(12) **United States Patent**　　(10) **Patent No.:**　　**US 7,343,187 B2**

Stetson　　(45) **Date of Patent:**　　*Mar. 11, 2008

(54) **BLIND SOURCE SEPARATION OF PULSE OXIMETRY SIGNALS**

(75) Inventor: **Paul F. Stetson**, Oakland, CA (US)

(73) Assignee: **Nellcor Puritan Bennett LLC**, North Haven, CT (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 215 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **11/318,796**

(22) Filed: **Dec. 27, 2005**

(65) **Prior Publication Data**

US 2006/0111623 A1　　May 25, 2006

Related U.S. Application Data

(63) Continuation of application No. 10/674,709, filed on Sep. 29, 2003, now Pat. No. 7,079,880, which is a continuation of application No. 10/033,703, filed on Nov. 2, 2001, now Pat. No. 6,701,170.

(51) **Int. Cl.**
A61B 5/00　　(2006.01)
(52) **U.S. Cl.** **600/336**; 600/324; 600/502
(58) **Field of Classification Search** 600/300, 600/309, 310, 322, 323, 324, 326, 481, 500, 600/501; 500/502
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,911,167 A　　3/1990　Corenman et al.

5,111,817 A　　5/1992　Clark et al.
5,315,532 A　　5/1994　Comon

(Continued)

FOREIGN PATENT DOCUMENTS

WO　　WO 00/42911 A1　　7/2000

OTHER PUBLICATIONS

Amari et al., "A New Learning Algorithm for Blind Signal Separation," *Advances in Neural Infromation Processing Systems 8*, pp. 757-763 (1996).

(Continued)

Primary Examiner—Eric F. Winakur
(74) *Attorney, Agent, or Firm*—Fletcher Yoder PC

(57)　　**ABSTRACT**

A method and apparatus for the application of Blind Source Separation (BSS), specifically independent Component Analysis (ICA) to mixture signals obtained by a pulse oximeter sensor. In pulse oximetry, the signals measured at different wavelengths represent the mixture signals, while the plethysmographic signal, motion artifact, respiratory artifact and instrumental noise represent the source components. The BSS is carried out by a two-step method including an ICA. In the first step, the method uses Principal Component Analysis (PCA) as a preprocessing step, and the Principal Components are then used to derive sat and the Independent Components, where the Independent Components are determined in a second step. In one embodiment, the independent components are obtained by high-order decorrelation of the principal components, achieved by maximizing the sum of the squares of the higher-order cumulants of the plurality of mixture signals.

31 Claims, 6 Drawing Sheets
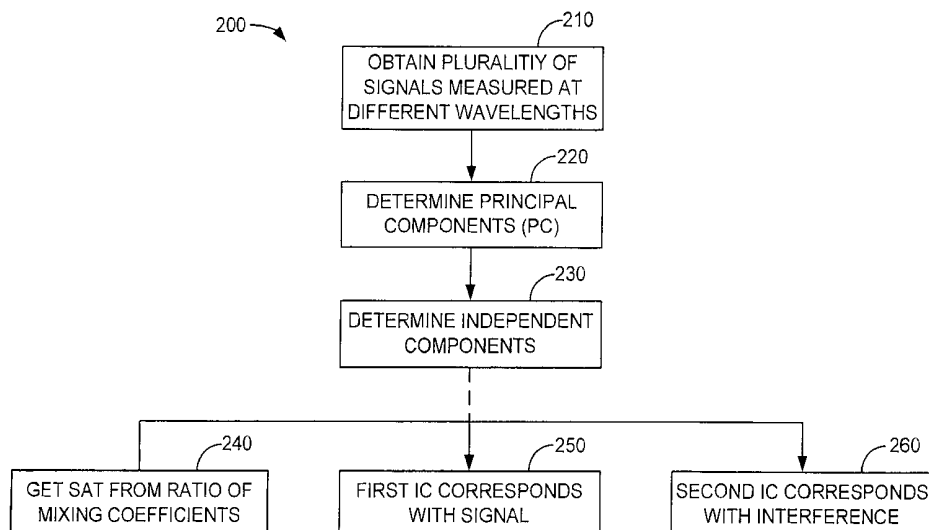
U.S. PATENT DOCUMENTS

5,337,745 A		8/1994	Benaron
5,349,953 A		9/1994	McCarthy et al.
5,398,681 A		3/1995	Kupershmidt
5,494,032 A	*	2/1996	Robinson et al. 600/323
5,553,615 A		9/1996	Carim et al.
5,645,059 A		7/1997	Fein et al.
5,706,402 A		1/1998	Bell
5,853,364 A		12/1998	Baker, Jr. et al.
5,909,646 A		6/1999	Deville
5,928,146 A		7/1999	Itagaki et al.
6,232,609 B1		5/2001	Snyder et al.
6,424,960 B1		7/2002	Lee et al.
6,701,170 B2		3/2004	Stetson
2002/0069242 A1		6/2002	Berns
2002/0085741 A1		7/2002	Shimizu

OTHER PUBLICATIONS

Comon, "Independent Component Analysis, a New Concept?", *Signal Processing*, 36(3):287-314 (1994).

De Lathauwer et al., "ICA Techniques for More Sources than Sensors," *Proceedings of the IEEE Signal Processing Workshop on Higher-Order Statistics*, pp. 121-124 (1999).

Makeig et al., "Independent Component Analysis of Electroencephalographic Data," *Advances in Neural Information Processing Systems 8*, pp. 145-151 (1996).

McKeown et al., "Analysis of fMRI Data by Blind Separation Into Independent Spatial Components," *Human Brain Mapping*, 6:160-188 (1998).
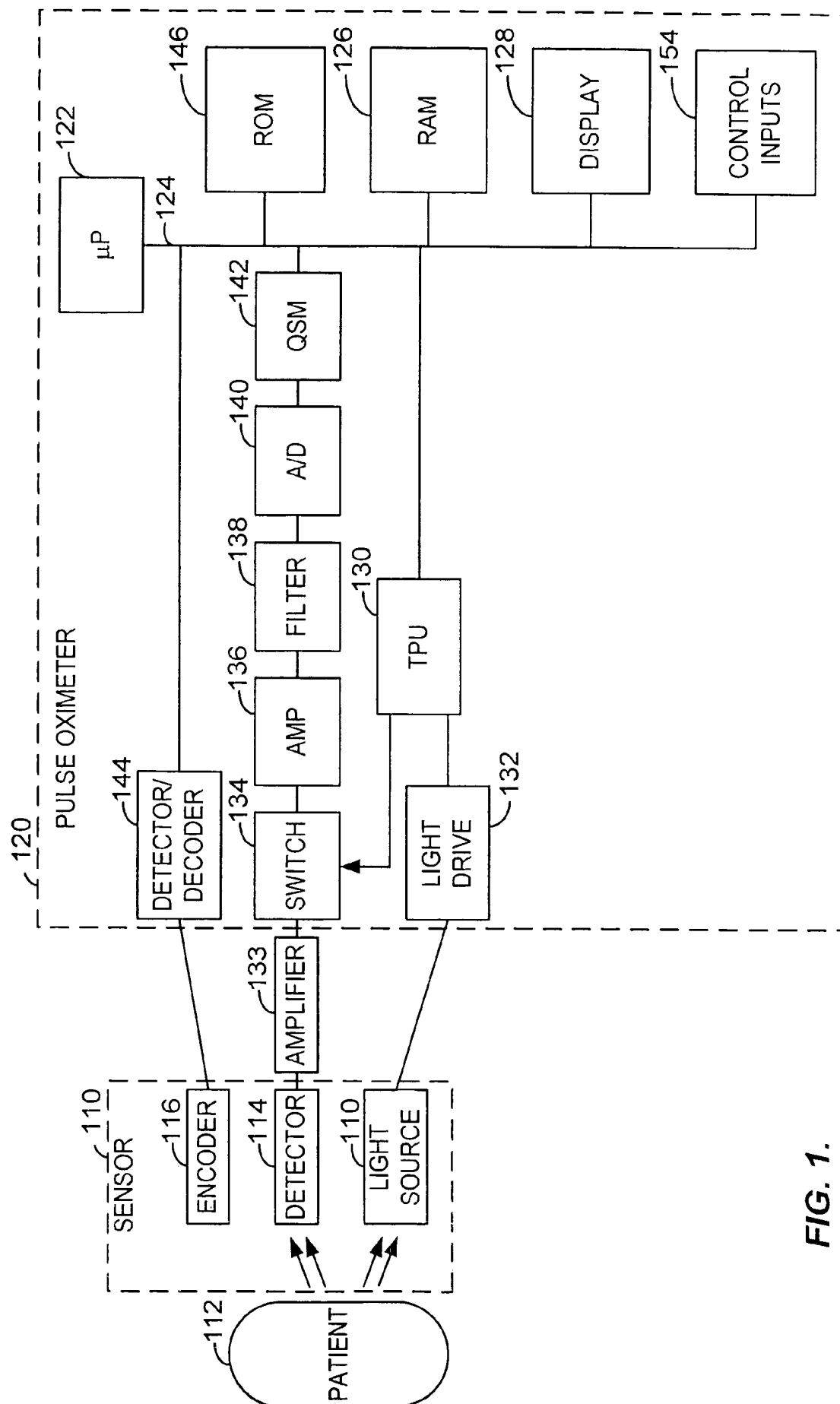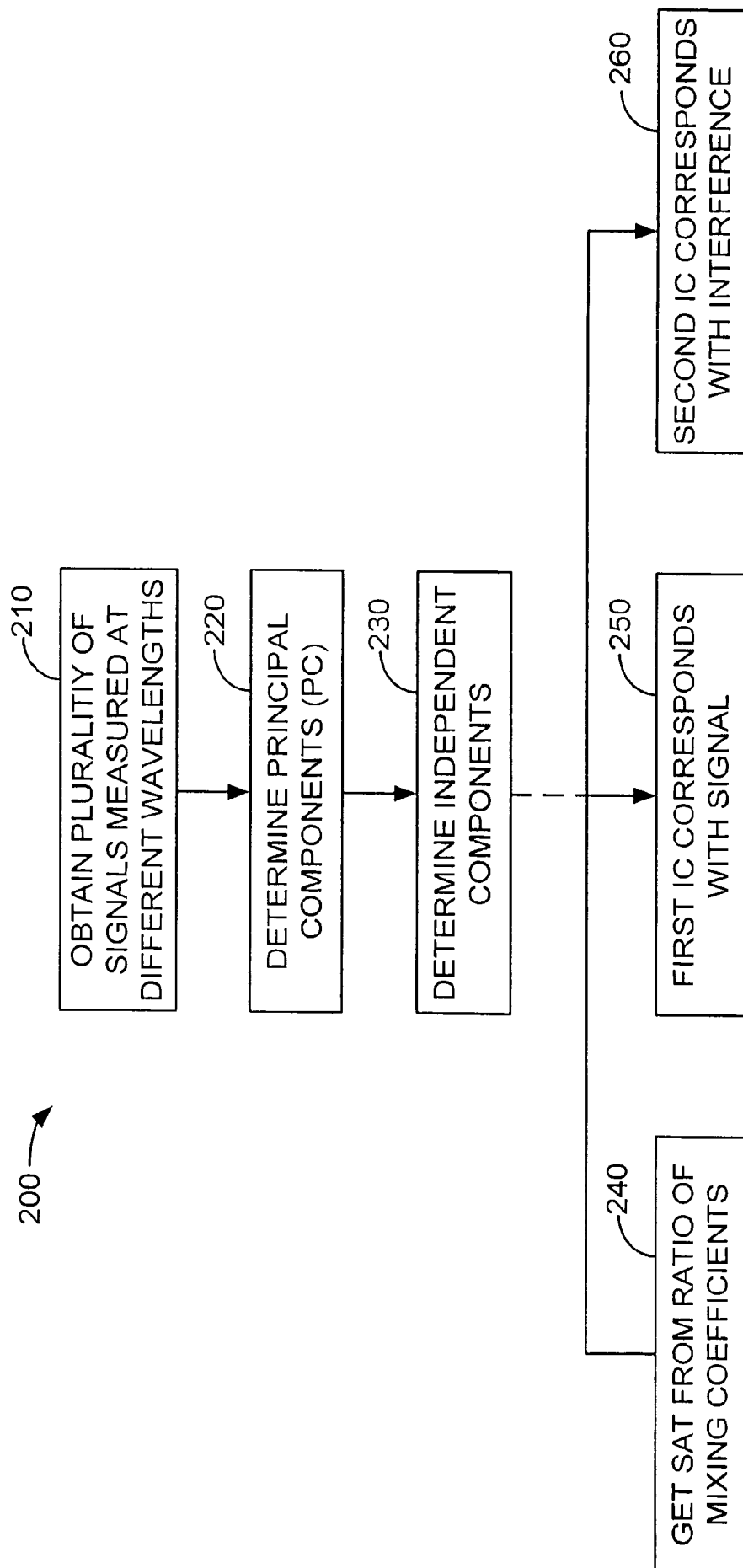
* cited by examiner

FIG. 1.

200

210 — OBTAIN PLURALITY OF SIGNALS MEASURED AT DIFFERENT WAVELENGTHS
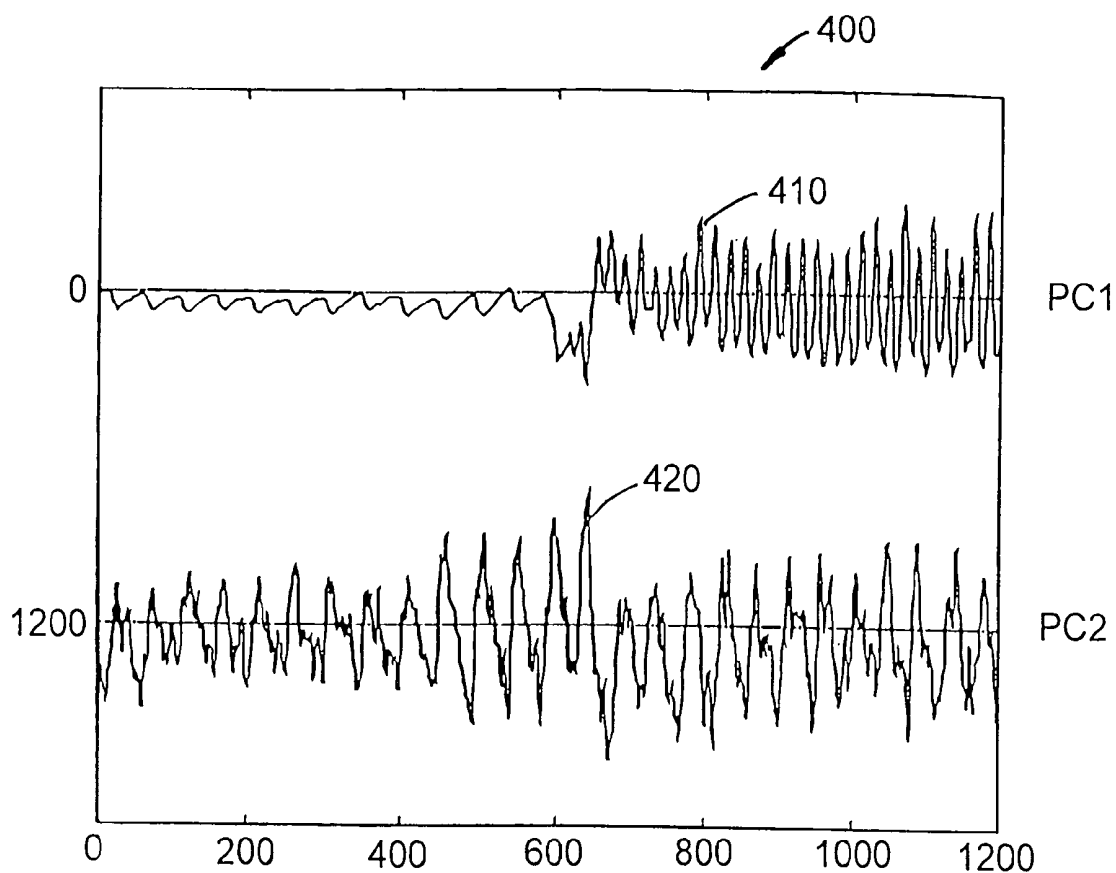
220 — DETERMINE PRINCIPAL COMPONENTS (PC)

230 — DETERMINE INDEPENDENT COMPONENTS

240 — GET SAT FROM RATIO OF MIXING COEFFICIENTS

250 — FIRST IC CORRESPONDS WITH SIGNAL

260 — SECOND IC CORRESPONDS WITH INTERFERENCE

FIG. 2.

FIG. 3.

400

410

0 ——————— PC1

420

1200 ——————— PC2

0   200   400   600   800   1000 1200

FIG. 4.

500

510

0

520

1200

0   200   400   600   800   1000 1200
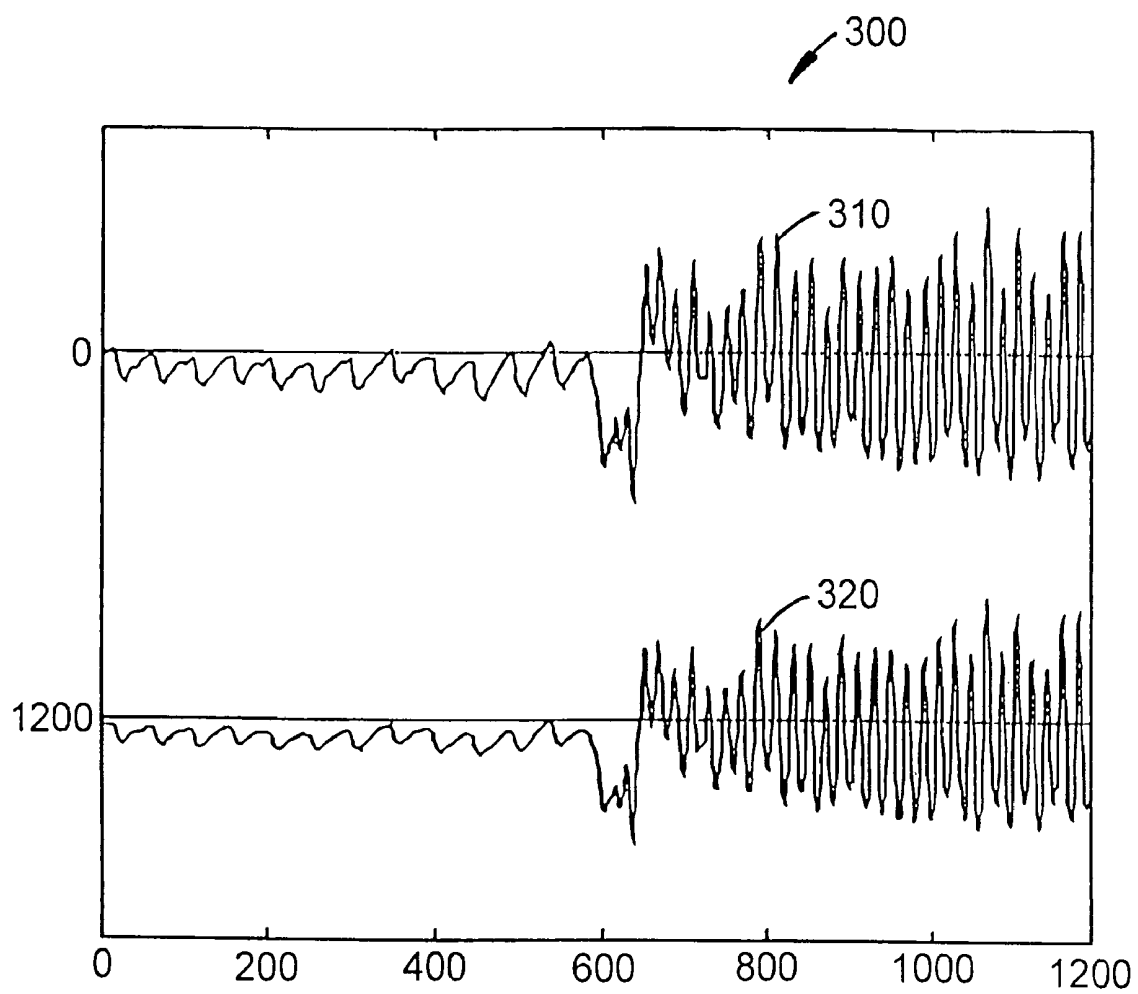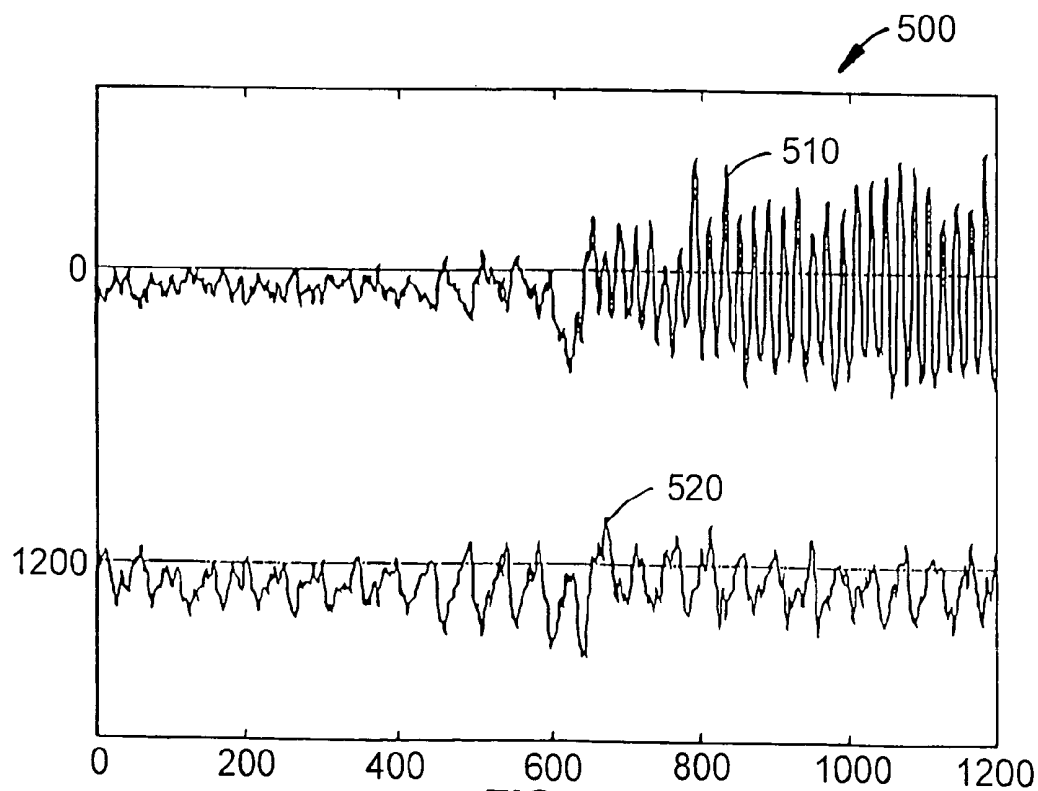
FIG. 5.

FIG. 6

FIG. 7.

FIG. 8

BLIND SOURCE SEPARATION OF PULSE OXIMETRY SIGNALS

CROSS-REFERENCES TO RELATED APPLICATIONS

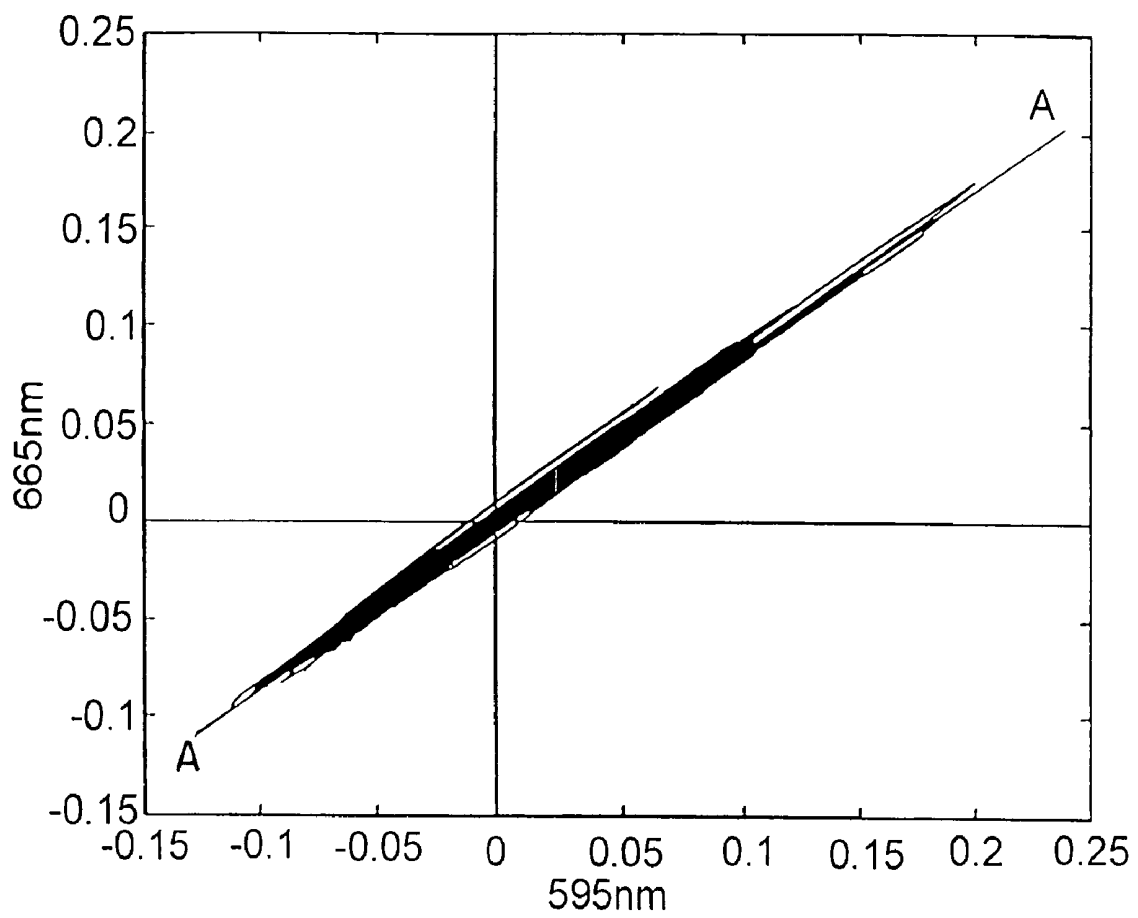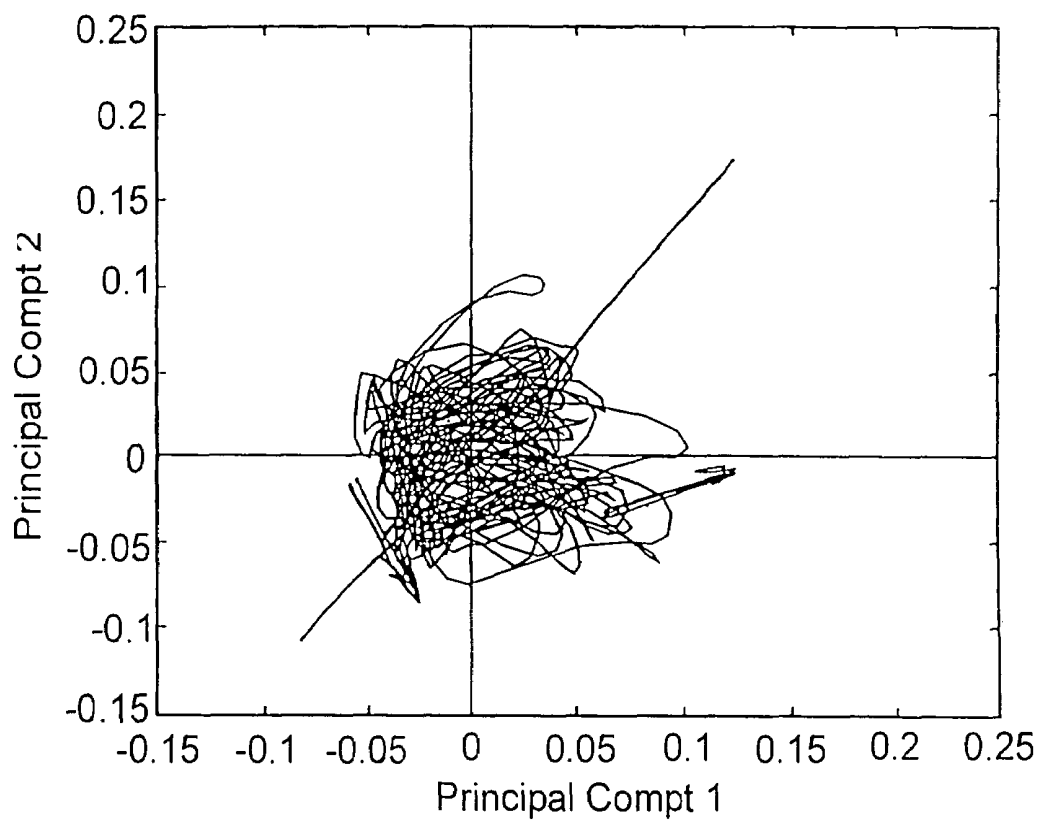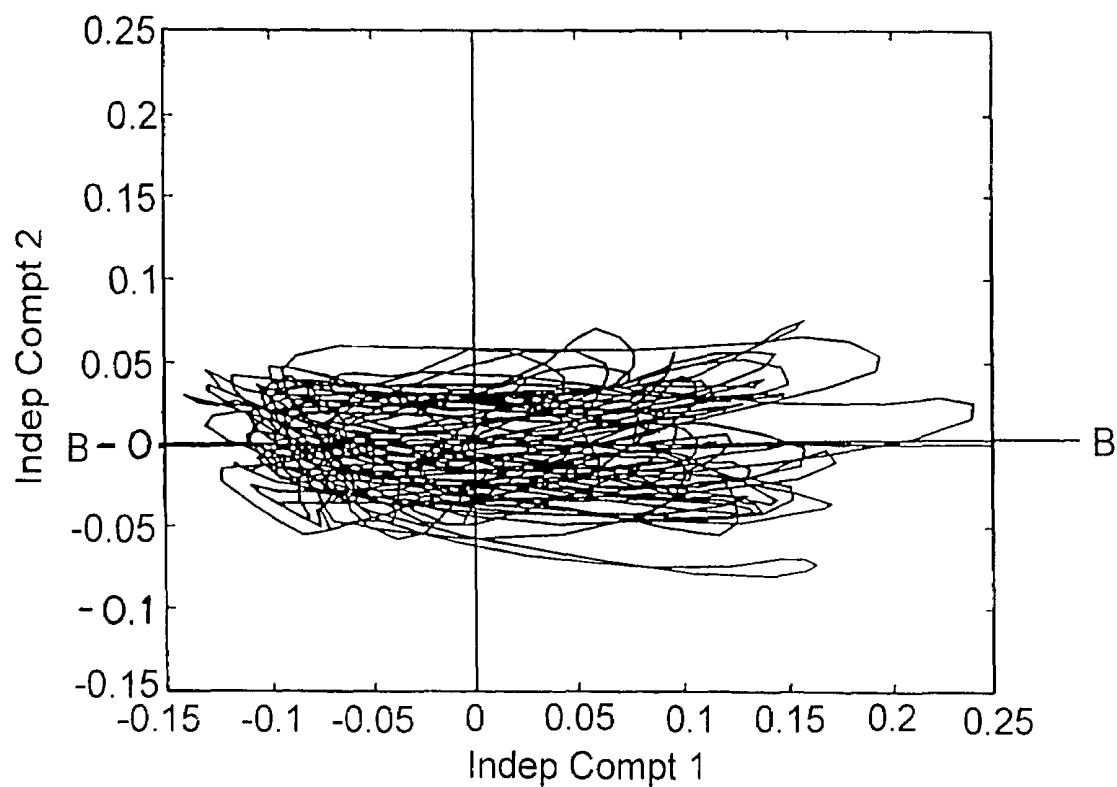This application is a continuation of U.S. patent application Ser. No. 10/674,709 filed on Sep. 29, 2003 now U.S. Pat. No. 7,079,880, which is a continuation of U.S. patent application Ser. No. 10/033,703, filed on Nov. 2, 2001, now U.S. Pat. No. 6,701,170, the full disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention relates to the processing of signals obtained from a medical diagnostic apparatus such as a pulse oximeter using a blind source separation technique to separate the obtained data without prior knowledge of its magnitude or frequency into data corresponding to the desired physiological data and the undesired interference sources.

A typical pulse oximeter measures two physiological parameters, percent oxygen saturation of arterial blood hemoglobin (SpO_2 or sat) and pulse rate. Oxygen saturation can be estimated using various techniques. In one common technique, the photocurrent generated by the photo-detector is conditioned and processed to determine the ratio of modulation ratios (ratio of ratios) of the red to infrared signals. This modulation ratio has been observed to correlate well to arterial oxygen saturation. The pulse oximeters and sensors are empirically calibrated by measuring the modulation ratio over a range of in vivo measured arterial oxygen saturations (SaO_2) on a set of patients, healthy volunteers, or animals. The observed correlation is used in an inverse manner to estimate blood oxygen saturation (SpO_2) based on the measured value of modulation ratios of a patient. The estimation of oxygen saturation using modulation ratios is described in U.S. Pat. No. 5,853,364, entitled "METHOD AND APPARATUS FOR ESTIMATING PHYSIOLOGI-CAL PARAMETERS USING MODEL-BASED ADAP-TIVE FILTERING", issued Dec. 29, 1998, and U.S. Pat. No. 4,911,167, entitled "METHOD AND APPARATUS FOR DETECTING OPTICAL PULSES", issued Mar. 27, 1990. The relationship between oxygen saturation and modulation ratio is further described in U.S. Pat. No. 5,645,059, entitled "MEDICAL SENSOR WITH MODULATED ENCODING SCHEME," issued Jul. 8, 1997. Most pulse oximeters extract the plethysmographic signal having first determined saturation or pulse rate, both of which are susceptible to interference.

A challenge in pulse oximetry is in analyzing the data to obtain a reliable measure of a physiologic parameter in the presence of large interference sources. Prior art solutions to this challenge have included methods that assess the quality of the measured data and determine to display the measured value when it is deemed reliable based upon a signal quality. Another approach involves a heuristic-based signal extraction technology, where the obtained signals are processed based on a series of guesses of the ratio, and which require the algorithm to start with a guess of the ratio, which is an unknown. Both the signal-quality determining and the heuristic signal extraction technologies are attempts at separating out a reliable signal from an unreliable one, one method being a phenomenological one and the other being a heuristic one.

On the other hand, a problem encountered in such disciplines as statistics, data analysis, signal processing, and

neural network research, is finding a suitable representation of multivariate data. One such suite of methods is generally known as Independent Component Analysis (ICA), which is an approach to the problem of Blind Source Separation (BSS).

In general terms, the goal of blind source separation in signal processing is to recover independent source signals after they are linearly mixed by an unknown medium, and recorded or measured at N sensors. The blind source separation has been studied by researchers in speech processing or voice processing; antenna array processing; neural network and statistical signal processing communities (e.g. P. Comon, "Independent Component Analysis, a New Concept?", Signal Processing, vol. 36. no. 3, (April 1994), pp. 287-314, "Comon") and applied with relative degrees of success to electroencephalogram data and functional MRI imaging.

Comon defined the concept of independent component analysis as maximizing the degree of statistical independence among outputs using "contrast" functions of higher-order cumulants. Higher-order statistics refer to the expectations of products of three or more signals (e.g. 3rd-order or 4th-order moments), and cumulants are functions of the moments which are useful in relating the statistics to those of the Gaussian distribution. The 3rd-order cumulant of a distribution is called a skew, and the 4th-order cumulant is the kurtosis. A contrast function is any non-linear function which is invariant to permutation and scaling matrices, and attains its minimum value in correspondence of the mutual independence among the output components. In contrast with decorrelation techniques such as Principal Component Analysis (PCA), which ensures that output pairs are uncorrelated, ICA imposes the much stronger criterion that the multivariate probability density function of output variables factorizes. Finding such a factorization requires that the mutual information between all variable pairs go to zero. Mutual information depends on all higher-order statistics of the output variables while decorrelation normally only takes account of 2nd-order statistics.

While the general use of ICA as a means of blindly separating independent signal sources is known, the method poses unique challenges to its implementation in pulse oximetry. For instance, the mixture signals may not be exactly a linear combination of the pulse signal and sources of interference. Also, most ICA techniques are based on fourth-order cumulants, as the signals and noise commonly encountered in communications have zero third-order cumulant (skew), and cumulants of higher than fourth order are difficult to estimate accurately.

Several ICA methods are known for separating unknown source signals from sets of mixture signals, where the mixture signals are a linear combination of the source signals. As used in pulse oximetry, the mixture signals refer to signals measured at multiple wavelengths. Source components refer to the desired physiologic data including signals corresponding to the plethysmographic signal obtained at multiple wavelengths in addition to undesired interference data, which may be caused by motion, light interference, respiratory artifacts, and other known sources of errors in pulse oximetry.

There is therefore a need to apply blind source separation techniques to the field of pulse oximetry to be able to deterministically separate a source signal from various interference sources.

BRIEF SUMMARY OF THE INVENTION

The present invention is directed towards a method and apparatus for the application of Blind Source Separation (BSS), specifically Independent Component Analysis (ICA) to pulse oximetry. ICA refers to any one of several methods for separating unknown source signals from a set of "mixture" signals, which are linear combinations of the source signals. These methods may use estimates of the second- and higher-order joint statistics of the mixture signals and separate the sources by seeking to minimize the mutual information of the outputs of separation. In pulse oximetry, the signals measured at different wavelengths represent the mixture signals, while the plethysmographic signal, motion artifact, respiratory artifact and instrumental noise represent the source components.

In one embodiment the BSS is carried out by a two-step method including PCA and a higher-order decorrelation. In the first step, the method uses PCA as a preprocessing step, and in a second step, the principal components are then used to derive the independent components and the desired physiological parameters. The PCA is performed to transform the data to have zero second-order correlation before higher-order decorrelation.

In one aspect of the method of the present invention, data corresponding to a plurality of signals measured at a plurality of wavelengths are first obtained. Next, the data are processed to obtain a plurality of principal components, where in one embodiment the principal components are obtained by decorrelating the data (to minimize the cross-correlation between the signals from different wavelengths), and normalizing the decorrelated data. Next, the principal components are processed to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds with a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients. In one embodiment, the independent components are obtained by higher-order decorrelation of the principal components, and where the higher-order decorrelation of the principal components is achieved by minimizing a function of the higher-order cross-correlation of the data or equivalently by maximizing a function of the higher-order cumulants of the plurality of mixture signals. Since the skew of the time-derivative of the pulse signal is generally much greater in magnitude than that of interference, performance of the ICA may be enhanced by using a "contrast" function that was derived from the third-order cumulants of the derivatives of the signals.

In an aspect of the method of the present invention directed towards a pulse oximeter measuring signals at multiple wavelengths, a first independent component corresponds with a plethysmographic signal, a second independent component corresponds with the interference sources, and sat may be determined from a ratio of mixing coefficients from the mixing matrix. In pulse oximetry, the technique provides the advantage of extracting the plethysmographic signal in the presence of large motion interference and especially without requiring prior knowledge of saturation or pulse rate.

For a further understanding of the nature and advantages of the invention, reference should be made to the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of an exemplary pulse oximeter.

FIG. 2 is a flow chart of an embodiment of the method of the present invention.

FIG. 3 is a graph showing a typical pulse oximetry signals at two wavelengths.

FIG. 4 is a graph showing the typical pulse oximetry signals at two wavelengths after PCA processing.

FIG. 5 is a graph showing a typical pulse oximetry signals at two wavelengths after ICA processing.

FIG. 6 is a graph of signals of FIG. 3 plotted against one another.

FIG. 7 is a graph of the principal components of FIG. 3 plotted against one another.

FIG. 8 is a graph of the independent components of FIG. 3 plotted against one another.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is directed towards the application of Blind Source Separation (BSS), specifically Independent Component Analysis (ICA) to pulse oximetry. ICA refers to any one of several methods for separating unknown source signals from a set of "mixture" signals, which are linear combinations of the source signals. The ICA method as embodied by the present invention, uses estimates of the second- and higher-order joint statistics of the mixture signals and separates the sources by seeking to minimize the mutual information of the outputs of separation. In pulse oximetry, the signals measured at different wavelengths represent the mixture signals, while the plethysmographic signal, motion artifact, respiratory artifact and instrumental and environmental noise represent the source components.

In one embodiment, the BSS is carried out by a two-step method including an ICA. In the first step, the method uses Principal Component Analysis (PCA) as a preprocessing step, and the Principal Components are then used to derive sat and Independent Components, where the Independent Components are determined in the second step. Before describing the BSS methods of the present invention an example of a pulse oximeter, which may be configured to practice the method of the present invention is described below.

FIG. 1 is a block diagram of one embodiment of a pulse oximeter implementing the present invention. Light from light source 110 passes into patient tissue 112, and is scattered and detected by photodetector 114. A sensor 100 containing the light source and photodetector may also contain an encoder 116 which provides signals indicative of the wavelength of light source 110 to allow the oximeter to select appropriate calibration coefficients for calculating oxygen saturation. Encoder 116 may, for instance, be a resistor.

Sensor 100 is connected to a pulse oximeter 120. The oximeter includes a microprocessor 122 connected to an internal bus 124. Also connected to the bus is a RAM memory 126 and a display 128. A time processing unit (TPU) 130 provides timing control signals to light drive circuitry 132 which controls when light source 110 is illuminated, and if multiple light sources are used, the multiplexed timing for the different light sources. TPU 130 also controls the gating-in of signals from photodetector 114 through an amplifier 133 and a switching circuit 134. These signals are sampled at the proper time, depending upon which of multiple light sources is illuminated, if multiple

5

light sources are used. The received signal is passed through an amplifier **136**, a low pass filter **138**, and an analog-to-digital converter **140**. The digital data is then stored in a queued serial module (QSM) **142**, for later downloading to RAM **126** as QSM **142** fills up. In one embodiment, there may be multiple parallel paths of separate amplifier filter and A/D converters for multiple light wavelengths or spectrums received.

Based on the value of the received signals corresponding to the light received by photodetector **114**, microprocessor **122** will calculate the oxygen saturation using various algorithms. These algorithms require coefficients, which may be empirically determined, corresponding to, for example, the wavelengths of light used. These are stored in a ROM **146**. The particular set of coefficients chosen for any pair of wavelength spectrums is determined by the value indicated by encoder **116** corresponding to a particular light source in a particular sensor **100**. In one embodiment, multiple resistor values may be assigned to select different sets of coefficients. In another embodiment, the same resistors are used to select from among the coefficients appropriate for an infrared source paired with either a near red source or far red source. The selection between whether the near red or far red set will be chosen can be selected with a control input from control inputs **154**. Control inputs **154** may be, for instance, a switch on the pulse oximeter, a keyboard, or a port providing instructions from a remote host computer. Furthermore any number of methods or algorithms may be used to determine a patient's pulse rate, oxygen saturation or any other desired physiological parameter. One such method, namely Blind Source Separation, is described below.

Blind Source Separation refers to the separation of signals given only linear combinations of those signals, such that:

$$x(t)=A \, s(t)$$

where x(t) is a matrix of a set of observed signals (mixed signals), $x_1(t) \ldots x_n(t)$,
A is an unknown mixing matrix,
and s(t) is a set of source signals $s_1(t) \ldots s_m(t)$,
assumed to be statistically independent, i.e.

$$p(s) = p(s_1, \ldots, s_m) = \prod_{i=1}^{m} p_i(s_i)$$

where p(s) is the probability distribution function of s.

As described above, in pulse oximetry, the mixture signals correspond with signals obtained by a pulse oximeter sensor, which include both the desired signal and the undesired noise components. In one embodiment of the method of the present invention, the mixture signals are first preprocessed using PCA to transform the mixture signal to principal components. To more fully separate the signal and the noise, the data are further processed: in mathematical terms, the data are rotated. In other words, the ICA processing includes a combination of PCA and rotation.

A criterion for determining the degree of signal-noise separation is statistical independence, as described above. However, since the probability distributions are not known, the challenge of an ICA algorithm becomes the measurement of statistical independence. A measure of statistical independence is the degree of mutual information, such that by minimizing the degree of mutual information between sets of data, independent components can be determined. Algorithms determining the mutual information are gener-

6

ally too complicated for a direct solution of its (i.e. mutual information) minimum, and thus they lend themselves best to iterative methods. For example, one possible approach would be to search for coefficients of the mixing matrix A that would lead to statistical independence (by minimizing the data set's mutual information). One could heuristically sweep through a large range of angles about which to rotate the principal components, which would yield an independent set of data, but this approach would be excessively time-consuming.

Thus the inventor of the present invention proposes separating the data by performing higher-order decorrelation of the data, or by removing the higher-order correlation of the data obtained from the mixture signals. Thus, the BSS-based method of the present invention: (1) uses PCA to find uncorrelated components, and (2) separates the data by removing higher-order correlation to find the independent components corresponding with the desired signal source(s) and the undesired noise sources. And as used herein, higher-order correlations are higher than second-order correlations, such as third-order and fourth-order cross-correlations. In one embodiment, independence is approximated by minimizing the sum of the squares of the third-order correlations r_{xxy} and r_{xyy}, e.g.,

$$r_{XXY} = \sum_{i} x_i^2 y_i \text{ and } r_{XYY} = \sum_{i} x_i y_i^2 \text{ [where } x \text{ and } y \text{ have zero mean]}$$

Alternately, independence is approximated by minimizing the sum of the squares of the fourth-order cross-cumulants.

In certain embodiments of the present invention, separation is achieved by maximizing the sum of the squares of the higher-order cumulants, which is equivalent to minimizing the sum of the squares of the higher-order cross-cumulants. In these and other embodiments, the second-order decorrelation and higher-order decorrelation may be effected simultaneously through an iterative, adaptive process.

The advantage of achieving separation by higher-order decorrelation is that it enables direct formulas and simple algorithms for the separation of data into its independent components.

FIG. **2** is a flow chart **200** of an embodiment the method of the present invention as applied to signals obtained by a pulse oximeter sensor. First, (step **210**) a plurality of signals measured at various wavelengths are obtained by a pulse oximeter sensor. In a typical pulse oximeter, emitting optical energy at two wavelengths, the photocurrent generated by the photo-detector is conditioned and processed to determine the modulation ratios of the red and infrared signals. The example of a two-wavelength pulse oximeter is for illustration purposes only, and is not meant to limit the scope of the present invention. The detected photocurrents include the mixture signals, where the mixture signals include the plethysmographic signal, motion artifact, respiratory artifact and instrument noise. An example plot of the measured photocurrent is shown on FIG. **3**. FIG. **3** shows a plot **300** of the photocurrent vs. time for measurements obtained at 595 nm (**310**) and at 665 nm (**320**). As can be seen from this figure (FIG. **3**), both signals (**310** and **320**) show a low amplitude section and a high amplitude section, where the high amplitude section corresponds to the signals measured while the sensor is moving.

Next, (step **220**) the mixture signals are processed using PCA analysis to obtain two principal components. Here, the PCA processing results in the determination of two principal

components, since the original mixture signals were obtained at two different wavelengths. Embodiments of the present invention are not limited to two mixture signals or two principal components. The embodiments of the present invention are directed to the decomposition of a matrix of a set of observed signals (mixed signals) into a set of source signals and a mixing matrix, as set forth above. However, describing more than two dimensions and visualizing more dimensions is at best difficult to visualize, hence the description provided herein is kept to a two-dimensional one. In one embodiment, the Singular Value Decomposition algorithm is used to obtain the principal components. In one alternate embodiment, the data are multiplied by the inverse of the square root of the covariance matrix. In another embodiment directed to a two wavelengths approach, for each possible pair of wavelengths, the data are rotated by the angle of the best linear fit between those two signals. FIG. 4 shows a plot 400 of the two principal components. As can be seen from this figure (FIG. 4), the first principal component 410 corresponds more with the noise due to the subject's motion, since it has a low amplitude portion, which is followed by a high amplitude portion. FIG. 4 also shows that the second principal component 420 corresponds less with the noise due to the subject movement, since it does not show a distinct high amplitude portion.

Furthermore, a comparison of FIGS. 6 and 7 shows that while the original mixture signals are not decorrelated, the principal components are decorrelated. FIG. 6 shows a graph of the photocurrent at 655 nm vs. the photocurrent at 595 nm. As can be seen from this figure (FIG. 6), there is a wealth of mutual information between the two photocurrents, since the data from the two photocurrents appear to be aligned along the positively sloping diagonal line A-A. FIG. 7 shows a plot of principal component 2 vs. principal component 1. A review of this figure (FIG. 7) shows that the principal components are decorrelated, since there is no significant linear fit to the data in these coordinates.

In an alternate embodiment, before the processing according to step 220, the time derivatives of the signals are obtained. For pulse oximetry, the third-order correlations of the pulse signals are often enhanced by taking the time derivative of the signals before performing PCA/ICA analyses.

Having decorrelated the data, the principal components are further processed by ICA processing to determine the independent components describing the photocurrent data (step 230). As described above, the principal components are processed to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds with a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients. In one embodiment, the independent components are determined by decorrelating the data by maximizing the sum of squares of the data set's higher-order cumulants. Since the skew of the time-derivative of the pulse signal is generally much greater in magnitude than that of interference, the ICA performance is enhanced by using a "contrast" function that was derived from the third-order cumulants of the derivatives of the signals. As stated above, a contrast function is any non-linear function which is invariant to permutation and scaling matrices, and attains its minimum value in correspondence of the mutual independence among the output components. In an alternate embodiment, the independent components are determined by minimizing the estimated mutual information. FIG. 5 shows a plot 500 of the two independent components. As can be seen from this figure (FIG. 5), a first independent component 510 corre-

sponds more with the noise due to the subject's motion, since it has a low amplitude portion, which is followed by a high amplitude portion. FIG. 5 also shows that a second principal component 520 apparently corresponds to a pulse component. Furthermore, FIG. 8 shows a plot of independent component 2 vs. independent component 1. As can be seen from this figure (FIG. 8), the plot of independent component 2 vs. independent component 1 lies along the horizontal line at (independent component=0) B-B, showing that the data sets have a minimal amount of mutual information, and thus can be approximated as independent data sets.

The decomposed data set of two independent components is further processed as follows. In one embodiment, sat is obtained from a ratio of mixing coefficients (step 240). In an alternate embodiment, one of the independent components is further processed to obtain the plethysmographic signal (step 250), and the other independent signal is recognized as a measure of the interference signal (step 260).

Alternately, instead of, or in addition to taking signals that are measured at different wavelengths (step 210), signals are also obtained that are additions of signals from different times, thus an alternate embodiment of the present invention starts by processing signals obtained from mixing signals in time.

In pulse oximetry, embodiments of the present invention have the advantage of extracting the plethysmographic signal in the presence of large motion interference and especially without requiring prior knowledge of saturation or pulse rate. Additionally, the present method is extendible to measurement of other physiological variables, such as pulse rate, blood pressure, temperature, or any other physiological variable measurable by non-invasive measurement of photocurrent provided an optical-based sensor.

Accordingly, as will be understood by those of skill in the art, the present invention which is related to blind source separation of pulse oximetry signals, may be embodied in other specific forms without departing from the essential characteristics thereof. Accordingly, the foregoing disclosure is intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the following claims.

What is claimed is:

1. A computer useable medium having computer readable code, the computer readable code comprising:
   code configured to process a plurality of signals to obtain a plurality of principal components, wherein the plurality of signals corresponds to sensed optical energies from a plurality of wavelengths and wherein each of the plurality of signals comprises a source component corresponding to a physiological parameter and an interference component;
   code configured to process the plurality of principal components to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds to a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients, and wherein the code configured to process the plurality of principal components comprises
   code configured to separate the source component from the interference component; and
   code configured to obtain a ratio of mixing coefficients from the matrix of mixing coefficients, wherein the ratio corresponds to a ratio of modulation ratios of red to infrared wavelengths of the plurality of wavelengths; and

code configured to extract a first measure of the physiological parameter corresponding to the source component from one of the plurality of independent components.

2. The medium of claim 1 wherein the physiological parameter comprises oxygen saturation of a person's blood.

3. The medium of claim 1 wherein the plurality of signals corresponds to the time derivative of the sensed optical energies from the plurality of wavelengths.

4. The medium of claim 1 wherein the interference component comprises signal components caused by motion, respiratory artifact, ambient light, optical scattering, or other interference between a tissue location being sensed and a sensor, or any combination thereof.

5. The medium of claim 1 wherein the code configured to process the plurality of signals comprises:

code configured to decorrelate the plurality of signals by minimizing a cross-correlation of the plurality of signals to obtain a plurality of decorrelated signals; and

code configured to normalize the plurality of decorrelated signals to obtain the plurality of principal components.

6. The medium of claim 1 wherein the code configured to process the plurality of signals comprises code configured to decorrelate the plurality of signals by singular-value decomposition of the plurality of signals to obtain the plurality of principal components.

7. The medium of claim 1 wherein the code configured to process the plurality of signals comprises code configured to decorrelate the plurality of signals by multiplying the plurality of signals by the inverse square root of the covariance matrix of the plurality of signals to obtain the plurality of principal components.

8. The medium of claim 1 wherein the code configured to process the plurality of principal components comprises code configured to perform successive transformations to simultaneously minimize higher-order correlations among the outputs of the transformations.

9. The medium of claim 1 wherein the code configured to process the plurality of principal components comprises code configured to perform successive rotations to minimize estimated mutual information among outputs of the rotations.

10. The medium of claim 1 comprising code configured to extract a second measure of the physiological parameter from the ratio, wherein the second measure of the physiological parameter corresponds to an oxygen saturation.

11. The medium of claim 1 wherein the first measure of a physiological parameter corresponds to a pulse rate.

12. A pulse oximeter, comprising:

a processor configured to:

process a plurality of signals to obtain a plurality of principal components, wherein each of the plurality of signals comprises a source component corresponding to a physiological parameter and an interference component;

process the plurality of principal components to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds to a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients; and

extract a first measure of the physiological parameter corresponding to the source component from one of the plurality of independent components, wherein the physiological parameter comprises a pulse rate.

13. A pulse oximeter, comprising:

a processor configured to:

process the plurality of signals to obtain a plurality of principal components, wherein each of the plurality of signals comprises a source component corresponding to a physiological parameter and an interference component;

process the plurality of principal components to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds to a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients; and

extract a first measure of the physiological parameter corresponding to the source component from one of the plurality of independent components, wherein the plurality of signals corresponds to sensed optical energies from a plurality of wavelengths.

14. The pulse oximeter of claim 13 wherein the physiological parameter comprises oxygen saturation.

15. The pulse oximeter of claim 13 wherein the plurality of signals corresponds to the time derivative of the sensed optical energies from a plurality of wavelengths.

16. The pulse oximeter of claim 13 wherein the interference component comprises signal components caused by motion, respiratory artifact, ambient light, optical scattering, or other interference between a tissue location being sense and a sensor, or any combination thereof.

17. The pulse oximeter of claim 13 wherein the processor is configured to:

decorrelate the plurality of signals by minimizing a cross-correlation of the plurality of signals to obtain a plurality of decorrelated signals; and

normalize the plurality of decorrelated signals to obtain the plurality of principal components.

18. The pulse oximeter of claim 13 wherein the processor is configured to decorrelate the plurality of signals by singular-value decomposition of the plurality of signals to obtain the plurality of principal components.

19. The pulse oximeter of claim 13 wherein the processor is configured to decorrelate the plurality of signals by multiplying the plurality of signals by the inverse square root of the covariance matrix of the plurality of signals to obtain the plurality of principal components.

20. The pulse oximeter of claim 13 wherein the processor is configured to perform a higher-order decorrelation of the plurality of principal components.

21. The pulse oximeter of claim 13 wherein the processor is configured to maximize a function of the higher-order cumulants of a mixture of the plurality of signals, thus separating the source component from the interference component.

22. The pulse oximeter of claim 21, wherein the higher-order cumulant is a cumulant having an order greater than two.

23. The pulse oximeter of claim 21, wherein the higher-order cumulant is a third-order cumulant of the plurality of signals.

24. The pulse oximeter of claim 21 wherein the higher-order cumulant is a fourth-order cumulant of the plurality of signals.

25. The pulse oximeter of claim 13 wherein the processor is configured to perform successive transformations to simultaneously minimize secondhand higher-order correlations among the outputs of the transformations.

26. The pulse oximeter of claim 13 wherein the processor is configured to perform successive rotations to minimize estimated mutual information among outputs.

27. The pulse oximeter of claim 13 wherein the processor is configured to obtain a ratio of mixing coefficients from the matrix of mixing coefficients, wherein the ratio corresponds to a ratio of modulation ratios of red to infrared signals.

28. The pulse oximeter of claim 27 wherein the processor is configured to extract a second measure of the physiological parameter from the ratio, wherein the second measure of the physiological parameter corresponds to an oxygen saturation.

29. The pulse oximeter of claim 13 wherein the first measure of a physiological parameter corresponds to a pulse rate.

30. The pulse oximeter of claim 13 wherein the processor is configured to extract the interference component from another one of the plurality of independent components.

31. A pulse oximeter, comprising:

a processor configured to:

process a plurality of signals to obtain a plurality of principal components, wherein each of the plurality of signals comprises a source component corresponding to a physiological parameter and an interference component;

process a plurality of principal components to obtain a plurality of independent components, wherein a matrix of the plurality of signals corresponds to a matrix product of a matrix of the plurality of independent components and a matrix of mixing coefficients; and

extract a first measure of the physiological parameter corresponding to the source component from one of the plurality of independent components, wherein the plurality of signals corresponds to sensed optical energies from a plurality of wavelengths from different times.

* * * * *

专利名称(译)	脉冲血氧饱和度信号的盲源分离		
公开(公告)号	US7343187	公开(公告)日	2008-03-11
申请号	US11/318796	申请日	2005-12-27
[标]申请(专利权)人(译)	内尔科尔普里坦贝内特公司		
申请(专利权)人(译)	NELLCOR PURITAN BENNETT INC.		
当前申请(专利权)人(译)	COVIDIEN LP		
[标]发明人	STETSON PAUL F		
发明人	STETSON, PAUL F.		
IPC分类号	A61B5/00 A61B5/145 A61B5/024 A61B5/1455		
CPC分类号	A61B5/02416 A61B5/14551 A61B5/7207 A61B5/7239		
其他公开文献	US20060111623A1		
外部链接	Espacenet USPTO		

摘要(译)

一种用于将盲源分离（BSS），特别是独立分量分析（ICA）应用于由脉冲血氧计传感器获得的混合信号的方法和装置。在脉搏血氧测定法中，在不同波长测量的信号代表混合信号，而体积描记信号，运动伪影，呼吸伪影和仪器噪声代表源组件。 BSS通过包括ICA的两步法进行。在第一步中，该方法使用主成分分析（PCA）作为预处理步骤，然后使用主成分导出sat和独立成分，其中独立成分在第二步中确定。在一个实施例中，通过主成分的高阶去相关来获得独立分量，通过最大化多个混合信号的高阶累积量的平方和来实现。