensor module and a base station module in accordance with the present disclosure.

[0013] FIG. **4** is a flow diagram of a method of reporting an ECG in accordance with the present disclosure.

[0014] FIG. **5** is a flow diagram of a training method in accordance with the present disclosure.

[0015] FIG. **6** is a flow diagram of a method of calculating morphology parameters in accordance with the present disclosure.

[0016] FIG. **7**A is a diagram of a training model compared to a normal ECG beat in accordance with the present disclosure.

[0017] FIG. **7**B is a diagram of a training model compared to an abnormal ECG beat in accordance with the present disclosure.

[0018] FIG. **8** is a flow diagram of operations of a sensor module in accordance with the present disclosure.

[0019] FIG. **9** is a flow diagram of a method of preprocessing a sensed ECG signal in accordance with the present disclosure.

[0020] FIG. **10** is a flow diagram of a method of detecting peaks in a sensed ECG signal in accordance with the present disclosure.

[0021] FIG. **11** is a flow diagram of a method of comparing interbeat parameters of a sensed ECG signal to a model ECG in accordance with the present disclosure.

[0022] FIG. **12** is a flow diagram of a method of comparing morphology parameters of a sensed ECG signal to a model ECG with a direct signal comparison approach in accordance with the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0023] The following discussion is presented to enable a person skilled in the art to make and use embodiments of the invention. Various modifications to the illustrated embodiments will be readily apparent to those skilled in the art, and the generic principles herein can be applied to other embodiments and applications without departing from embodiments of the invention. Thus, embodiments of the invention are not intended to be limited to embodiments shown, but are to be accorded the widest scope consistent with the principles and features disclosed herein. The following detailed description is to be read with reference to the figures, in which like elements in different figures have like reference numerals. The figures, which are not necessarily to scale, depict selected embodiments and are not intended to limit the scope of embodiments of the invention. Skilled artisans will recognize the examples provided herein have many useful alternatives and fall within the scope of embodiments of the invention.

[0024] As used herein, the singular forms “a”, “an” and “the” include plural referents unless the context clearly dictates otherwise. “And” as used herein is interchangeably used with “or” unless expressly stated otherwise. All embodiments of the invention can be combined unless the context clearly dictates otherwise.

[0025] The ECG signal bas been extensively studied and used for cardiac diagnosis. The basic unit of an ECG is a beat, and its shape is referred to as the ECG morphology. Referring to FIG. **1**, a single beat consists of P, Q, R, S and T waves, with a U wave present in some cases. The R wave is typically the most prominent and easy to identify in a beat. The Q, R and S waves are often jointly considered in a single complex, called the QRS complex. The shape, amplitude and relative locations of the constituent waves are key features of an ECG, and are referred to herein as morphology features. These features vary across individuals, but are expected to remain fairly stable for a given person, in the absence of pathological conditions.

[0026] The distance between two consecutive R peaks is called the R-R interval, and its reciprocal gives the instantaneous heart rate. Even in a healthy person, the R-R interval varies across beats due to several physiological factors. This variation is described using temporal features such as mean and standard deviation of heart rate, and spectral features such as Low Frequency/High Frequency (LF/HF) ratio. The temporal and spectral features of the ECG are referred to herein as interbeat features.

[0027] ECG is inherently a low amplitude electrical signal and is often corrupted by noise from various sources such as electrical mains, muscle noise and patient movement or respiration. As a result, the measured signal must be filtered as described below to extract the underlying ECG waveform. Among the constituent waves, the QRS complex can be extracted using computationally lightweight algorithms. The extraction of P and T waves, however, requires advanced filtering techniques that are computationally expensive to implement on sensors. Further, several conditions such as bradycardia, tachycardia, myocardial intimation and bundle branch block can be diagnosed from the QRS complex alone. As a result, some embodiments in accordance with the present disclosure may collect and analyze only the QRS complex of a set of ECG beats, to the exclusion of the other waves. In other embodiments, one or more of the P, Q, R, S, T, and U waves may be analyzed individually or collectively in order to obtain more complete diagnostic or condition-focused information.

[0028] The embodiments of the present disclosure may use a generative ECG model configured to produce synthetic ECG signals based on a set of input parameters. Some embodiments may use one or a combination of known dynamic model generators, such as ECGSYN. ECGSYN models an ECG signal as a point moving around a unit circle, and uses differential equations to describe its motion. The individual waves are modeled as Gaussian attractors/repellers placed at specific points on the circle. The inter-beat features of ECG are modeled using 3 parameters: hrmean, hrstd and lfhfratio, corresponding to mean heart rate, standard deviation of heart rate and LF/HF ratio respectively. For the morphology features, each wave is represented by 3 parameters: (a, b, θ), which determine its height, width and distance to R peak, respectively. For example, the Q wave is represented by the 3-tuple (a_Q, b_Q, and θ_Q).

[0029] Referring to FIG. **2**, a BSN system model for sensing the ECG of a patient **18**, processing the ECG, transmitting and storing data related to the ECG, and generating a visual representation of the ECG includes one or more sensors **20** in electrical communication with a sensor platform **22**. The sensors **20** may be any suitable ECG sensor, such as a SHIMMER 3-lead wired or wireless sensor. The sensors **20** may be connected to the sensor platform **22** by wires, or may communicate wirelessly with the sensor platform **22**. In some embodiments, the sensors **20** may be dumb sensors, in that the sensors **20** simply collect sensor data, specifically an ECG signal, and transmit the raw sensor data to the sensor platform **22**. In other embodiments, the sensors **20** may be smart sensors equipped with a central processing unit (“CPU”) or microprocessor having sufficient computing resources to perform some of the ECG signal processing described below. A sensor **20** may be configured to collect sensor data in either integer or floating-point format, with integer-based implementation exhibiting improved memory footprint over floating-point. For example, integer implementation on the sensor platform may reduce the memory requirement of the sensor application from 9 KB down to 4 KB as compared to floating-point implementation.

[0030] The sensor platform **22** may be configured to receive data from the sensors **20** and to communicate data to a gateway device **24**. In some embodiments, the sensor platform **22** may be a standalone device that transmits data through wired or wireless electrical connection to the gateway device **24**. An example of such a sensor platform **22** is the SHIMMER Wireless Sensor Unit/Platform SH-SHIM-KIT-004, which is configured to transmit data via Bluetooth to a Bluetooth-enabled gateway device **24**. In other embodiments, the sensor platform **22** may be a hardware or software module attached to or contained within the gateway device **24**. The sensor platform **22** may comprise computing hardware and software, including a CPU, memory, data storage, and input/output terminals, having sufficient computing capacity to implement the sensor platform module described below. The sensor platform **22** may therefore receive raw or processed sensor data from the sensors and perform additional processing on the sensor data before transmitting data to the gateway device **24**. In some embodiments, such as those embodiments implementing the methods described in detail below, the sensor platform **22** may receive a sensed ECG signal from the sensors, process the sensed ECG signal to produce deviation data, and transmit the deviation data to the gateway device **24**.

[0031] The gateway device **24** may be configured to receive data from the sensor platform **22** and to communicate the data to a base station **26**. The gateway device **24** may be any device suitable for receiving data transmitted by the sensor platform **22**, which may be over a first communication network, and for transmitting the data to the base station **26** over a second communication network, which may be different from or may use different communication protocols or data security measures than the first communication network. In some embodiments, the gateway device **24** may be a personal mobile communication device, such as a smartphone. The gateway device **24** may communicate with the sensor platform **22** via Bluetooth, wired or wireless Local Area Network, or another limited-range wireless communication protocol or network. The gateway device **24** may communicate with the base station **26**, which may be remote from the gateway device **24**, via a cell network, a Wide Area Network, a telephone network, or another long-range data transfer network. The described communication system may use any suitable data encryption algorithm, username/password authentication, and other forms of data security to protect transmitted data.

[0032] In some embodiments, the base station **26** may be a computer, such as a personal computer, medical office or hospital server or mainframe, or another suitable computer for receiving data from the gateway device **24** and processing the data in order to display ECG information to a user, such as the patient or the patient's physician. The base station **26** may comprise computing hardware and software, including a CPU, memory, data storage, and input/output terminals, having sufficient computing capacity to implement the base station module described below. The base station **26** may therefore be configured to communicate with a body sensor network in order to receive a training ECG signal and to generate, distribute, and use a model ECG signal according to the present disclosure. In some embodiments, the base station **26** may be sufficiently robust to operate the ECGSYN dynamic model generator or another similar model generator.

[0033] Other embodiments in accordance with the invention may omit the gateway device **24**. In such an embodiment, the sensor platform **22** may communicate the sensor data directly to the base station **26**. The sensor platform **22** may be a standalone device as described above, or may be a hardware or software module attached to or contained within the base station **26**. The base station **26** may be a personal mobile device such as a smartphone configured with Bluetooth or other data sharing technology, and further having a user interface for presenting ECG and receiving user input.

[0034] Referring to FIG. **3**, a sensor platform module **30** may be implemented as hardware or software, or a combination thereof, on the sensor platform **22**, and a base station module **32** may be implemented as hardware or software, or a combination thereof, on the base station **26**. As described above, the sensor platform module **30** and base station module **32** may be on the same or different physical devices. Data may be transmitted between the modules **30**, **32** via wired or wireless connection, or a combination thereof. For example, the sensor platform module **30** may be initialized as described below through temporary wired attachment of the sensor platform **22** to the base station **26** in order to receive the initial or updated model or to offload stored data from the sensor platform **22** to the base station **26**. During operation of the BSN, however, the sensor platform **22** transmits data wirelessly to the base station **26** in this example.

[0035] The base station module **32** may be configured to train a dynamic model ECG based on input from one or more training sensors **60** attached to the patient. Prior to deploying the BSN for the patient, the base station module **32** may receive training data comprising an ECG signal recorded by the training sensors **60**. At node **52**, model learning takes place, wherein the base station module **32** may execute a stored dynamic model generator, such as ECGSYN. The model generator takes the training data as input parameters to generate the model ECG. The base station module **32** may be configured to distribute the model ECG to any device in the BSN that uses the model ECG for processing. FIG. **3** shows a base station instance **38** of the ECG model, and a sensor platform instance **34** of the ECG model. The sensor platform instance **34** may be a "lightweight" embodiment of the ECG model, in that the sensor platform instance **34** includes fewer datapoints or is otherwise streamlined in comparison to the base station instance **38**. This allows the ECG model to consume less resources, with respect to both storage requirements and for data comparison purposes as described below. The complexity of the sensor platform instance **34** may be selected to maximize efficient use of computing resources without compromising accuracy. In particular, in some embodiments the sensor platform, which may not have a training module, implementsthe ECG model using integer point arithmetic which provides requisite precision without needing the floating point support.

[0036] During regular operation, the sensor platform module **30** may use the sensor platform instance **34** to, at node **40**, generate a model ECG signal. The sensor platform module **30** may, at node **42**, receive a sensed ECG signal from the sensors **20**. Where the sensed ECG signal is a raw signal, the sensor platform module **30** may deliver the sensed ECG signal to a pre-processing module **36** that may be configured to format the sensed ECG signal for comparison to the model ECG signal as described in detail below. At nodes **44** and **48**, the sensor platform module **30** may compare the sensed ECG signal to the model ECG signal. Specifically, at node **44** the sensor platform module **30** may compare the morphology features of the two ECG signals, and at node **48** the sensor platform module **30** may compare the interbeat features of the two ECG signals. If the ECG signals match within one or more predefined thresholds, the sensor platform module **30** may not report any data to the base station module **32**. Conversely, if the sensed data deviates from the model beyond the thresholds, the sensor platform module **30** may transmit one or more data updates to the base station module **32**. Specifically, at node **46** the sensor platform module **30** may transmit one or more deviation values, and at node **50** the sensor platform module **30** may transmit a portion of the sensed ECG signal as raw data. These comparisons and transmissions are described in detail below.

[0037] Returning to the base station module **32**, at node **58** the base station module **32** may use the base station instance **38** of the ECG model to generate an output ECG and transmit the output ECG to a display device **62**. The base station instance of the ECG model may be updated at node **54** using received deviation values as input parameters to update the corresponding parameters of the ECG model. Node **58** may further include temporally aligning the ECG model with the sensed ECG signal received at node **56** as raw data. Thus, while no data is received from the sensor platform module **30**, the base station module **30** assumes that the ECG of the patient is close to the ECG model and uses the model to generate a synthetic ECG signal, which is used at the display device **62** to represent the patient's ECG. When data is received from the sensor platform module **30**, it may be directly recorded as the patient's ECG to modify the representation of the patient's ECG at the display device **62**. The sensor platform module **30** may be configured to periodically transmit connection acknowledgement messages to the base station module **32** so that the base station module **32** may differentiate between periods of conforming ECG signal (i.e. no data sent) and device or network failure.

[0038] Several features of ECG data, such as mean heart rate and the LF/HF ratio, vary over time with activities such as sleeping, walking and exercise. As a result, a single, static ECG model may not effectively represent a patient's ECG over extended periods of time. For effective operation, the present BSN may dynamically update the ECG model as the patient's ECG changes. Since the deviation of sensed ECG from model-based values is first detected at the sensor platform module **30**, the sensor platform module **30** may trigger the modifications to the ECG model through communication of data to the base station module **30**. This may be achieved on the computationally-limited sensor platform **22** using one or a combination of feature updates and raw signal updates. For feature updates, interbeat features of the sensed ECG signal (e.g. mean heart rate) may be calculated from sensed data, and when these values change significantly, the sensor platform module **30** may update the corresponding parameters of its own instance **34** of the ECG model, and further may report the calculated deviation values to the base station module **32** for updating the base station instance **38** as described above. For raw signal updates, when the morphology of the patient's ECG deviates from the ECG model, the sensor platform module **30** may send the raw sensed data to the base station module **32**. Based on received data, the base station module **32** may derive new parameter values for the ECG model using the model learning functionality at node **52**. These values may be communicated to the sensor platform module **30** for updating the sensor platform instance **34**.

[0039] FIG. **4** illustrates a method of using a BSN to monitor ECG of a patient according to the present disclosure. At step **70**, the base station module **32** may train the ECG model. At step **72**, the base station module **32** may distribute the ECG model to the sensor platform module, which loads the ECG model at step **76**. When the base station **26** and sensor platform **22** are configured with the ECG model, patient monitoring may commence. While no data describing deviations from the ECG model is received, the base station module **32** generates an output ECG signal that comprises the ECG model at step **74**. Meanwhile, the sensors **20** on the patient sense the patient's ECG at step **78** and transmit the sensor data, comprising a sensed ECG signal, to the sensor platform **22**. At step **80**, the sensor platform module **30** collects the sensed ECG signal and, at step **82**, compares the sensed ECG signal to a model ECG signal of the ECG model. If there are any deviations in the sensed ECG signal from the model ECG signal, at step **84** the sensor platform module **30** reports the deviations. However, if there are no deviations beyond preset thresholds, described further below, the sensor platform module **30** does not transmit any data. By defining suitable thresholds for the comparison between the sensed and model-generated ECG, a large fraction of data transmission at the sensor can be suppressed, thus significantly reducing sensor energy consumption, These threshold values can be specified by the physician based on the application requirements as well as the patient's age, lifestyle and health condition. Further, they can be adjusted over time to accommodate a tradeoff between data accuracy and communication energy.

[0040] The deviations may be reported first to the gateway device **24**, which stores the deviations at step **86**. The present method provides reduced ECG data size for storage by representing ECG using model parameters instead of data samples. For example, for a time interval denoted $[t_A, t_B]$, if the patient's ECG follows the ECG model with parameter values $[p_1, p_2, \ldots P_N]$, the data can be stored in a table or database as: "$[t_A, t_B]$:$[p_1, p_2, \ldots P_N]$". These values can be used at a later time as inputs to the ECG model to regenerate the corresponding ECG data. This representation significantly reduces data size, and can enable local storage of ECG data on a resource-limited device, such as the patient's smartphone, which is not feasible with direct storage of sample values. The deviation data may also or alternatively be stored on the sensor platform **22** or base station **26**. At step **88**, the base station module **32** may receive the deviation data and use the deviation data as input parameters to update the ECG model at step **90**. At step **92**, the base station module may temporally align any abnormal ECG signal with the model ECG signal and create a modified output ECG signal for displaying the abnormal ECG.

[0041] Referring to FIG. **5**, the model learning function takes a real ECG signal as input, and generates a set of suitable input parameters for ECGSYN. The suitable input parameters may include interbeat parameters describing the interbeat features, and morphology parameters describing the morphology. In one embodiment of the step **70**, training the model may include, at step **100**, receiving the patient's ECG, such as from one or more training sensors **60** as described above. At step **102**, the interbeat parameters may be calculated from the patient's ECG. These parameters may include the parameters hrmean, hrstd and lfhfratio, corresponding to the mean heart rate, standard deviation of heart rate and LF/HF ratio features of ECG respectively. In one embodiment of calculating the LF/HF ratio, a set of 256 R-R interval values is obtained from the patient ECG data and the Power Spectral Density (PSD) of this set is computed. The Low Frequency (LF) and High Frequency (HF) components are then obtained by integrating the PSD over the ranges (0.04 Hz-0.15 Hz) and (0.15 Hz-0.4 Hz), respectively. The ratio between these components gives the value of the lfhfratio parameter. The hrmean and hrsrd values may be obtained by performing averaging and standard deviation calculations on a discrete set of about 60 R-R interval values.

[0042] At step **104**, the morphology parameters may be calculated from the patient's ECG. These parameters may include the (a, b, θ) parameters for each of the P, Q, R, S, T, and U waves. In one embodiment where only the QRS complex is evaluated, to the exclusion of the other waves, only 9 paratneters (a_Q, a_R, a_S, b_Q, b_R, b_S, θ_Q, θ_R, θ_S) are used to represent the beat morphology. Referring to FIG. **6**, at step **110** the θ for each wave may be calculated. In the QRS-only embodiment, θ_Q and θ_S are calculated using the distance of the R peak from the Q and S peaks, respectively, while θ_R is zero, by definition. For learning the remaining parameters (a_Q, a_R, a_S, b_Q, b_R, b_S), a curve fitting approach may be used at step **112**. A set of initial values for these parameters may be obtained by solving a system of linear equations using a number of points on the ECG signal equal to the number of parameter values to be obtained (six in the present example). Starting with these initial values, a least squares curve fitting function may adjust the values until the noise floor is reached.

[0043] Thus, the interbeat and morphology parameters are learned from the patient's ECG and used to generate a matching synthetic ECG. The morphology of ECG may depend on the lead configuration of the sensors, and may vary across patients. Hence, the data used for learning the model should be obtained from the intended user of the system, and using the same lead configurations for training sensors **60** that are used for sensors **20**. Referring back to FIG. **5**, the obtained parameters may be used as input parameters for the dynamic model generator, such as ECGSYN, to generate the model at step **106**. FIGS. **7**A and **7**B illustrate example fits of the model ECG signal, generated using the extracted parameters, to the patient's ECG signal collected by the training sensors **60**, where FIG. **7**A is a fit against a normal ECG and FIG. **7**B is a fit against an ECG from a patient showing congestive heart failure.

[0044] Referring to FIG. **8**, the step **82** of comparing the sensed ECG signal to the model ECG signal may include, at step **120**, pre-processing of the sensed ECG signal to convert it into a format suitable for comparison with the stored model. Referring to FIG. **9**, preprocessing may include operations such as scaling, filtering, and peak detection. Example implementation details for each of these operations are as follows:

[0045] 1) Scaling (step **140**): the amplitude of the sensed ECG signal is highly dependent on the sensor **20** hardware and the ECG lead configuration of the sensor **20**. To ensure an accurate comparison between the sensed ECG signal and the model ECG signal, both signals may be converted to a normalized, device-independent scale. This is achieved by linearly scaling each signal to a maximum of 1.2 mV and minimum of −0.4 mV.

[0046] 2) Filtering (step **142**): the sensed ECG signal is typically noisy, and may be filtered to remove the noise. For extracting the QRS complex, a passband of 5-12 Hz may be achieved by cascading lowpass and highpass filters with cutoff frequencies at about 5 Hz and about 12 Hz, respectively. For low computational overhead, a Finite Impulse Response (FIR) filter design of 6 taps and order 32 may be used.

[0047] 3) Peak Detection (step **144**): measuring ECG features such as R-R intervals or QRS complex width requires the identification of Q, R, and S peaks. FIG. **10** illustrates, in pseudocode, an algorithm for performing this peak detection at low computational overhead. This algorithm detects all the positive and negative peaks in a signal, and then imposes a relative threshold on the amplitude to qualify peaks as Q, R, and S. Further, false positives are reduced by imposing conditions based on the previous peak detected. For example, for a negative peak to be declared as 'S', the previous peak must be an R peak.

[0048] Referring again to FIG. **8**, at step **122**, the sensed ECG signal obtained from preprocessing may be compared to the model ECG signal. Such a comparison may be performed in two ways: the sensed ECG signal can be directly compared to the model ECG signal; or, a set of representative feature values can be extracted from each signal and these feature values can be compared. The feature comparison approach is more accurate for noisy measurements but incurs computational overhead for the calculation of the feature values. The feature values for interbeat features (mean and standard deviation of heart rate, and the LF/HF ratio) may be calculated at low computational cost, and so the feature comparison approach may be used for comparing interbeat features of the two signals. On the other hand, calculating the feature values of morphology features may be too resource-consuming because it requires a curve fitting approach. For devices where curve fitting calculations are not feasible or efficient, the direct signal comparison approach may be used to compare the ECG morphologies of the two signals.

[0049] Referring to FIG. **11**, where comparing the sensed ECG signal to the model ECG signal includes performing feature value calculations, the mean and standard deviation of the heart rate within the sensed ECG signal are obtained by, at step **160**, obtaining a discrete set, such as **30**, of consecutive R-R intervals and, at step **162**, calculating the mean and standard deviation of the set of R-R intervals. The LF/HF ratio may be calculated as described above. Alternatively, to optimize computation speed and power consumption, a Fast Fourier Transform (FFT) configured particularly for performing in-place computations within the sensor platform module **30** may be used at step **164** to obtain the LF/HF ratio. Once these calculations are complete, at step **166** the calculated feature values are compared to model parameter values hrmean, hrstd and lfhfratio, respectively.

[0050] Referring to FIG. **12**, where comparing the sensed ECG signal to the model ECG signal includes performing direct comparisons of the two signals, at step **180** a discrete set, such as **10**, of consecutive beats within the sensed ECG may be obtained. At step **182** a sample, representative beat, referred to as meanBeat, for the sensed ECG signal may be obtained by averaging the set of consecutive beats. At step **184**, a representative beat, referred to as modelBeat, for the model ECG signal may be obtained with a similar method to that of obtaining meanBeat, or the model generator may be configured to generate modelBeat. At step **186**, the modelBeat and meanBeat are aligned by superimposing the respective R peaks, and at step **188** the fit is compared using a mean square error approach or another suitable comparison approach. The mean square metric may be advantageous because it captures shape as well as amplitude of the Q, R and S waves. The generation of modelBeat may be so computationally expensive that it is preferable to be performed only once, when new morphology parameter values are assigned. The generated modelBeat is then stored in memory for future use.

[0051] Referring again to FIG. **8**, based on these comparisons, if the sensed ECG signal is found to deviate from the model, the sensor platform module **30** may report the deviation to the base station module **32**. For interbeat features, if the mismatch between true feature values and corresponding model parameter values exceeds a pre-defined threshold, the sensor platform module **30** may update its own model parameters in the sensor platform instance **34**. At step **124**, the sensor platform module **30** may also report the feature update to the base station module **32**. In the morphology comparison, if the error between meanBeat and modelBeat is above a specified threshold, the sensed ECG signal for the corresponding time interval (i.e. 10 beats as collected for determining meanBeat) may be sent to the base station module **32**, at step **126**. If the base station module **32** receives multiple such raw signal updates, it may retrain the morphology parameters of the ECG model, and may communicate the new values to the sensor platform module **30**. Although such raw signal updates can incur significant data transmission at the sensor platform **22**, the impact on overall energy consumption is minimal, since the ECG morphology of a person is not expected to vary much over time. Furthermore, current or future data compression schemes may be added to the present methods to reduce the data size in cases where the sensor platform **22** transmits raw data to the base station **26**. This will help to further reduce energy consumption.

[0052] It will be appreciated by those skilled in the art that while the invention has been described above in connection with particular embodiments and examples, the invention is not necessarily so limited, and that numerous other embodiments, examples, uses, modifications and departures from the embodiments, examples and uses are intended to be encompassed by the claims attached hereto. The entire disclosure of each patent and publication cited herein is incorporated by reference, as if each such patent or publication were individually incorporated by reference herein. Various features and advantages of the invention are set forth in the following claims.

We claim:

1. A method for monitoring an electrocardiogram (ECG) of a patient, the method comprising:

receiving a sensed ECG signal from one or more sensors configured to collect the sensed ECG signal from the patient;

comparing the sensed ECG signal to a model ECG signal; and

if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmitting deviation data describing the deviation to a base station.

2. The method of claim **1**, further comprising transmitting no data other than the deviation data to the base station.

3. The method of claim **1**, further comprising periodically transmitting an acknowledgment signal to the base state, and transmitting no data other than the deviation data and the acknowledgment signal to the base station.

4. The method of claim **1**, wherein comparing the sensed ECG signal to the model ECG signal comprises one or more of: performing feature value calculations; and performing direct comparisons of the sensed ECG signal to the model ECG signal.

5. The method of claim **1**, further comprising generating an output ECG signal, wherein the output ECG signal comprises the model ECG signal when no deviation data is transmitted, and wherein the output ECG signal comprises a modification to the model ECG signal when deviation data is transmitted, the modification being generated based on the deviation data.

6. The method of claim **1**, wherein the deviation data comprises one or more feature updates.

7. The method of claim **6**, further comprising updating the model ECG signal based on the one or more feature updates.

8. The method of claim **1**, wherein the deviation data is raw data comprising a portion of the sensed ECG signal.

9. A method for monitoring an electrocardiogram (ECG) of a patient, the method comprising

receiving at a sensor platform a sensed ECG signal from one or more sensors configured to collect the sensed ECG signal from the patient;

comparing, at the sensor platform, the sensed ECG signal to a model ECG signal;

if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmitting, from the sensor platform, deviation data describing the deviation to a base station; and

generating, at the base station, an output ECG signal to be displayed on a display device, wherein the output ECG signal comprises the model ECG signal and, when deviation data is received, further comprises a modification to the model ECG signal.

10. The method of claim **9**, wherein comparing the sensed ECG signal to a model ECG signal comprises performing calculations of one or more feature values of the sensed ECG signal, comparing the one or more feature values to one or more corresponding model parameter values of the model ECG signal, and generating the deviation data comprising any of the one or more feature values that deviates from the corresponding model parameter values beyond the threshold.

11. The method of claim **10**, further comprising updating an ECG model, from which the model ECG signal is derived, based on the deviation data.

12. The method of claim **9**, wherein comparing the sensed ECG signal to a model ECG signal comprises:

obtaining a set of consecutive beats from the sensed ECG signal;

calculating a representative beat for the sensed ECG signal, comprising the average of the set of consecutive beats;

directly comparing the representative beat for the sensed ECG signal to a representative beat for the model ECG signal; and

generating the deviation data as raw data comprising either or both of the set of consecutive beats and the representative beat for the sensed ECG signal.

13. The method of claim **12**, wherein the modification to the model ECG signal comprises an abnormal ECG signal generated using the deviation data.

14. The method of claim **9** further comprising periodically transmitting, from the sensor platform to the base station module, an acknowledgment signal, wherein the sensor platform does not transmit any data to the base station module other than the deviation data and the acknowledgement signal.

15. The method of claim **9**, further comprising training, at the base station, an ECG model from which the model ECG signal is derived, the training comprising:

receiving a training ECG from the patient;

calculating one or more interbeat parameters from the training ECG;

calculating one or more morphology parameters from the training ECG; and

generating the ECG model using the interbeat parameters and the morphology parameters as inputs.

16. The method of claim **15**, further comprising distributing the ECG model from the base station to the sensor platform.

17. A body sensor network for monitoring an electrocardiogram of a patient, the body sensor network comprising:

a base station comprising a base station module configured to generate an ECG model and to generate an output ECG signal for displaying on a display device; and

a sensor platform in electrical communication with the base station, the sensor platform comprising a sensor platform module configured to:

receive a sensed ECG signal from one or more sensors attached to the patient and collecting the patient's ECG embodied in the sensed ECG signal;

receive an instance of the ECG model and produce a model ECG signal from the instance;

compare the sensed ECG signal to the model ECG signal; and

if a deviation of the sensed ECG signal from the model ECG signal exceeds a threshold, transmit deviation data describing the deviation to the base station module;

wherein the sensor platform module does not transmit the sensed ECG signal if there is no deviation of the sensed ECG signal from the model ECG signal exceeding the threshold.

18. The body sensor network of claim **17**, wherein the sensor platform module compares the sensed ECG signal to a model ECG signal by:

performing calculations of one or more feature values of the sensed ECG signal;

comparing the one or more feature values to one or more corresponding model parameter values of the model ECG signal; and

generating the deviation data comprising any of the one or more feature values that deviates from the corresponding model parameter values beyond the threshold;

and wherein the base station module is configured to update the ECG model based on the deviation data.

19. The body sensor network of claim **17**, wherein the sensor platform module compares the sensed ECG signal to a model ECG signal by:

obtaining a set of consecutive beats from the sensed ECG signal;

calculating a representative beat for the sensed ECG signal, comprising the average of the set of consecutive beats;

directly comparing the representative beat for the sensed ECG signal to a representative beat for the model ECG signal; and

generating the deviation data as raw data comprising either or both of the set of consecutive beats and the representative beat for the sensed ECG signal;

and wherein the output ECG signal comprises an abnormal ECG signal that is based on the deviation data.

* * * * *

专利名称(译)	身体传感器网络中生成模型驱动的资源有效监测		
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摘要(译)

身体传感器网络（BSN）和使用这种BSN监视心电图的方法包括生成ECG模型的基站和用于在显示设备上显示的输出ECG信号，以及与基站电通信的传感器平台。传感器平台可以被配置为从一个或多个传感器接收感测的ECG信号，接收ECG模型的实例，并从实例产生模型ECG信号。传感器平台将感测的ECG信号与模型ECG信号进行比较，并且如果感测的ECG信号与模型ECG信号的偏差超过阈值，则将描述偏差的偏差数据发送到基站模块。如果没有这种偏差，传感器平台模块不会向基站发送任何数据。