(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
9 August 2012 (09.08.2012)

WIPO | PCT

(10) International Publication Number
WO 2012/103585 A1

(51) International Patent Classification:
*A61B 5/025* (2006.01) *A61B 5/0468* (2006.01)
*A61B 5/11* (2006.01)

(21) International Application Number:
PCT/AU2012/000087

(22) International Filing Date:
2 February 2012 (02.02.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2011900326 2 February 2011 (02.02.2011) AU

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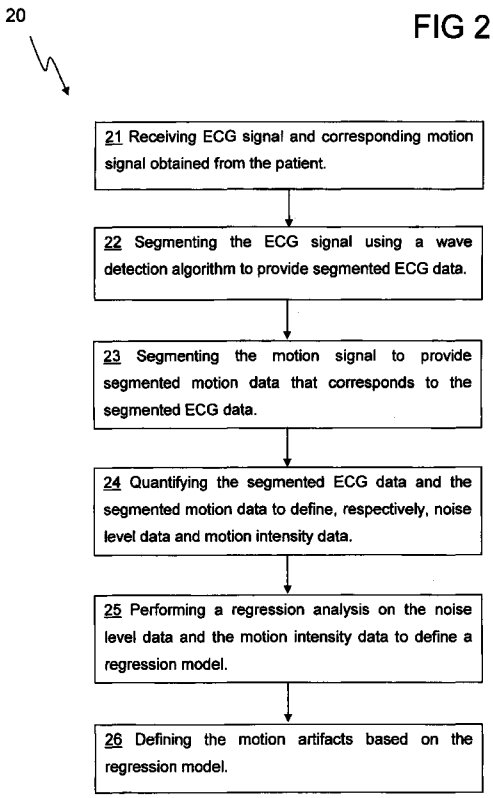
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,

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(54) Title: A METHOD AND SYSTEM FOR DEFINING MOTION ARTIFACTS IN ELECTROCARDIOGRAM (ECG) SIGNALS

FIG 2




(57) Abstract: A method for defining motion artifacts in a corrupted signal, such as an electrocardiogram (ECG) signal, enables improved signal acquisition and analysis. The method includes receiving the corrupted signal and a corresponding motion signal (step 21); segmenting the corrupted signal to provide segmented corrupted data (step 22); segmenting the motion signal to provide segmented motion data that corresponds to the segmented corrupted data (step 23); quantifying the segmented corrupted data and the segmented motion data to define, respectively, noise level data and motion intensity data (step 24); performing a regression analysis on the noise level data and the motion intensity data to define a regression model (step 25); and quantifying the motion artifacts based on the regression model (step 26).

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DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Published**:

— *with international search report (Art. 21(3))*

# TITLE

# A METHOD AND SYSTEM FOR DEFINING MOTION ARTIFACTS IN ELECTROCARDIOGRAM (ECG) SIGNALS

## FIELD OF THE INVENTION

This invention relates generally to defining motion artifacts in corrupted signals such as Electrocardiogram (ECG) signals, and in particular to a method and system for defining motion artifacts based on a regression analysis of noise level data.

## BACKGROUND TO THE INVENTION

An Electrocardiogram (ECG) is a graphical recording of the electrical activity of the heart of a patient, and may be used to evaluate cardiac function. An ECG is usually recorded when the patient is stationary. However, many heart problems are only noticeable during physical activity. Thus it is often necessary to record an ECG during physical activity, which is known as an ambulatory ECG. Recording an ambulatory ECG has been found to be useful for various purposes such as health promotion, cardiac disease risk predictions, cardiovascular disease prevention and treatments, and sports medicine.

In order to record an ambulatory ECG, electrodes and devices have been specially developed. However, interference or noise is commonly introduced into an ECG when a patient moves, which is known as a Motion Artifact (MA) and which may adversely affect analysis of the ECG recording, resulting in a corrupted signal. Thus an effective choice of ambulatory ECG electrodes and devices to minimize MA levels is critical in many applications. Additionally, it is often necessary to reduce the amount of MA in an ambulatory ECG to an acceptable level, and in particular in clinical applications.

However, quantification of MA is often difficult due to the irregular and non-stationary nature of MA. The conventional method of measuring noise by measuring a peak-to peak Voltage (Vpp) is not suitable for MA

quantification, as it is difficult to identify characteristic signal peaks of the ECG within irregular MA waveforms. Furthermore, Vpp does not reliably reflect real power (energy per unit time) of the MA because the MA waveform can vary depending on a type of activity, individual patients, a type of electrode and ECG device setups. It has also been difficult to use conventional filter techniques to extract MA waveforms for quantification, because both MA and ECG signals share very similar spectral characteristics in the frequency domain. Moreover, the irregular and non-stationary nature of MA can lead to significant variations in MA amplitudes, frequency spectral characteristics, and waveform patterns, which further complicate the quantification of MA.

Previous research relating to MA quantification has been limited, and has mainly been focused on trying to find solutions to detect and reduce MA, rather than to quantify MA. There is therefore a need for an improved method and system for defining motion artifacts in ECG signals.

## OBJECT OF THE INVENTION

It is an object of the invention to overcome or alleviate one or more of the above disadvantages and/or to provide the consumer with a useful or commercial choice.

## SUMMARY OF THE INVENTION

In one form, although it need not be the only or indeed the broadest form, the invention resides in a method for defining motion artifacts in an electrocardiogram (ECG) signal, the method comprising:

receiving the ECG signal and a corresponding motion signal obtained from a patient;

segmenting the ECG signal to provide segmented ECG data;

segmenting the motion signal to provide segmented motion data that corresponds to the segmented ECG data;

quantifying the segmented ECG data and the segmented motion data to define, respectively, noise level data and motion intensity data;

performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

quantifying the motion artifacts based on the regression model.

Preferably, quantifying the segmented ECG data and the segmented motion data comprises performing a root mean square (RMS) analysis.

Preferably, quantifying the motion artifacts based on the regression model comprises calculating and analyzing parameters of the regression model.

Preferably, deviations of the noise level data and motion intensity data from the regression model define whether the noise level data is unrelated to the motion signal or is part of the ECG signal.

Preferably, analyzing the deviations of the noise level data and motion intensity data from the regression model comprises performing an entropy analysis of the noise level data and the motion intensity data.

Preferably, the entropy analysis comprises determining a probability density function (PDF) of motion artifact variation.

Preferably, the ECG signal is segmented using a QRS wave detection algorithm.

Preferably, the regression analysis comprises a linear regression analysis using a least squares method.

Preferably, the ECG signal and the motion signal are received from a single monitoring device and the motion signal comprises an acceleration signal.

Preferably, the method is performed in real time while the patient is wearing an ECG monitoring device to assist in positioning of the ECG monitoring device on the patient.

Preferably, the method further comprises excluding from post ECG analysis portions of the ECG signal corresponding to the segmented ECG data that is contaminated with defined motion artifacts.

Preferably, the method is performed to validate an ECG monitoring device that acquires the ECG signal.

In another form the invention resides in a system for defining motion artifacts in an electrocardiogram (ECG) signal, the system comprising:

a processor; and

a memory operatively coupled to the processor, wherein the memory comprises:

computer readable program code components for processing the ECG signal and a corresponding motion signal obtained from a patient;

computer readable program code components for segmenting the ECG signal to provide segmented ECG data;

computer readable program code components for segmenting the motion signal to provide segmented motion data that corresponds to the segmented ECG data;

computer readable program code components for quantifying the segmented ECG data and the segmented motion data to define, respectively, noise level data and motion intensity data;

computer readable program code components for performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

computer readable program code components for quantifying the motion artifacts based on the regression model.

Preferably, the system includes computer readable program code for quantifying the segmented ECG data and the segmented motion data comprises performing a root mean square (RMS) analysis.

Preferably, deviations of the noise level data and motion intensity data from the regression model define whether the noise level data is unrelated to the motion signal or is part of the ECG signal.

Preferably, analyzing the deviations of the noise level data and motion intensity data from the regression model comprises performing an entropy analysis of the noise level data and the motion intensity data.

Preferably, defining the motion artifacts based on deviations from the regression line comprises performing an entropy analysis of the noise level data and the motion intensity data.

Preferably, the entropy analysis comprises determining a probability density function (PDF) of motion artifact variation.

Preferably, the ECG signal is segmented using a QRS wave detection algorithm.

Preferably, the regression analysis comprises a linear regression analysis using a least squares method.

Preferably, the ECG signal and the motion signal are received from a single monitoring device operatively coupled to the processor, and the motion signal comprises an acceleration signal.

Preferably, the system operates in real time while the patient is wearing an ECG monitoring device to assist in positioning of the ECG monitoring device on the patient.

Preferably, the system further comprises computer readable program code components for excluding from post ECG analysis portions of the ECG signal corresponding to the segmented ECG data that is contaminated with defined motion artifacts.

Preferably, the system operates to validate an ECG monitoring device that acquires the ECG signal.

According to yet another aspect, the present invention resides in a method for defining motion artifacts in a corrupted signal, the method comprising:

receiving the corrupted signal and a corresponding motion signal;

segmenting the corrupted signal to provide segmented corrupted data;

segmenting the motion signal to provide segmented motion data that corresponds to the segmented corrupted data;

quantifying the segmented corrupted data and the segmented motion data to define, respectively, noise level data and motion intensity data;

performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

quantifying the motion artifacts based on the regression model.

## BRIEF DESCRIPTION OF THE DRAWINGS

To assist in understanding the invention and to enable a person skilled in the art to put the invention into practical effect, preferred embodiments of the invention will be described by way of example only with reference to the accompanying drawings, in which:

FIG 1 shows a block diagram of a system for defining motion artifacts in an electrocardiogram (ECG) signal according to an embodiment of the present invention;

FIG 2 shows a flow diagram of a method for defining motion artifacts in an ECG signal according to an embodiment of the present invention;

FIG 3 shows a graph of noisy ECG signal data sets according to an embodiment of the present invention;

FIG 4 shows a graph of ECG signal data sets separated from the noisy ECG signal data sets of FIG 3 according to an embodiment of the present invention;

FIG 5 shows a graph of noise data sets separated from the noisy ECG signal data sets of FIG 3 according to an embodiment of the present invention;

FIG 6 shows a graph of singular values against a rank of singular values according to an embodiment of the present invention;

FIG 7 shows a graph of Motion Artifact versus Motion Intensity and a corresponding linear regression line of a Zephyr electrode according to an embodiment of the present invention;

FIG 8 shows a graph of Motion Artifact versus Motion Intensity and a corresponding linear regression line of a Polar electrode according to an embodiment of the present invention;

FIG 9 shows a graph of Motion Artifact versus Motion Intensity and a corresponding linear regression line of a 3M RedDot electrode according to an embodiment of the present invention;

FIG 10 shows a graph comparing the linear regression lines of FIGs 8, 9 and 10 according to an embodiment of the present invention;

FIG 11 shows a graph of a probability density function of the Polar and 3M electrodes of FIGs 8 and 9 according to an embodiment of the present invention;

FIG 12 shows a graph of entropy value under different test conditions for the Zephyr, Polar and 3M RedDot electrodes according to an embodiment of the present invention;

FIG 13 shows a graph of a Motion Artifact quantification error and R-wave detection error against noise amplitude according to an embodiment of the present invention; and

FIG 14 shows a graph of a Motion Artifact quantification error against noise for different singular value rank selections according to an embodiment of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

Elements of the invention are illustrated in concise outline form in the drawings, showing only those specific details that are necessary to understanding the embodiments of the present invention, but so as not to clutter the disclosure with excessive detail that will be obvious to those of ordinary skill in the art in light of the present description.

In this patent specification, adjectives such as first and second, left and right, top and bottom, etc., are used solely to define one element or method step from another element or method step without necessarily requiring a specific relative position or sequence that is described by the adjectives. Words such as "comprises" or "includes" are not used to define

an exclusive set of elements or method steps. Rather, such words merely define a minimum set of elements or method steps included in a particular embodiment of the present invention.

FIG 1 shows a block diagram of a system 10 for defining motion artifacts in a corrupted signal, such as a corrupted electrocardiogram (ECG) signal, according to an embodiment of the present invention. The system 10 includes a processor 12, a memory 14 operatively coupled to the processor 12 and an ECG monitoring device 16 operatively coupled to the processor 12. The connection between the processor 12 and the ECG monitoring device 16 is preferably wireless, for example using Bluetooth®, ZigBee, or cellular networks. However it should be appreciated that any suitable wired connection may also be used. The memory 14 includes computer readable program code components for carrying out the method of the present invention.

The ECG monitoring device 16 connects to one or more electrodes 18-1, 18-2, 18-n that are positioned on a patient to obtain an ECG signal from the patient, as would be understood by a person skilled in the art. The ECG monitoring device 16 also includes an accelerometer (not shown) that generates an acceleration signal according to movement of the patient. The ECG signal and a corresponding motion signal from the accelerometer are received and processed by the processor 12 according to the computer readable program code components stored in the memory 14.

FIG 2 shows a flow chart 20 of a method for defining motion artifacts in an ECG signal according to an embodiment of the present invention. By using a method of the present invention, motion artifacts may be quantified according to a type of activity, an individual patient, a type of electrode or an ECG device setup. For example an electrode may be quantified for use in measuring stationary and ambulatory ECGs. Once an ECG signal and a corresponding motion signal have been received, they undergo both an entropy analysis and a regression analysis to determine a level of performance of an ECG setup or a type of electrode.

At step 21, the ECG signal and the corresponding motion signal are received by the processor 12, having been obtained from the patient. The ECG signal and the corresponding motion signal are converted to a digital signal and are denoted as:

$$SS: \{(E_1, Ax_1, Ay_1, Az_1), (E_2, Ax_2, Ay_2, Az_2), (E_i, Ax_i, Ay_i, Az_i), \ldots (E_n, Ax_n, Ay_n, Az_n)\} \quad \text{Eq. 1}$$

where:

n is a total number of sampling points;

E represents sampled digital data of the ECG signal;

$E_i$, $Ax_i$, $Ay_i$, $Az_i$ are the i-th sampled data set; and

Ax, Ay and Az are acceleration data defined as motion intensity (MI) data according to the acceleration (or movement) of the patient in the x, y, and z axes.

At step 22, the sampled ECG signal is segmented using a wave detection algorithm to provide segmented ECG data.

The ECG signal comprising of $E:\{E_1, E_2, E_i \ldots E_n\}$ is segmented using a wave detection algorithm, for example as is well known in the art a Pan-Tompkins method can be used to detect the QRS wave of the ECG. However it should be appreciated that other applicable wave detection algorithms and signal segmentation techniques, as are well known in the art, may be used. The output from the wave detection algorithm is denoted as:

$R:\{R_1, R_2, \ldots R_j, \ldots R_m\}$,

where the value of $R_j$ is the sampling point where an R wave is detected;

m is the total number of QRS waves in the ECG data; and

j represents the j-th detected R wave.

Based on the position of the R wave within the data $\{R_1, R_2, \ldots R_j, \ldots R_m\}$, the ECG signal $\{E_1, E_2, \ldots E_n\}$ is segmented and the segmented ECG data (ES) is denoted by:

$$ES: \{ES_1, ES_2, \ldots ES_j, \ldots ES_m\}^T, \quad \text{Eq. 2}$$

Similarly, a subset of $ES_j$ at the j-th sampled data set is expressed as:

$$ES_j = (ER_{j-30}, ER_{j-29}, \ldots, ER_{j+70}) \quad \text{Eq. 3}$$

The time period from $ER_{j-30}$ to $ER_{j+70}$ typically has a duration of approximately 0.33 seconds and is mainly occupied by the QRST wave segment of the ECG signal. This segment period may be selected as it is relatively stable, and it does not overlap with a neighbouring PQRST waveform for heart rates of up to 180 beats per minute (BPM). However it should be appreciated that other durations may be used depending on the application and heart rates that may be encountered.

Correspondingly, at step 23, the motion signal is segmented to provide segmented motion data that corresponds to the segmented ECG data.

Similar to the ECG signal, the motion signal is segmented and expressed as segmented motion data as follows:

$$AS: \{AS_1, AS_2, \ldots AS_j, \ldots AS_m\}^T, \quad \text{Eq. 4}$$

where:

$$AS_j = \{Am_{Rj-30}, Am_{Rj-29}, \ldots Am_{Rj+70}\} \quad \text{Eq. 5}$$

and:

$$Am_t = (Ax_t, Ay_t, Az_t) \quad \text{Eq. 6}$$

The ECG signals containing the MA or noise may be modelled by the equation:

$$ES = ER + MR \quad \text{Eq. 7}$$

where:

ES is the acquired ECG data, as in Eq. 3;

ER is the real ECG; and

MR is the real MI generated by the movement of the patient and obtained from the accelerometer of the ECG monitoring device 16.

Other types of noise are relatively less significant than the MA and thus are excluded. ER and MR are separated by applying a Principle Component Analysis (PCA). The principle components are obtained by a Singular Vector Decomposition (SVD) method. In the present invention, the source matrix is $ES_{p\times q}$, where p = m and q = 101 (number of samples), according to Eq 3. By applying the SVD, $ES_{p\times q}$ is decomposed to:

$$ES_{p\times q} = U_{p\times q} \cdot S_{p\times q} \cdot V^{CT}_{q\times q} \qquad \text{Eq. 8}$$

where:

*U* is a unitary matrix;

S is a diagonal matrix with non-negative singular values on its diagonal;

V is the eigenvector matrix where the matrix columns are eigenvectors; and

$V^{CT}$ denotes the conjugate transpose of V.

q is the number of samples in one ES data set and is set according to a number of samples acquired. It should be appreciated that q may be any suitable number depending of the resolution of the data set.

The PCA for separating the ER signal and MR signal from an acquired ECG signal is demonstrated graphically in FIGs 3 to 5. In this example, one hundred and fifty (150) QRS waveforms are extracted from acquired ECG signals (ES) using the PanTomkins method previously described. The ECG signals are acquired from a resting patient.

Random noise added to the acquired ECG signals is shown in FIG 3. The noisy acquired ECG signal is extracted using PCA and the extracted ECG signal (ER) is shown in FIG 4, and the noise signal (MR) is shown in FIG 5. In FIGs 3-5 the z-axis 32, 42, 52 is the amplitude of the signal, the y-axis 34, 44, 54 is a data set of the extracted QRS waveforms and the x-axis 36, 46, 56 is a sample of the data set.

Next, the singular values in the diagonal matrix S are ranked by arranging singular values from the highest values first to the lowest values last. A high singular value reflects the significance of the information contained in a corresponding Eigenvector. It is considered that ER, containing the ECG signals, represents major information in the ES and that the MR, which is close to "white noise", contains no information. Based on ranks of the singular values, ER and MR are separated and reconstructed by the equations:

$$ER_{p\times q} = U_{p\times q} \cdot Se_{p\times q} \cdot V^{CT}_{q\times q} \quad \text{Eq. 9}$$

$$MR_{p\times q} = U_{p\times q} \cdot Sa_{p\times q} \cdot V^{CT}_{q\times q} \quad \text{Eq. 10}$$

where:

$Se_{i\times i} = Si\times iW$, if $i \geq Nr$;

$Se_{i\times i} = 0$, if $i < Nr$. $Sa_{i\times i} = Si\times iW$, if $i < Nr$; and

$Sa_{i\times i} = 0$, if $i \geq Nr$.

where:

Nr is the rank of the singular value and is determined experimentally from the data obtained in FIG 3.

FIG 6 shows a graph 60 of an Eigen spectral analysis of MA showing singular values 61 plotted against a sequence of singular values 62. As shown in the graph 60, there is a dramatic drop from the first ranked singular value to the second ranked singular value. Singular values from the third rank onwards remain largely unchanged. Therefore in this case the selection of Nr = 2 can effectively separate the ECG signal from the motion signal. It should be appreciated that in other situations a different value of Nr may be used.

At step 24, the segmented ECG data and the segmented motion data are quantified to define, respectively, noise level data and motion intensity (MI) data. A Root Mean Square (RMS) method is used to quantify the motion

artifact segments and motion segments to respectively reflect the noise level and the motion intensity.

{(MAp1, MIp1), (MAp2, MIp2), ... (MApj, MIpj), ... (MApm, MIpm)} denotes the noise level data (MAp) and the motion intensity data (MIp), thus

$$MAp_j = \sqrt{[\sum_{k=1}^{k\le 101}(MR_{j,k})^2] \div 101} \qquad \text{Eq. 11}$$

and

$$MIp_j = \sqrt{[\sum_{k=1}^{k\le 101}(Am_{Rj-29+k})^2] \div 101} \qquad \text{Eq. 12}$$

where:

$$Am_{Rj-29+k} = \sqrt{Ax_{Rj-29+k}^2 + Ay_{Rj-29+k}^2 + Az_{Rj-29+k}^2} \qquad \text{Eq. 13}$$

At step 25 a regression analysis is performed on the noise level data and the motion intensity data to define a regression model. At step 26, from the regression model the motion artifacts may be quantified based on the regression model parameters.

A linear relationship between MAp and MIp is analysed by the linear regression analysis using a linear regression model that takes the form of:

$$MAp = A + B \cdot MIp \qquad \text{Eq. 14}$$

where:

MAp is the power of MA in an extracted segment and is calculated by the root mean squared (RMS) value;

A and B are output variables of the regression analysis model and define the characteristics of the MA; and

MIp is a power of MI of a corresponding MA segment.

The regression line of the regression analysis model is obtained using a least squares method.

The regression analysis is demonstrated graphically in FIGS 7-9 for three types of electrode, namely a Zephyr electrode (FIG 7), a Polar electrode (FIG 8) and a 3M RedDot electrode (FIG 9) for differing motion states. FIGs 7-9 show MI 71, 81, 91 plotted against MA 72, 82, 92, respectively, a corresponding regression line 73, 83, 93 and a formula 74, 84, 94, respectively, of a regression line 73, 83, 93 relating to Eq. 14. Also shown is a probability of statistic significance of null hypothesis of linear correlation, p 75, 85, 95 and a square of the correlation coefficient $r^2$ 76, 86, 96. Data for a stationary motion state is depicted by "+" signs, a jogging motion state is depicted by "o" signs and a running motion state is depicted by "x" signs. A value of p 75, 85, 95 of less than 0.05 indicates that the linear regression analysis between MA and MI is linearly correlated.

The regression line may be analysed to determine a performance of an electrode. The regression lines 101, 102, 103 for, respectively, the Polar electrode, the Zephyr electrode, and the 3M RedDot electrode are shown in FIG 10. A slope of the regression line (parameter B in Eq. 14) indicates the electrode or measurement set-up's suitability for use in ambulatory conditions. The lower the value of B the more suited the electrode or set-up is for ambulatory conditions. From FIG 10, the Polar Electrode is most suited for ambulatory ECG measurements as the slope of the regression line 101 is the least steep.

An intersection (parameter A in Eq. 14) of the regression line on the y-axis demonstrates an electrode or an ECG measurement setup's suitability for resting ECG measurements. A lower value of A demonstrates that the electrode is more suited for resting ECG measurements. As shown in FIG 10, the 3M RedDot electrode is most suited to resting ECG measurements as its regression line intersects the x-axis at the lowest value.

Entropy-based algorithms quantify the regularity of a control system. Entropy increases with the degree of disorder and is a maximum for completely random systems. In the present invention entropy is used to

quantify how well the MA and MI data points align with a linear regression line, or how much the MA and MI data points deviate from a regression model. That assists in determining whether noise level data is unrelated to a motion signal or whether such data is part of an ECG signal.

Deviation data (from the regression line) are denoted as V = {v1, v2, ... vj, ... vm}, thus component vj can be expressed as:

$$vj = MAp_j - [A + B \cdot MIp_j] \qquad \text{Eq.15}$$

In one embodiment of the present invention, a probability density function (PDF) of motion artifact variation is estimated by the Parzen PDF estimation method (see, e.g., Parzen, E., On Estimation of Probability Density Function and Mode. Annals of Mathematical Statistics, 1962. 33: p. 1065-1076). However it should be appreciated that any other applicable estimation method may be used. The Parzen method is used as it may provide relatively consistent results even where some sections of data are missing. When the number of data grows the standard deviation decreases and the estimated conditional probability approaches a true value (see, e.g., Scott, D.W., OPTIMAL AND DATA-BASED HISTOGRAMS. Biometrika, 1979. 66(3): p. 605-610).

If the PDF of V is denoted as P(v), P(v) can be expressed as:

$$P(v) = \frac{1}{m \times h} \sum_{k=1}^{k \le m} K[\frac{v_k - v}{h}] \qquad \text{Eq. 16}$$

where:

h is a window width parameter, and

K[u] is a weighting function, or window function.

A normal distribution is used as a weighting function as proposed by Parzen and is expressed as:

$$K[u] = (2\pi)^{-1/2} \cdot \exp[-u^2/2] \qquad \text{Eq. 17}$$

It is assumed that the PDF is normally distributed, thus *h* is estimated by the equation:

$$h = \frac{3.49 \times \sigma}{m^{1/3}} \qquad \text{Eq. 18}$$

where:

σ is the standard deviation of V; and

*m* is the total number of calculated v.

The PDF may be used to demonstrate the consistency of various types of electrodes for different patients, patient movements and different ECG set-ups. FIG 11 shows a graph 110 of the probability values 111 of the probability density function (PDF) of MI for the polar electrode 112 and a 3M electrode 113 whilst a patient is jogging. The PDF of the Polar electrode 112 has a single dominant peak 115, whereas the PDF of the 3M electrode 113 displays a dominant peak 116 and a secondary peak 117, as well as some fluctuations between the dominant peak 116 and the secondary peak 117. This indicates that Polar electrode performance is more consistent and more independent of different motion states and different ECG measurement setups. In contrast, the performance of the 3M electrode is less consistent as the PDF shifts from one motion state to another depending on the test condition and different patients.

Entropy quantifies the PDF of V to reflect how well V aligns with the regression line, and can be calculated by the equation:

$$ENT = -\int P(v) \times \log_{10}(P(v))\, dx \qquad \text{Eq. 19}$$

where:

P(v) is discrete; and

integration is computed from -5 σ to 5σ .

According to one embodiment of the present invention a bin size is 10σ /1000 and the ENT ranges from three to zero. A lower entropy value

means that values of v are more closely aligned with the regression line, thus the performance of a type of electrode is more independent of the variation of motion intensity and individual patients.

FIG 12 shows a graph 120 of entropy values 121 for the Zephyr electrode 122, the Polar electrode 123 and the 3M electrode 124. The entropy values 121 indicate how well the MA and MI data points align with the linear regression line of FIGs 7, 8 and 9 when a patient is resting 125, walking 126 and jogging 127. A lower entropy value indicates that the MA and MI points are closely aligned with the regression line and are thus suitable for a particular motion state. In the example provided in FIG 12, the 3M RedDot electrode is most suited for resting states, as it has the lowest entropy value in the resting motion state. The Polar electrodes are more suited for ambulatory states as they have the lowest entropy values in the jogging and running motion states.

As shown in FIG 13, MA quantification error rates 134 are not significantly affected when the amplitude of noise on an ECG signal increases. FIG 13 shows that when the PanTompkins QRS detection error rate 132 starts to increase, at point 138, the MA quantification error rate 134 (for Nr = 2, 3 or 4) does not increase. However, the MA quantification error rate 134 is highest when Nr = 1.

FIG 14 shows a graph of the mean MA quantification error 142 against noise amplitude 144 for singular value ranks 146, Nr, of 1, 2, 3 and 4. As shown in FIG 14, the MA quantification error 142 for Nr = 1 is generally higher than for higher ranks. Furthermore, Nr = 2 is the optimum value which is consistent with the Eigen spectral analysis of FIG 6. A lowest possible singular value rank is chosen as there is a risk that for Nr > 2, noise not relating to MA will be mistaken.

Thus, according to the detailed description provided herein, the method and system of the present invention allows ECG electrodes and ECG set-ups to be quantified. This means that electrodes and ECG set-ups can be effectively selected, from a linear regression and entropy analysis performed on acquired ECG signals, to best suit particular applications.

In particular, parameters of a regression model may be used to determine an electrode's suitability for resting or ambulatory ECG measurements. Furthermore, an entropy and a Probability Density Function analysis may be used to determine an electrode's consistency for use in different motion states.

Those skilled in the art will appreciate that the teachings of the present invention also can be applied to analyse corrupted signals other than ECG signals. For example, the present invention can be used to define motion artifacts in other biometric signals such as blood pressure signals, muscle tremor signals, and electroencephalograph (EEG) signals. Thus the present invention can be used in the analysis of various signals that are corrupted by motion artifacts and which have a characteristic pattern that can be effectively segmented as described herein.

Limitations in any patent claims associated with the present disclosure should be interpreted broadly based on the language used in the claims, and such limitations should not be limited to specific examples described herein. In this specification, the terminology "present invention" is used as a reference to one or more aspects within the present disclosure. The terminology "present invention" should not be improperly interpreted as an identification of critical elements, should not be improperly interpreted as applying to all aspects and embodiments, and should not be improperly interpreted as limiting the scope of any patent claims.

## CLAIMS

1. A method for defining motion artifacts in an electrocardiogram (ECG) signal, the method comprising:

receiving the ECG signal and a corresponding motion signal obtained from a patient;

segmenting the ECG signal to provide segmented ECG data;

segmenting the motion signal to provide segmented motion data that corresponds to the segmented ECG data;

quantifying the segmented ECG data and the segmented motion data to define, respectively, noise level data and motion intensity data;

performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

quantifying the motion artifacts based on the regression model.

2. The method of claim 1, wherein quantifying the segmented ECG data and the segmented motion data comprises performing a root mean square (RMS) analysis.

3. The method of claim 1, wherein quantifying the motion artifacts based on the regression model comprises calculating and analyzing parameters of the regression model.

4. The method of claim 1 wherein deviations of the noise level data and motion intensity data from the regression model define whether the noise level data is unrelated to the motion signal or is part of the ECG signal.

5. The method of claim 3, wherein analyzing the deviations of the noise level data and motion intensity data from the regression model comprises performing an entropy analysis of the noise level data and the motion intensity data.

6. The method of claim 5, wherein the entropy analysis comprises determining a probability density function (PDF) of motion artifact variation.

7. The method of claim 1, wherein the ECG signal is segmented using a QRS wave detection algorithm.

8. The method of claim 1, wherein the regression analysis comprises a linear regression analysis using a least squares method.

9. The method of claim 1, wherein the ECG signal and the motion signal are received from a single monitoring device and the motion signal comprises an acceleration signal.

10. The method of claim 1, wherein the method is performed in real time while the patient is wearing an ECG monitoring device to assist in positioning of the ECG monitoring device on the patient.

11. The method of claim1, further comprising excluding from post ECG analysis portions of the ECG signal corresponding to the segmented ECG data that is contaminated with defined motion artifacts.

12. The method of claim 1, wherein the method is performed to validate an ECG monitoring device that acquires the ECG signal.

13. A system for defining motion artifacts in an electrocardiogram (ECG) signal, the system comprising:

a processor; and

a memory operatively coupled to the processor, wherein the memory comprises:

computer readable program code components for processing the ECG signal and a corresponding motion signal obtained from a patient;

computer readable program code components for segmenting the ECG signal to provide segmented ECG data;

computer readable program code components for segmenting the motion signal to provide segmented motion data that corresponds to the segmented ECG data;

computer readable program code components for quantifying the segmented ECG data and the segmented motion data to define, respectively, noise level data and motion intensity data;

computer readable program code components for performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

computer readable program code components for quantifying the motion artifacts based on the regression model.

14. The system of claim 14, wherein quantifying the segmented ECG data and the segmented motion data comprises performing a root mean square (RMS) analysis.

15. The system of claim 14 wherein deviations of the noise level data and motion intensity data from the regression model define whether the noise level data is unrelated to the motion signal or is part of the ECG signal.

16. The system of claim 15, wherein analyzing the deviations of the noise level data and motion intensity data from the regression model comprises performing an entropy analysis of the noise level data and the motion intensity data.

17. The system of claim 14, wherein defining the motion artifacts based on deviations from the regression line comprises performing an entropy analysis of the noise level data and the motion intensity data.

18. The system of claim 17, wherein the entropy analysis comprises determining a probability density function (PDF) of motion artifact variation.

19. The system of claim 13, wherein the ECG signal is segmented using a QRS wave detection algorithm.

20. The system of claim 13, wherein the regression analysis comprises a linear regression analysis using a least squares method.

21. The system of claim 13, wherein the ECG signal and the motion signal are received from a single monitoring device operatively coupled to the processor, and the motion signal comprises an acceleration signal.

22. The system of claim 13, wherein the system operates in real time while the patient is wearing an ECG monitoring device to assist in positioning of the ECG monitoring device on the patient.

23. The system of claim 13, further comprising computer readable program code components for excluding from post ECG analysis portions of the ECG signal corresponding to the segmented ECG data that is contaminated with defined motion artifacts.

24. The system of claim 13, wherein the system operates to validate an ECG monitoring device that acquires the ECG signal.

25. A method for defining motion artifacts in a corrupted signal, the method comprising:

receiving the corrupted signal and a corresponding motion signal;

segmenting the corrupted signal to provide segmented corrupted data;

segmenting the motion signal to provide segmented motion data that corresponds to the segmented corrupted data;

quantifying the segmented corrupted data and the segmented motion data to define, respectively, noise level data and motion intensity data;

performing a regression analysis on the noise level data and the motion intensity data to define a regression model; and

quantifying the motion artifacts based on the regression model.

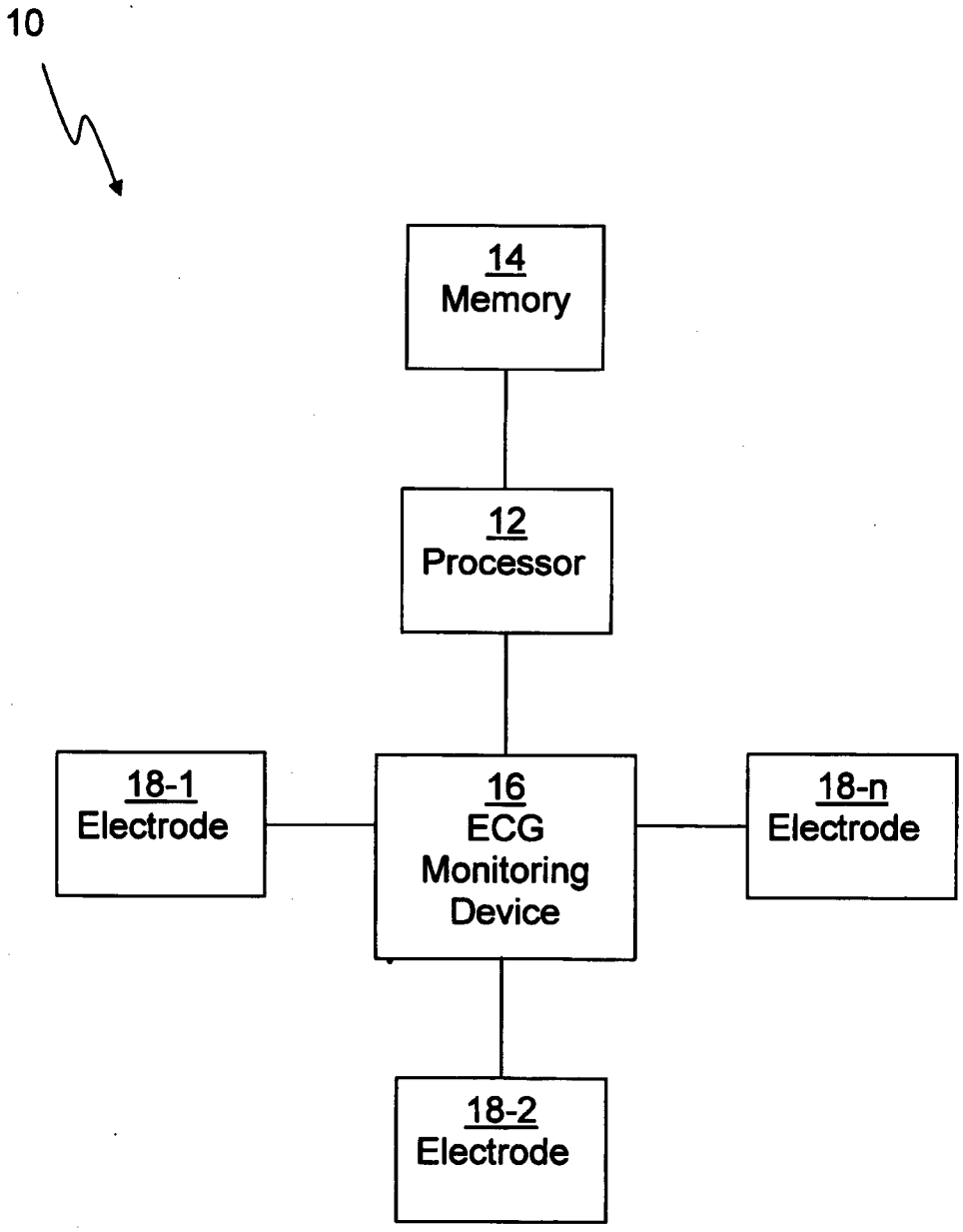

10
14
Memory
12
Processor
18-1
Electrode
16
ECG
Monitoring
Device
18-n
Electrode
18-2
Electrode

FIG 1

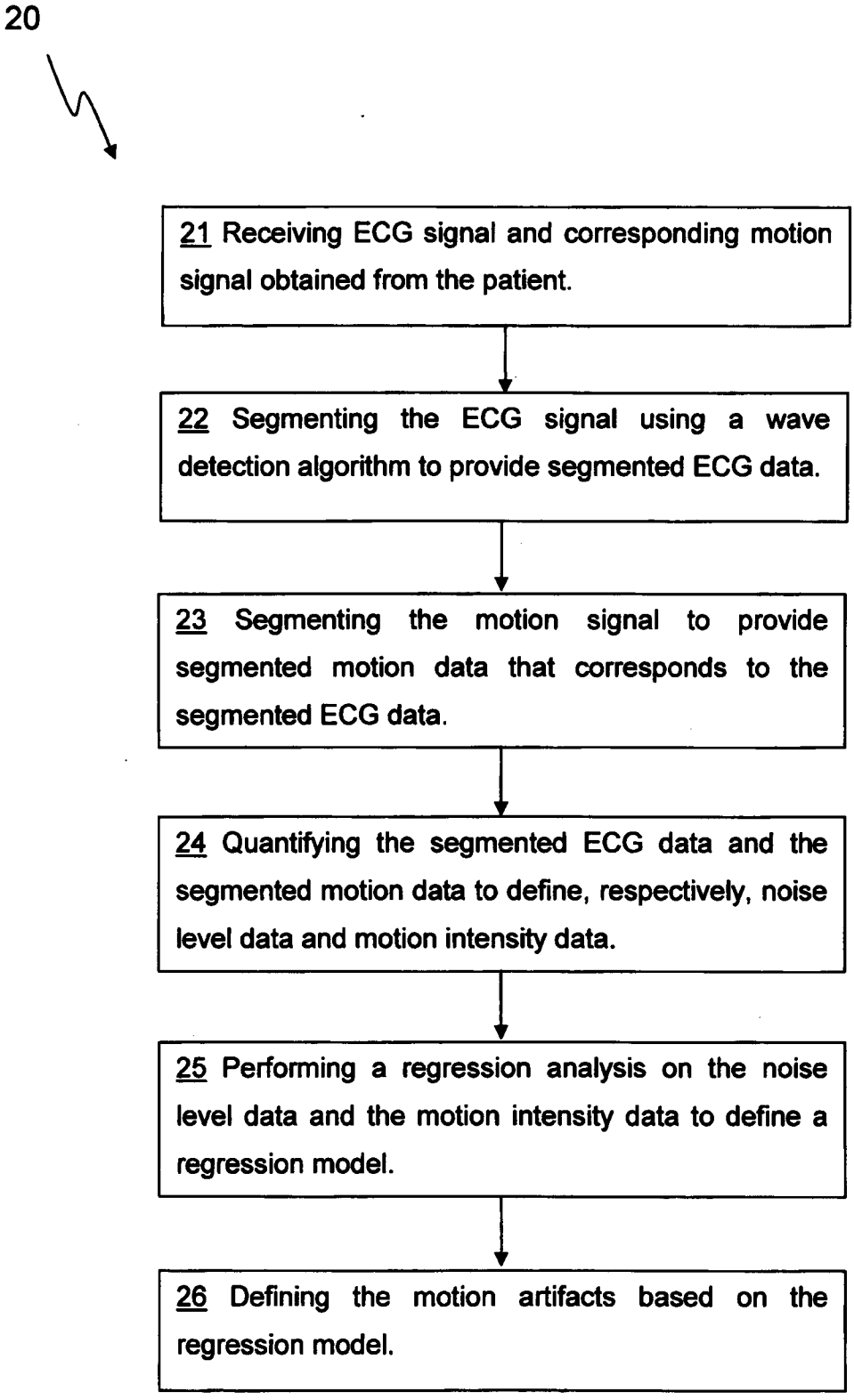

20
21 Receiving ECG signal and corresponding motion signal obtained from the patient.
22 Segmenting the ECG signal using a wave detection algorithm to provide segmented ECG data.
23 Segmenting the motion signal to provide segmented motion data that corresponds to the segmented ECG data.
24 Quantifying the segmented ECG data and the segmented motion data to define, respectively, noise level data and motion intensity data.
25 Performing a regression analysis on the noise level data and the motion intensity data to define a regression model.
26 Defining the motion artifacts based on the regression model.

FIG 2

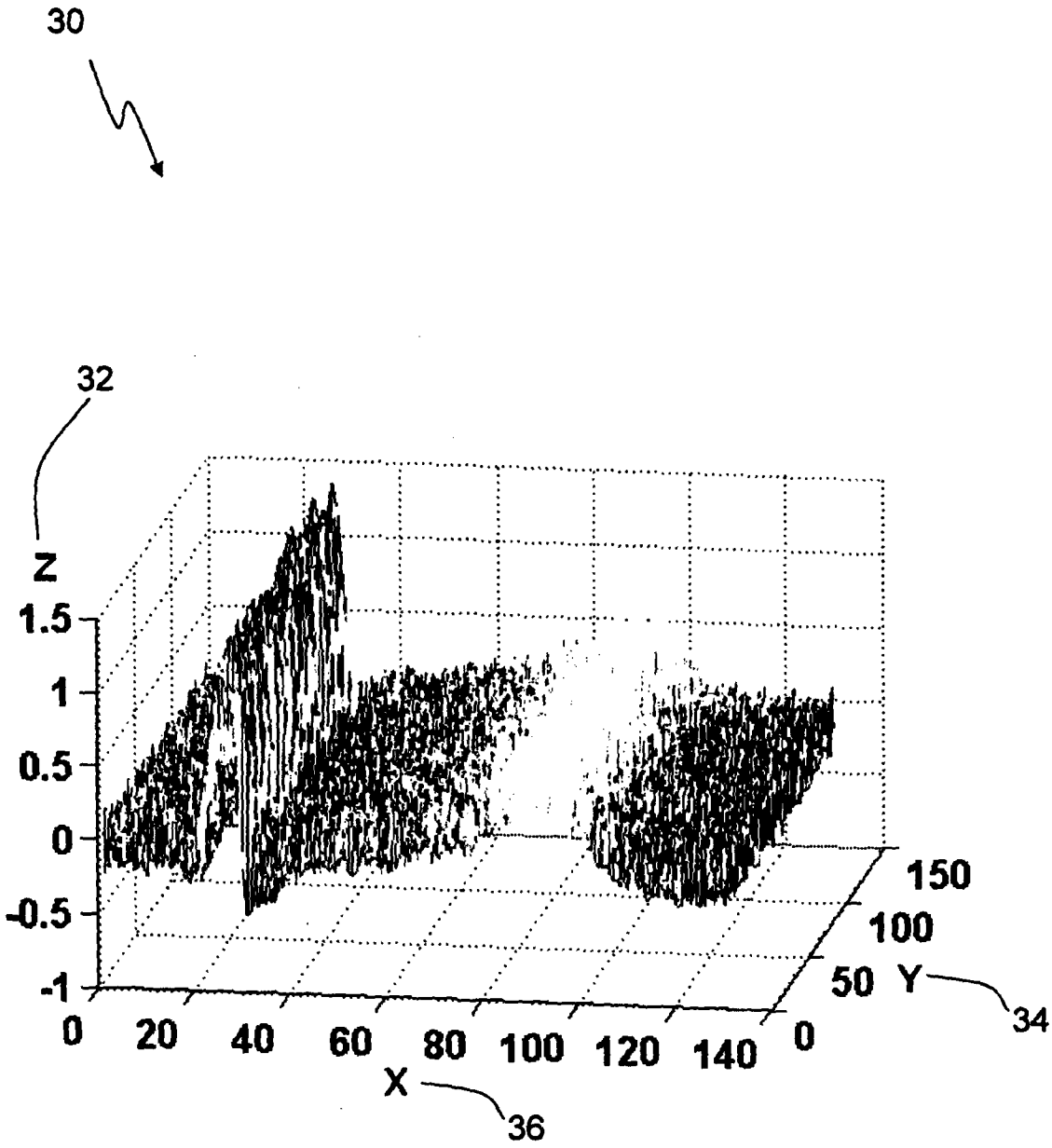



FIG 3

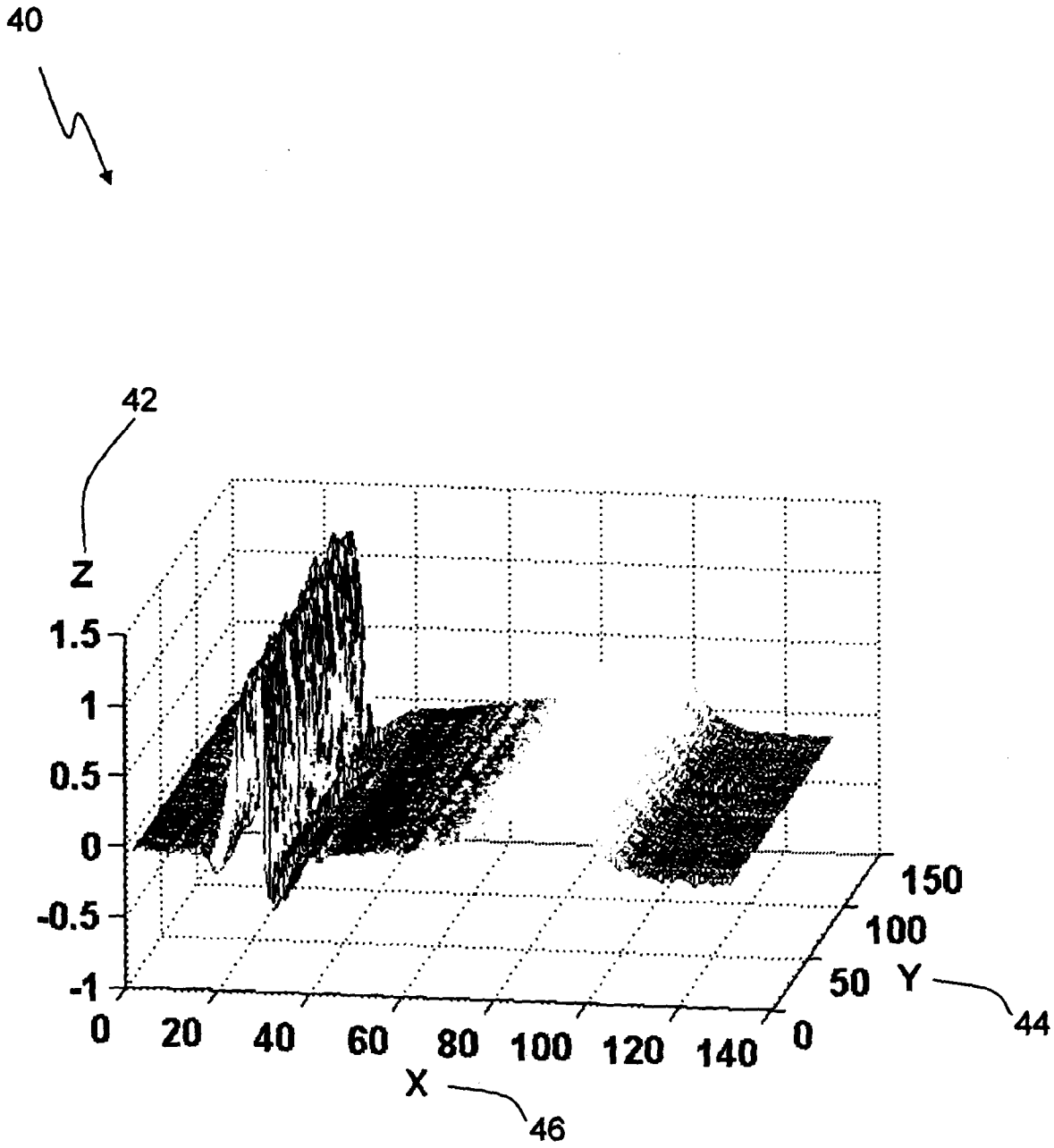



FIG 4

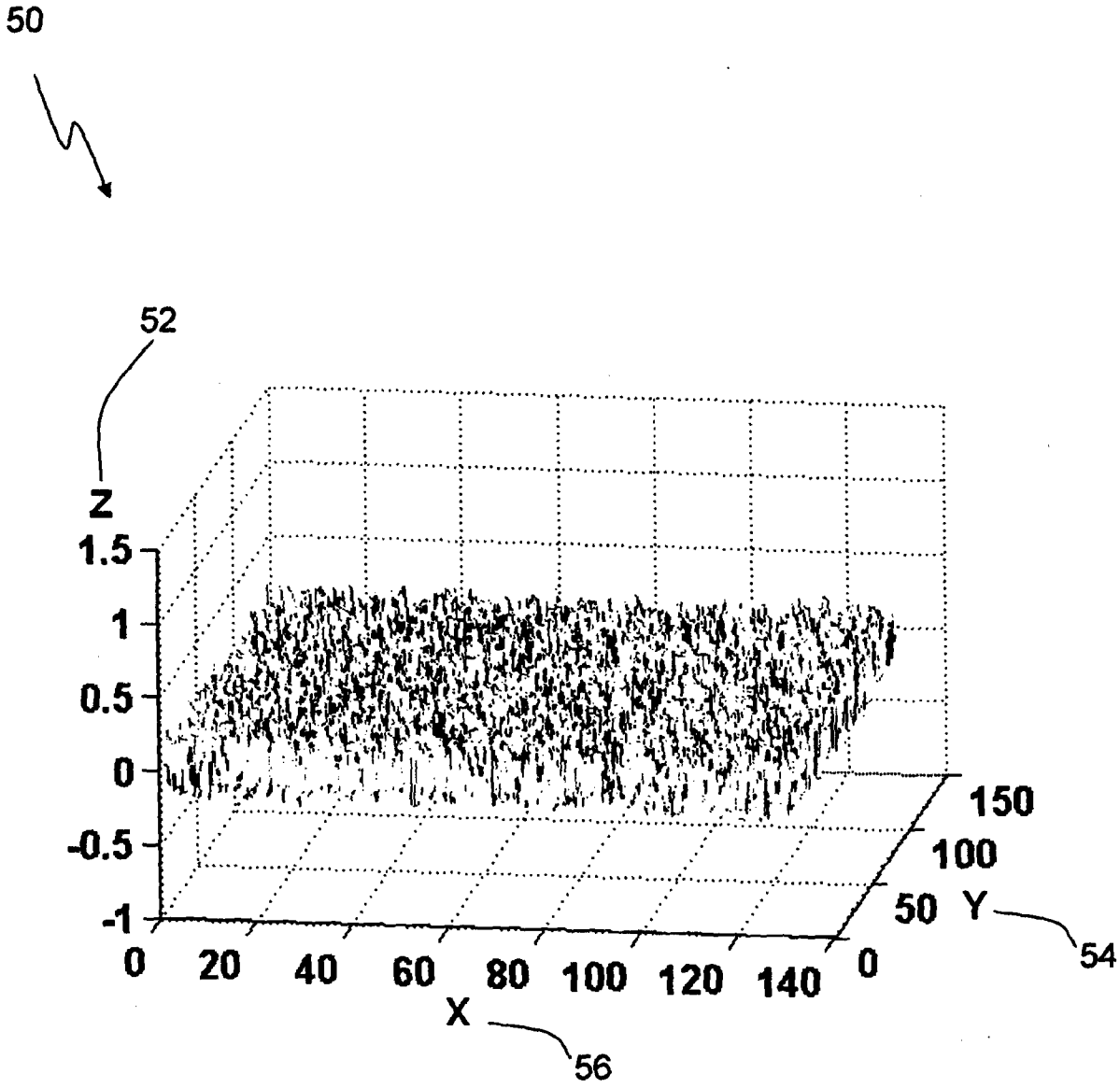



FIG 5

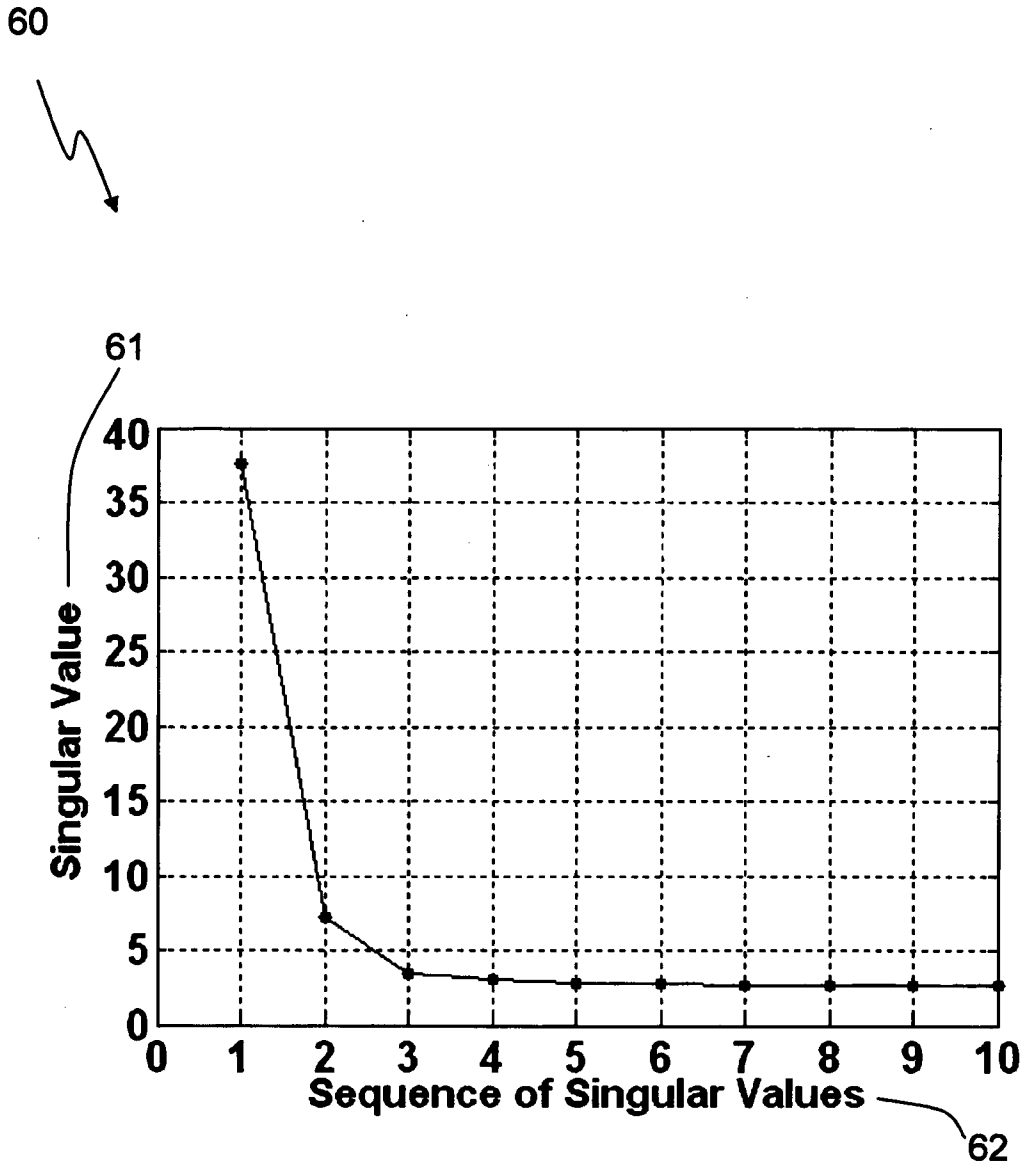

60
61
Singular Value
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10
Sequence of Singular Values
62

FIG 6

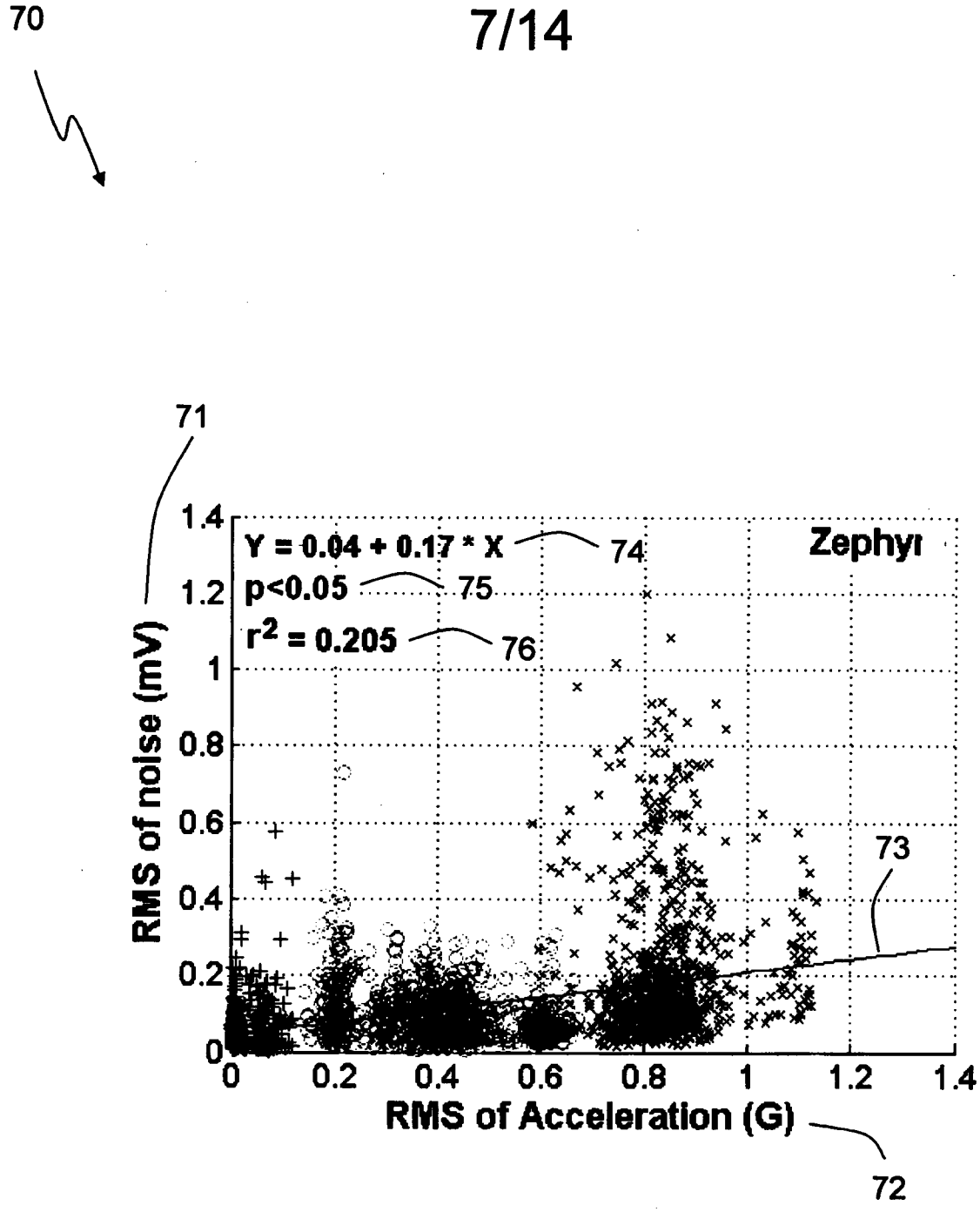

70
71
Y = 0.04 + 0.17 * X
74
Zephyr
p<0.05
75
r2 = 0.205
76
RMS of noise (mV)
RMS of Acceleration (G)
73
72
0
0.2
0.4
0.6
0.8
1
1.2
1.4

FIG 7

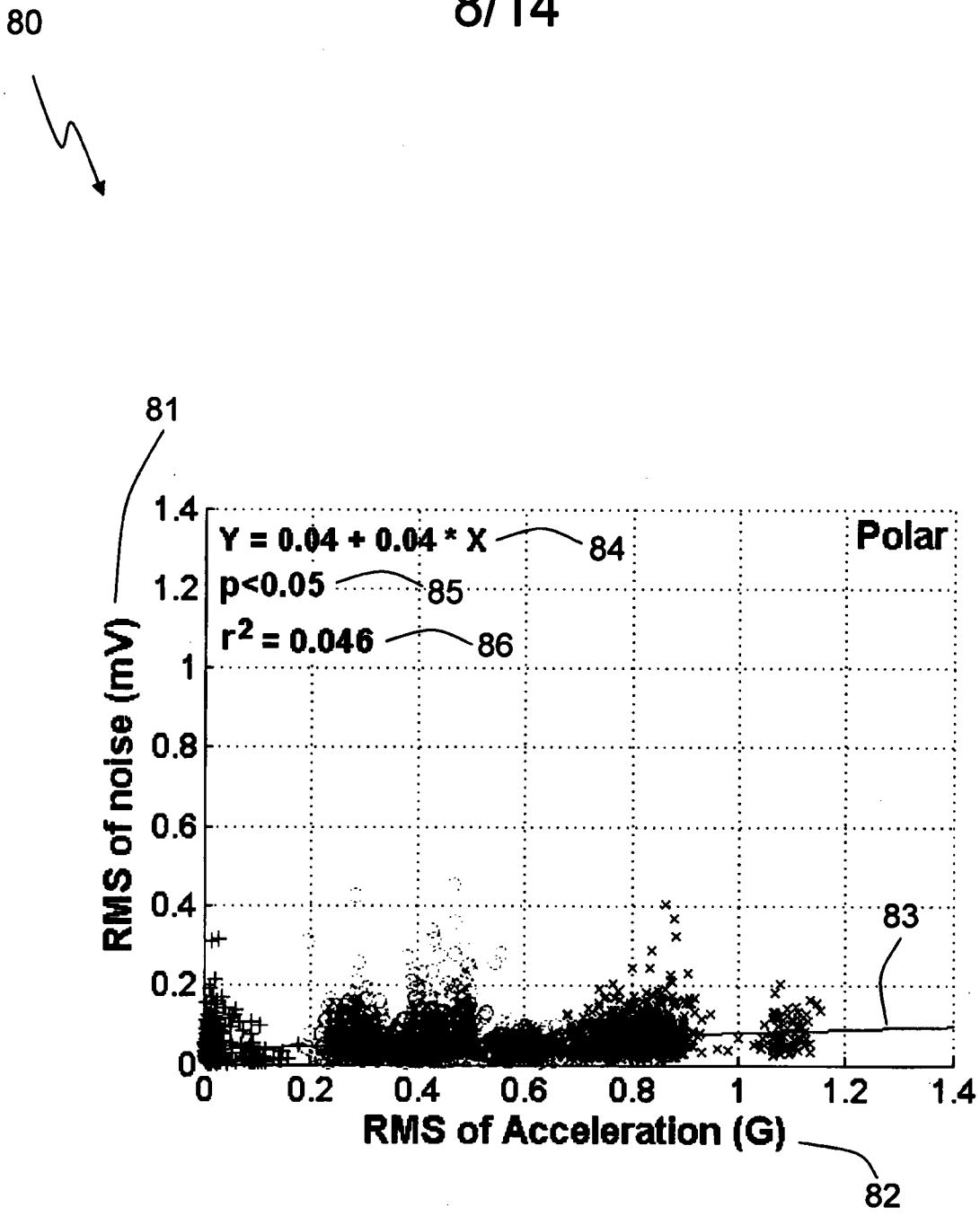

80
81
Y = 0.04 + 0.04 * X
84
Polar
p<0.05
85
r² = 0.046
86
RMS of noise (mV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
83
0
0.2
0.4
0.6
0.8
1
1.2
1.4
RMS of Acceleration (G)
82

FIG 8

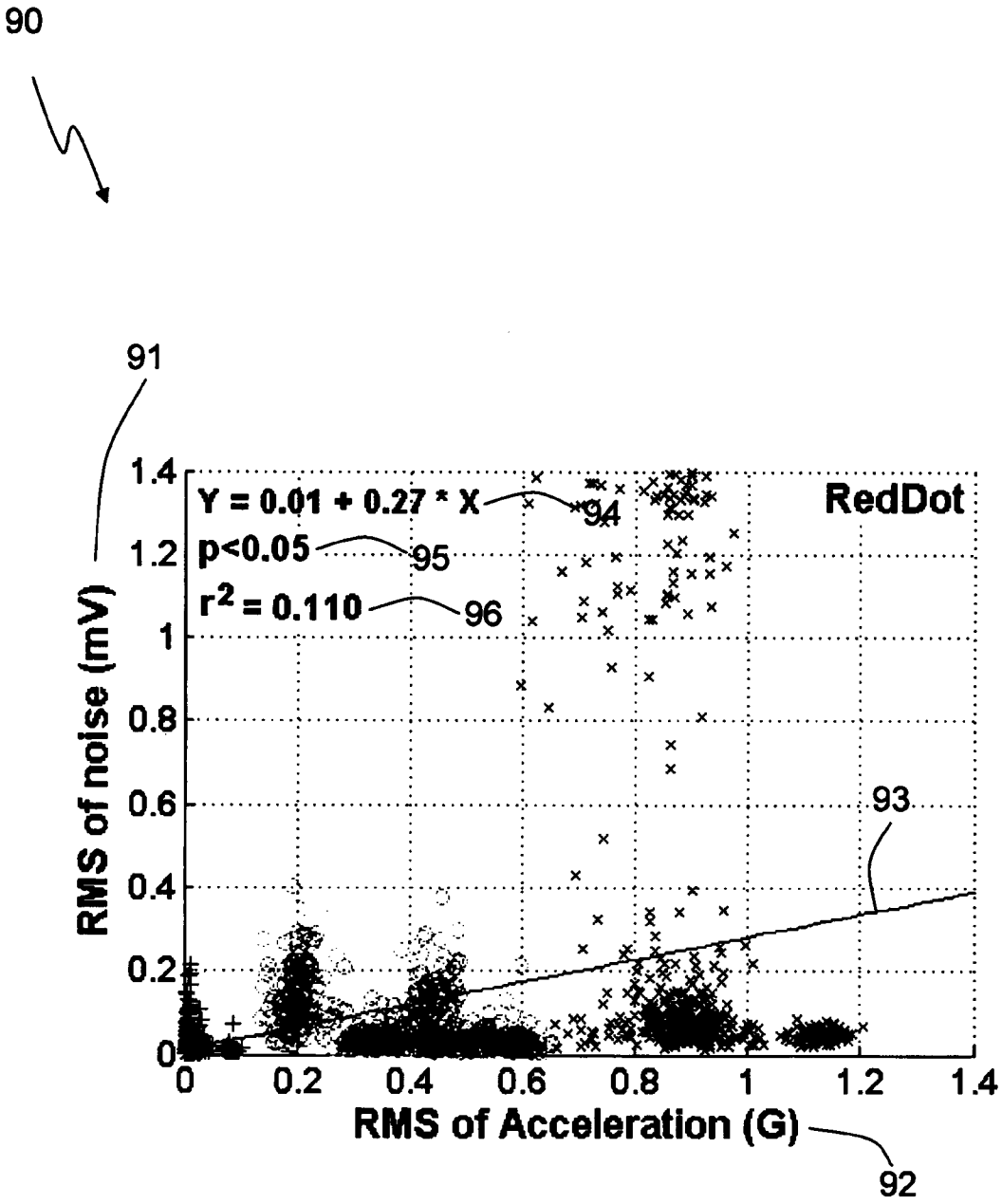

90
91
Y = 0.01 + 0.27 * X
94
RedDot
p<0.05
95
r2 = 0.110
96
93
RMS of noise (mV)
RMS of Acceleration (G)
92
0
0.2
0.4
0.6
0.8
1
1.2
1.4

FIG 9

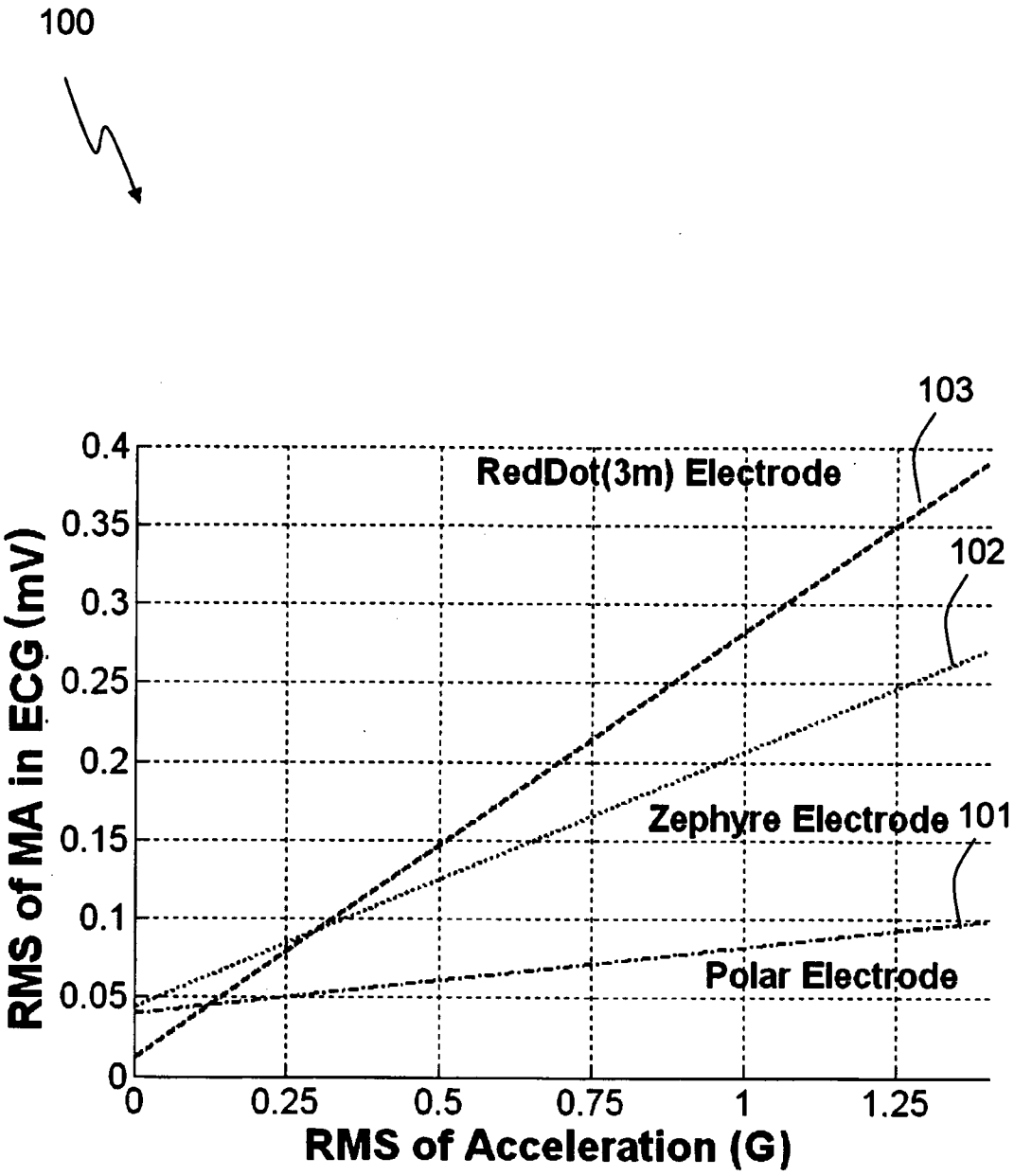

100
103
RedDot(3m) Electrode
102
Zephyre Electrode
101
Polar Electrode
RMS of MA in ECG (mV)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.25
0.5
0.75
1
1.25
RMS of Acceleration (G)

FIG 10

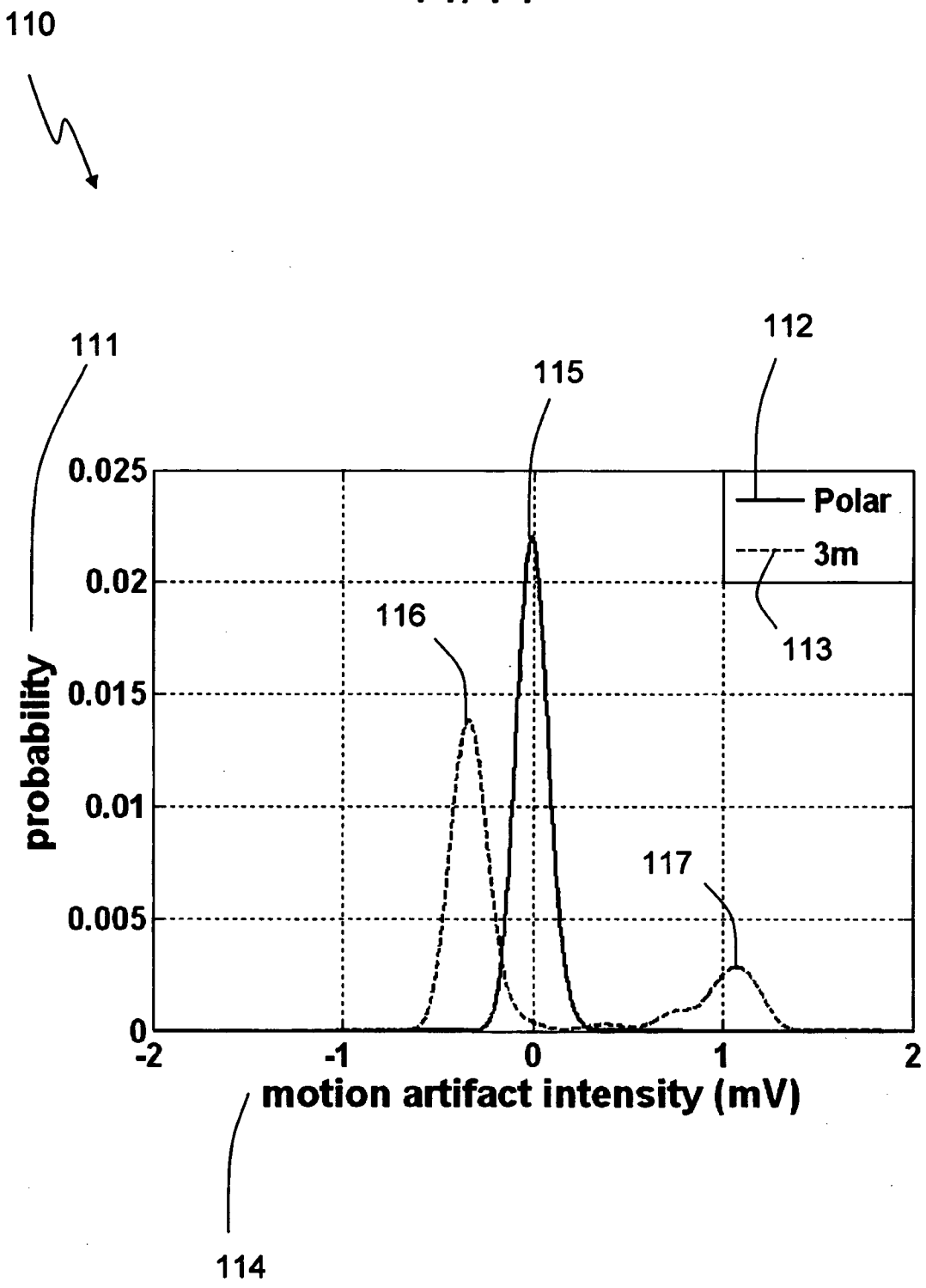

110
111
112
115
Polar
3m
113
116
117
probability
0.025
0.02
0.015
0.01
0.005
0
-2
-1
0
1
2
motion artifact intensity (mV)
114

FIG 11

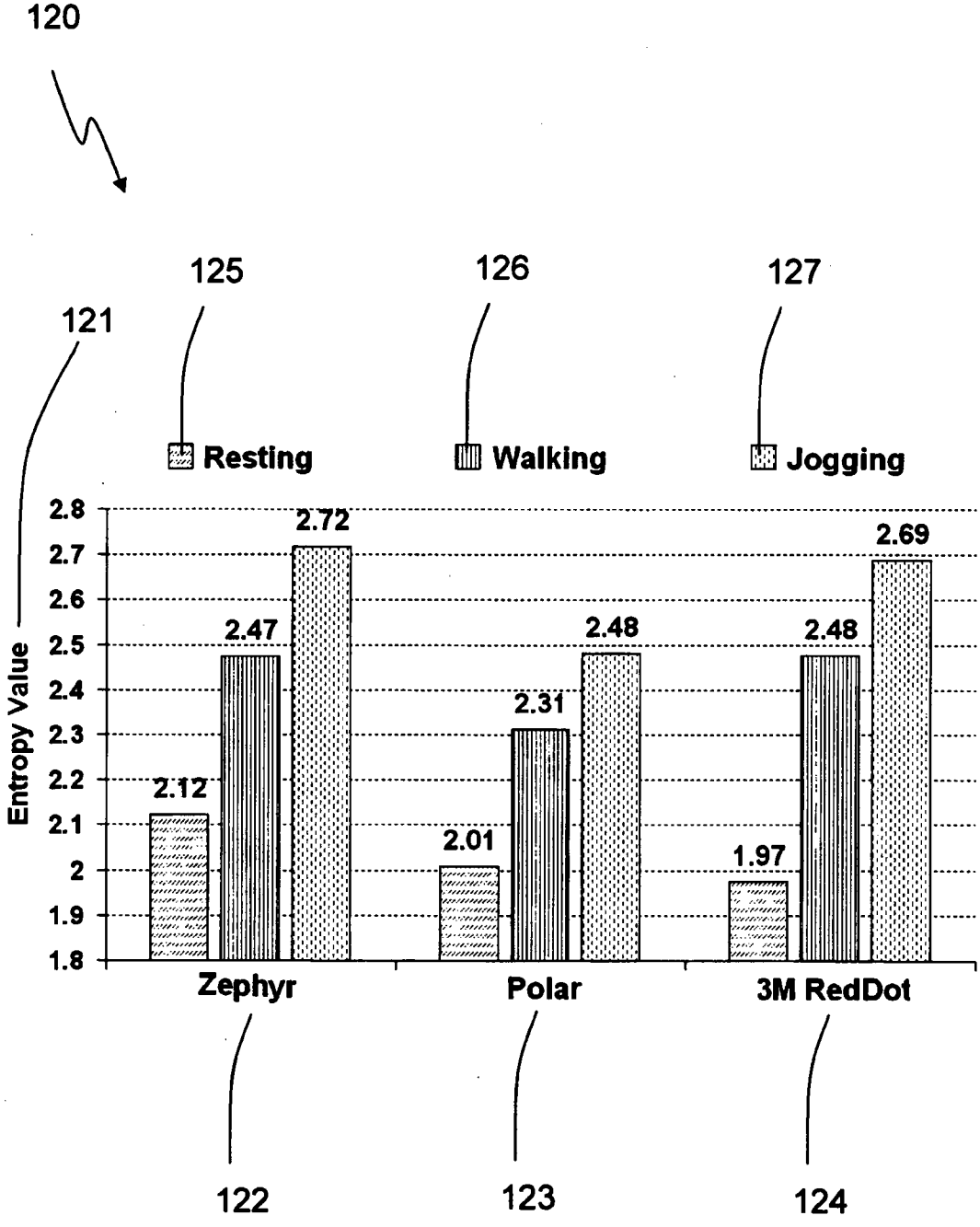

120
125
126
127
121
Resting
Walking
Jogging
Entropy Value
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
2.12
2.47
2.72
2.01
2.31
2.48
1.97
2.48
2.69
Zephyr
Polar
3M RedDot
122
123
124

FIG 12

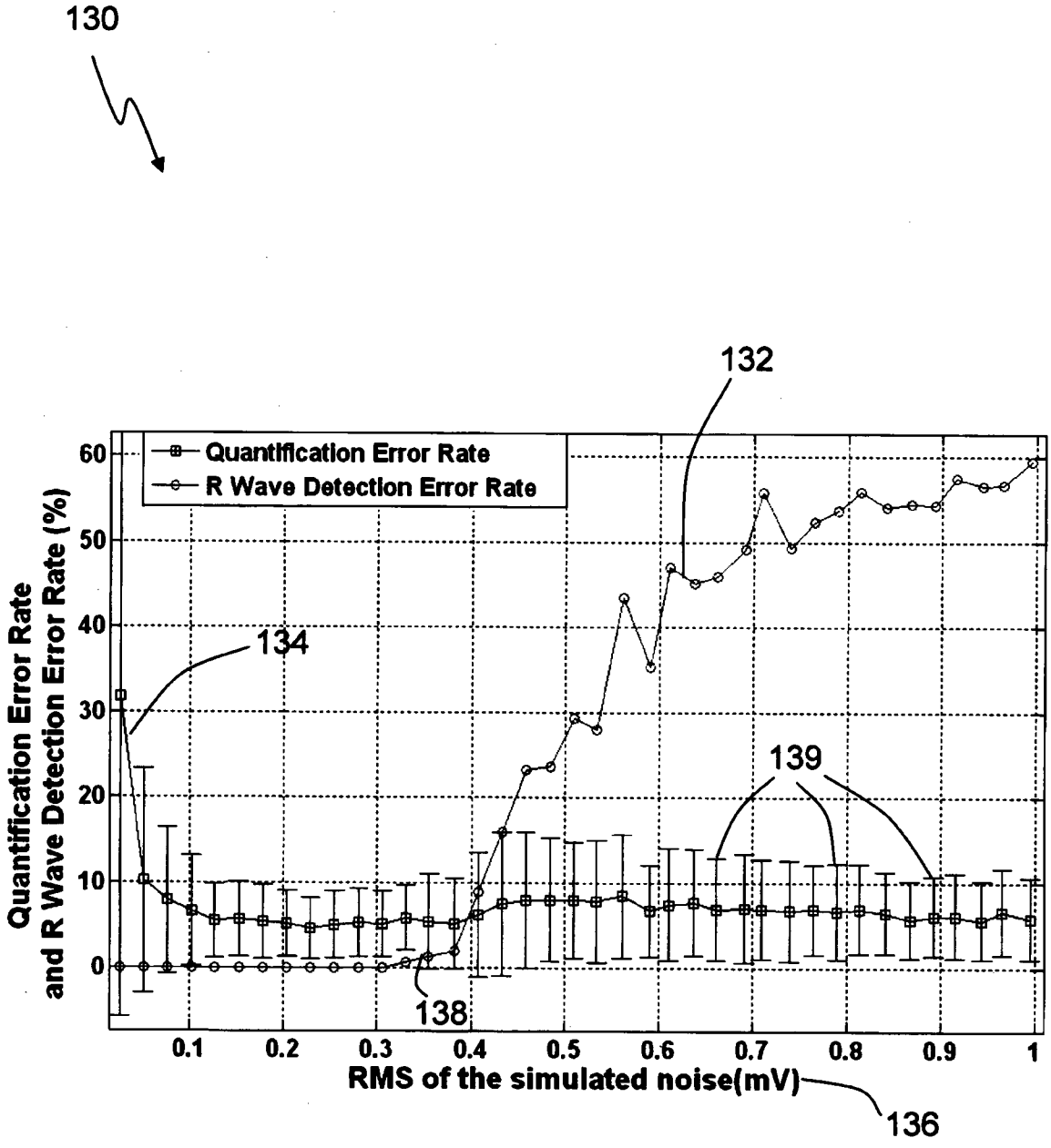

130
132
Quantification Error Rate
R Wave Detection Error Rate
Quantification Error Rate and R Wave Detection Error Rate (%)
134
139
138
RMS of the simulated noise(mV)
136
0
10
20
30
40
50
60
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

FIG 13

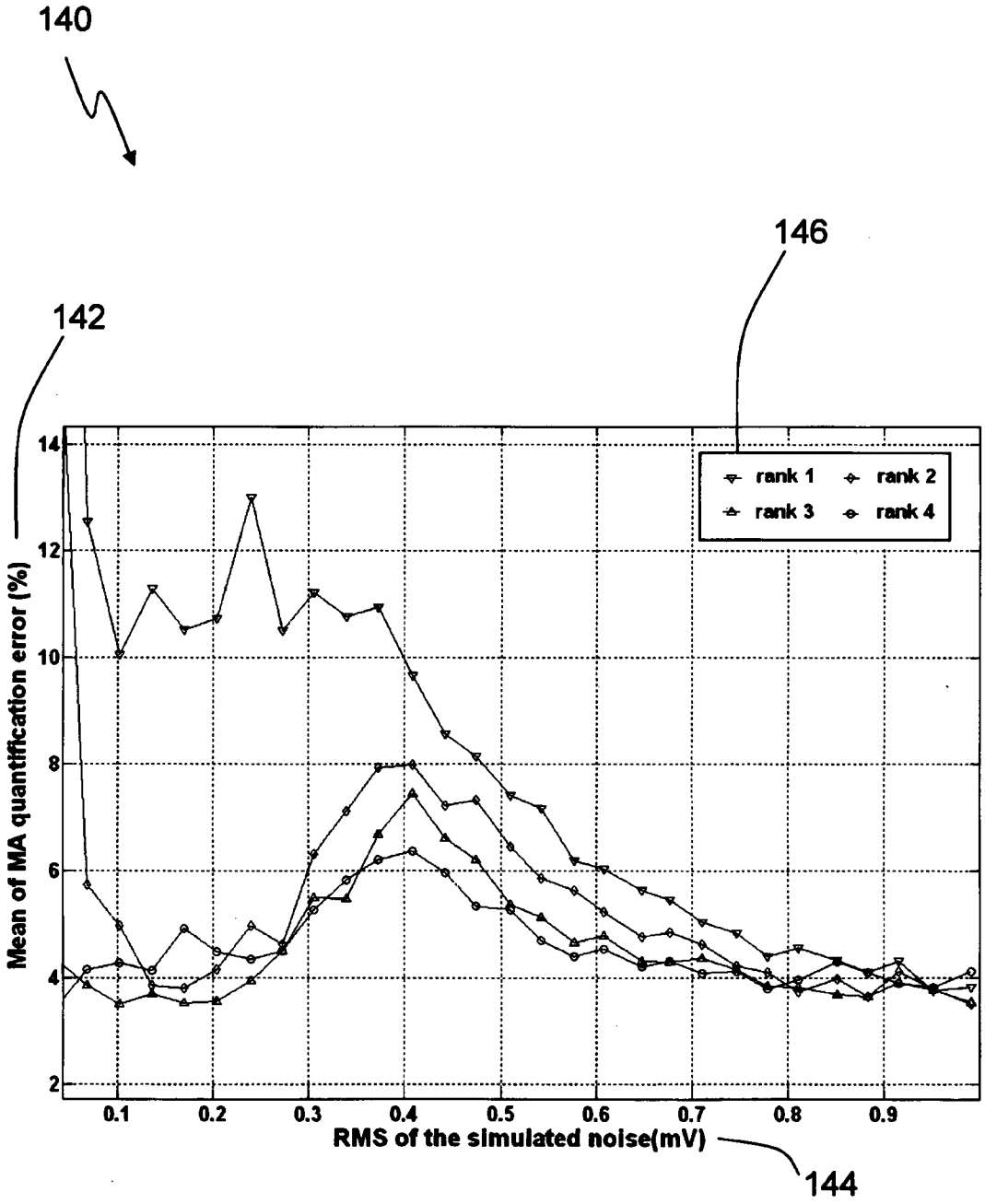

140
146
142
rank 1
rank 2
rank 3
rank 4
Mean of MA quantification error (%)
14
12
10
8
6
4
2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
RMS of the simulated noise(mV)
144

FIG 14

**INTERNATIONAL SEARCH REPORT**

International application No.
**PCT**/AU2012/000087

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

***A61B 5/025*** (2006.01) ***A61B 5/11*** (2006.01) **A61B 5/0468** (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPODOC, WPI; electrocardiogram, artefact, regression, motion, waveform (and like terms in various combinations)
Google Patents; +regression, analysis, electrocardiogram, motion, segment+, accelerometer, noise, window, model (in various combinations)
Pubmed/Google Scholar; regression, independent component analysis, electrocardiogram, model, artefact (in various combinations)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | US 5,704,365 A (ALBRECHT et al.) 6 January 1998<br>See Abstract, Figure 5, column 4 line 59-column 18 line 7 | |
| A | Rheinberger et al. "Removal of CPR Artifacts from the Ventricular Fibrillation ECG by Adaptive Regression on Lagged Reference Signals" *IEEE Transactions on Biomedical Engineering* (2008) 55(1):130-136<br>See whole document | |

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 23 April 2012 | 26 April 2012 |
| Name and mailing address of the ISA/AU<br>AUSTRALIAN PATENT OFFICE<br>PO BOX 200, WODEN ACT 2606, AUSTRALIA<br>E-mail address: pct@ipaustralia.gov.au<br>Facsimile No. +61 2 6283 7999 | Authorized officer<br>**EMMA FRANCIS**<br>AUSTRALIAN PATENT OFFICE<br>(ISO 9001 Quality Certified Service)<br>Telephone No : +61 3 9935 9631 |

**INTERNATIONAL SEARCH REPORT**

International application No.
PCT/AU2012/000087

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | Milanesi et al. "Independent Component Analysis Applied to the Removal of Motion Artefacts from Electrocardiographic Signals" *Med Biol Eng Compt* (2008) 46:251-261<br>See whole document | |
| A | WO 2010/135516 A2 (SOTERA WIRELESS, INC.) 25 November 2010<br>See whole document | |
| A | Chawla et al. "Artifacts and Noise Removal in Electrocardiograms using Independent Component Analysis" *Int J Cardiol* (2008) 129:278-281<br>See whole document | |

**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.
**PCT/AU2012/000087**

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

| Patent Document Cited in Search Report | | Patent Family Member | | | | | |
|---|---|---|---|---|---|---|---|
| US | 5704365 | EP | 0746229 | EP | 0957760 | JP | H09508293 |
| | | US | 5570696 | US | 5713367 | US | 5724984 |
| | | US | 5791944 | US | 5935082 | WO | 9520351 |
| | | WO | 9614796 | WO | 9749143 | | |
| WO | 2010135516 | EP | 2432378 | SG | 176189 | US | 2010298650 |
| | | US | 2010298651 | US | 2010298652 | US | 2010298653 |
| | | US | 2010298654 | US | 2010298655 | | |

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX