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(54) **PLETHYSMOGRAPHIC SIGNAL PROCESSING METHOD AND SYSTEM**

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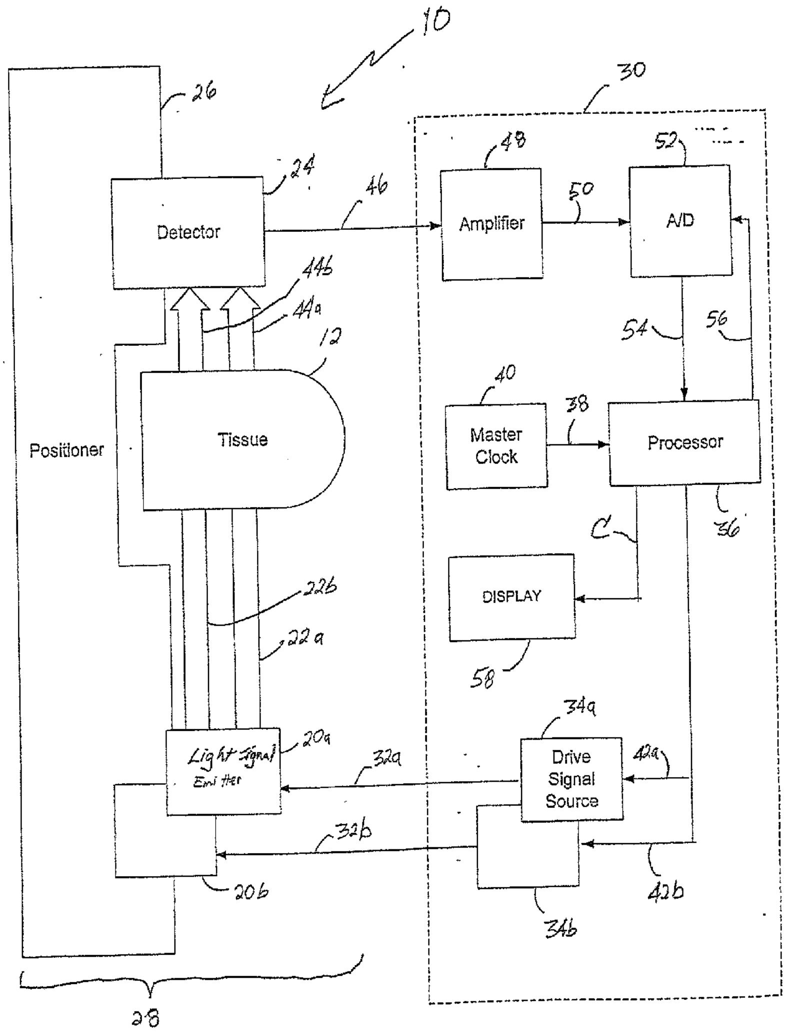
(57) **ABSTRACT**

The present invention provides a plethysmographic signal processing method and system that achieves improved S/N ratios leading to improved patient heart rate estimates and improved plethysmographic waveform displays. The plethysmographic signal processing method and system of the present invention may be implemented using analog and/or digital components within a pulse oximeter. In one embodiment, first and second plethysmographic signals S_1, S_2 associated with first and second wavelengths, respectively (e.g., infrared and red), are received on first and second channels **210, 212**. First and second multipliers **214, 216** multiply the first and second plethysmographic signals S_1, S_2 by first and second multiplication factors T_1, T_2. A summer **218** sums the products from the first and second multipliers **214, 216** to output a composite plethysmographic signal C on an output channel **220**. The composite plethysmographic signal C may then be displayed and/or utilized to make heart rate determinations and the like.



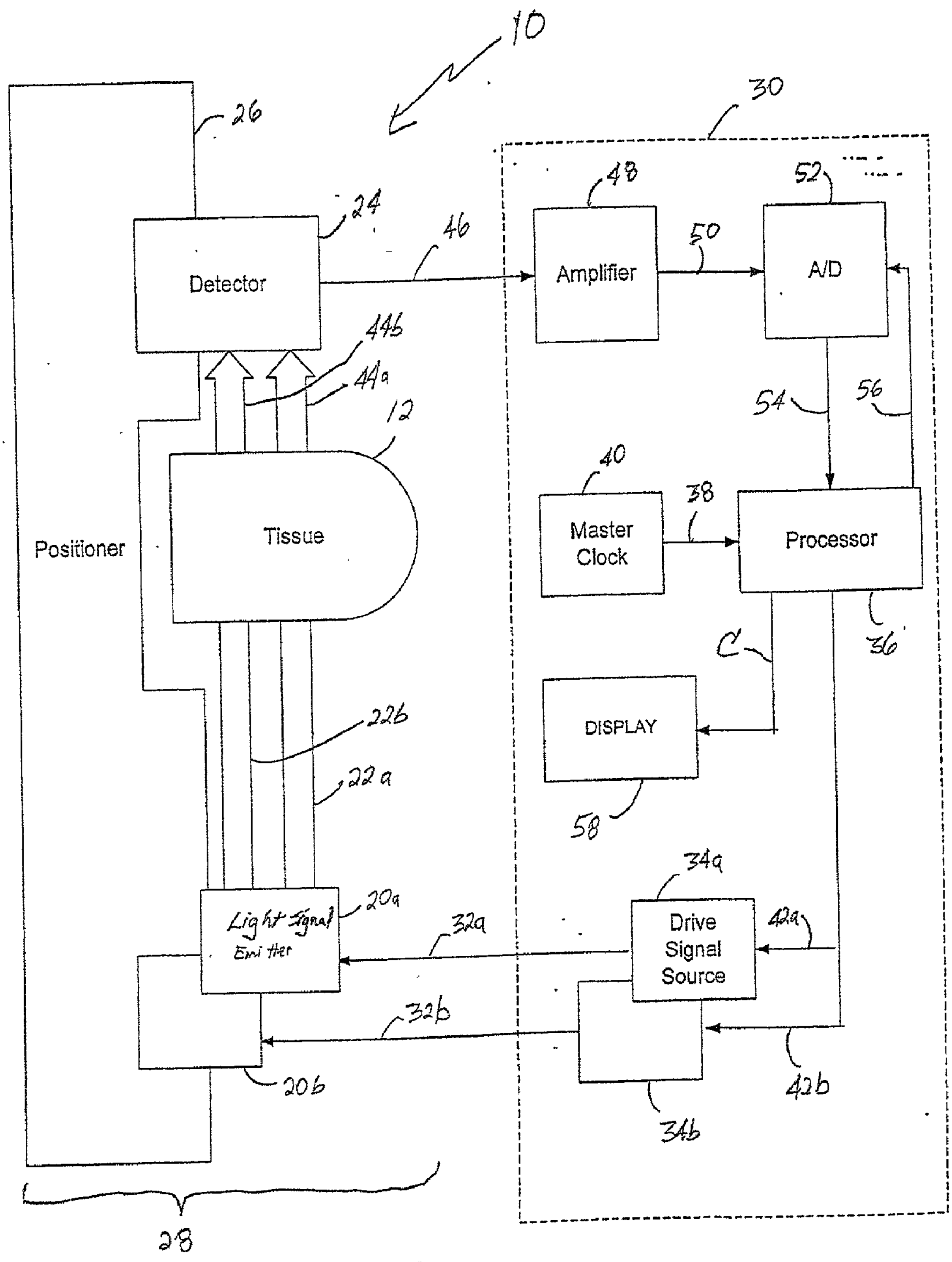

10
26
30
48
52
24
46
50
Detector
Amplifier
A/D
44b
44a
12
54
56
Positioner
Tissue
40
38
Master
Clock
Processor
36
C
DISPLAY
22b
22a
58
34a
Light Signal
Emitter
20a
32a
Drive
Signal
Source
42a
32b
20b
42b
34b
28

FIG. 1

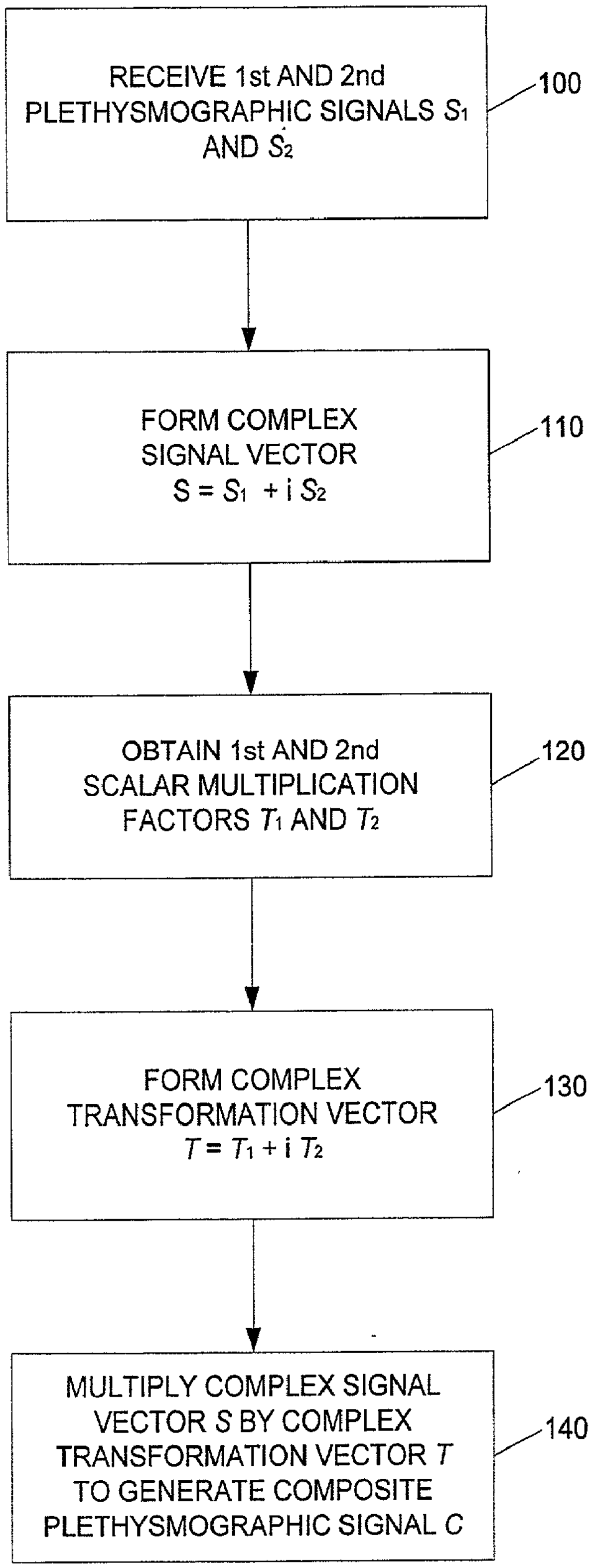

RECEIVE 1st AND 2nd PLETHYSMOGRAPHIC SIGNALS S_1 AND S_2
100
FORM COMPLEX SIGNAL VECTOR $S = S_1 + i S_2$
110
OBTAIN 1st AND 2nd SCALAR MULTIPLICATION FACTORS T_1 AND T_2
120
FORM COMPLEX TRANSFORMATION VECTOR $T = T_1 + i T_2$
130
MULTIPLY COMPLEX SIGNAL VECTOR S BY COMPLEX TRANSFORMATION VECTOR T TO GENERATE COMPOSITE PLETHYSMOGRAPHIC SIGNAL C
140

FIG. 2

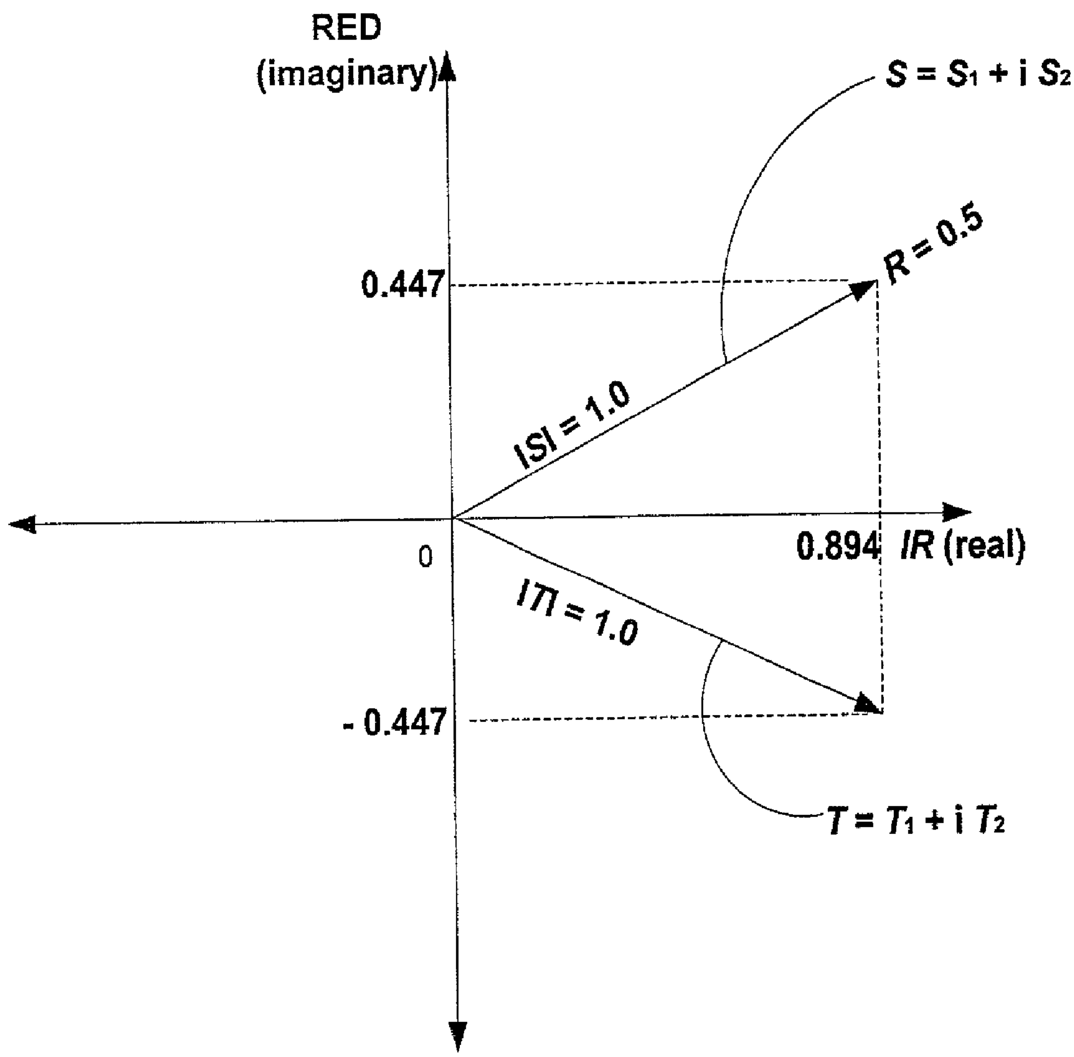

RED
(imaginary)
S = S1 + i S2
R = 0.5
0.447
|S| = 1.0
0
0.894
IR (real)
|T| = 1.0
- 0.447
T = T1 + i T2

FIG. 3A

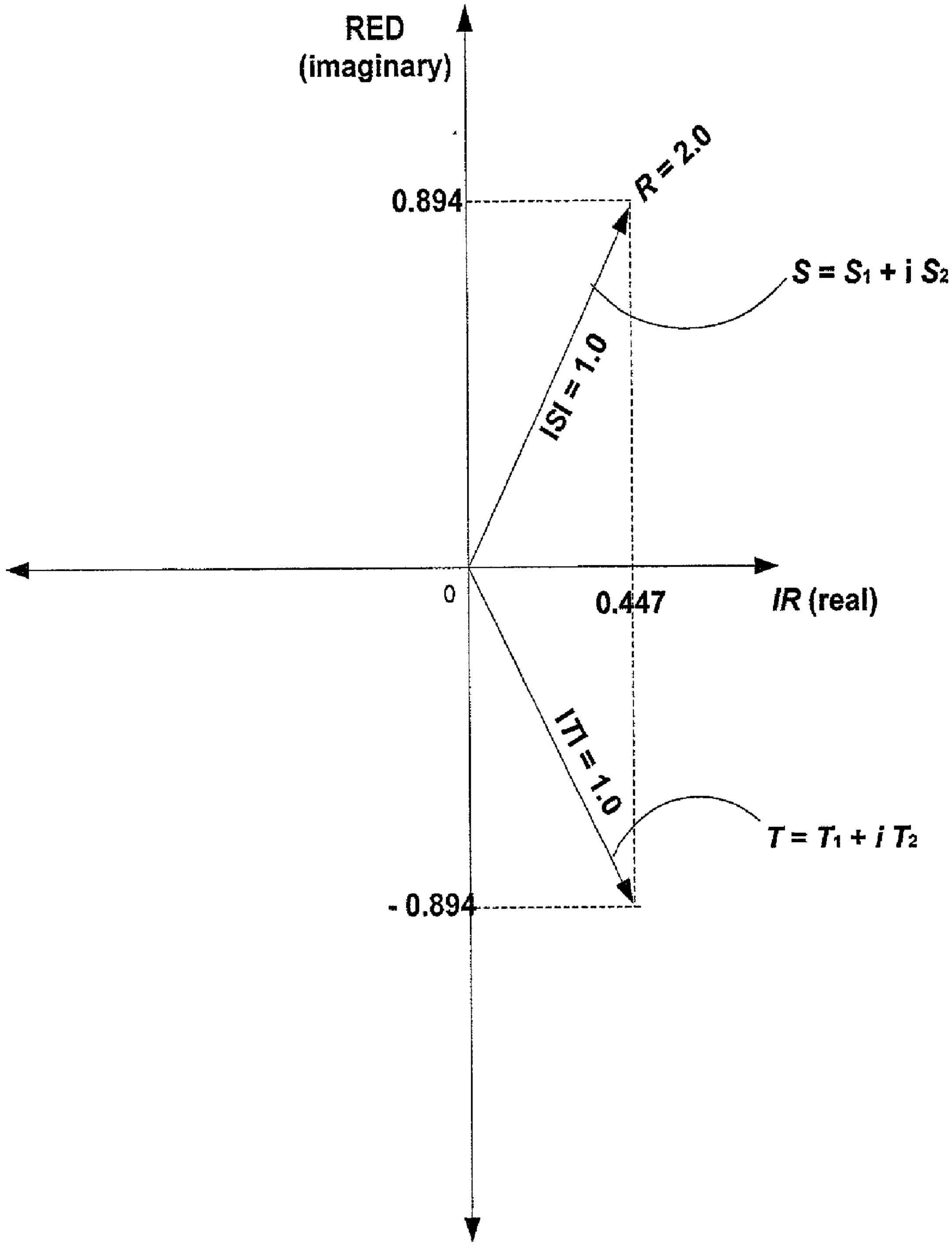
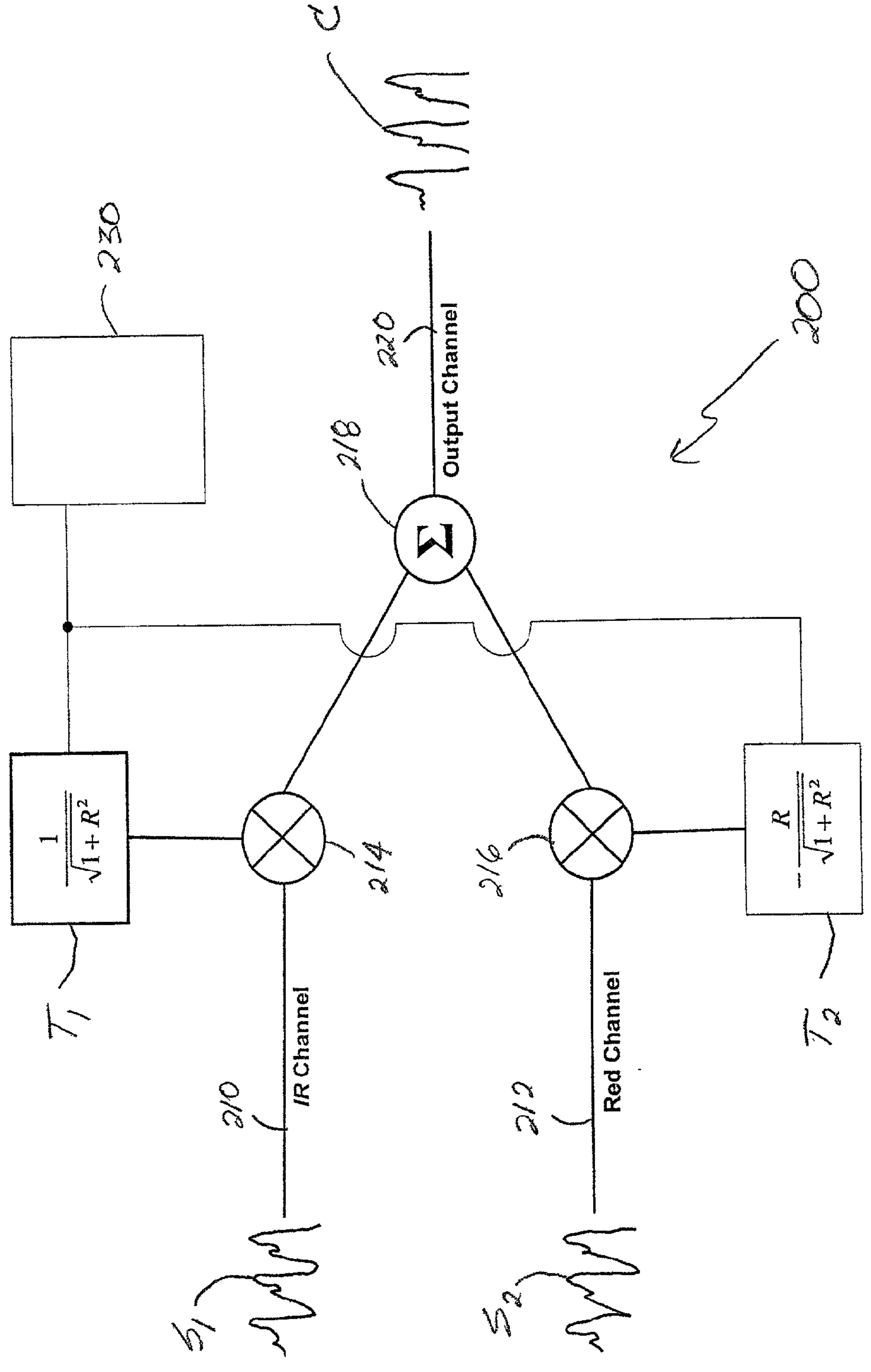

RED
(imaginary)
R = 2.0
0.894
S = S1 + i S2
ISI = 1.0
0
0.447
IR (real)
ITI = 1.0
T = T1 + i T2
- 0.894

FIG. 3B



230
C
220
Output Channel
218
200
$\frac{1}{\sqrt{1+R^2}}$
$-\frac{R}{\sqrt{1+R^2}}$
214
216
T_1
T_2
IR Channel
Red Channel
210
212
S_1
S_2

FIG. 4

R	T1	T2
0.0	1.000	0.000
0.1	0.995	0.100
0.2	0.981	0.196
0.3	0.958	0.287
0.4	0.928	0.371
0.5	0.894	0.447
0.6	0.857	0.514
0.7	0.819	0.573
0.8	0.781	0.625
0.9	0.743	0.669
1.0	0.707	0.707
1.1	0.673	0.740
1.2	0.640	0.768
1.3	0.610	0.793
1.4	0.581	0.814
1.5	0.555	0.832
1.6	0.530	0.848
1.7	0.507	0.862
1.8	0.486	0.874
1.9	0.466	0.885
2.0	0.447	0.894
2.1	0.430	0.903
2.2	0.414	0.910
2.3	0.399	0.917
2.4	0.385	0.923
2.5	0.371	0.928
2.6	0.359	0.933
2.7	0.347	0.938
2.8	0.336	0.942
2.9	0.326	0.945
3.0	0.316	0.949
3.1	0.307	0.952
3.2	0.298	0.954
3.3	0.290	0.957
3.4	0.282	0.959
3.5	0.275	0.962
3.6	0.268	0.964
3.7	0.261	0.965
3.8	0.254	0.967
3.9	0.248	0.969
4.0	0.243	0.970

Fig. 5

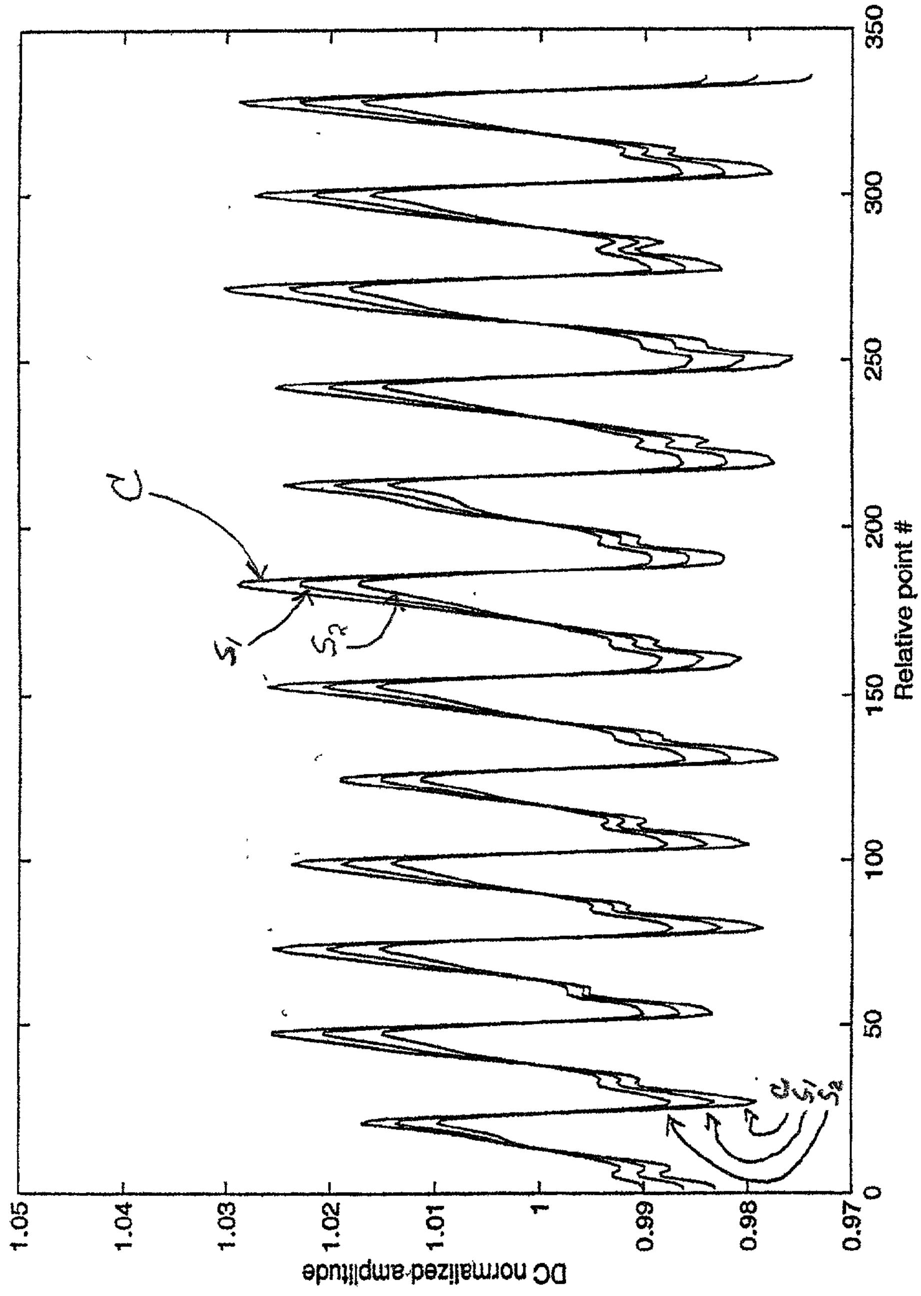

DC normalized amplitude
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
Relative point #
0
50
100
150
200
250
300
350
C
S1
S2

Fig. 6

PLETHYSMOGRAPHIC SIGNAL PROCESSING METHOD AND SYSTEM

FIELD OF THE INVENTION

[0001] The present invention relates generally to the non-invasive determination of patient heart rates from plethysmographic signals, and more particularly to achieving improved signal-to-noise ratios in plethysmographic signals used to estimate patient heart rates and the like.

BACKGROUND OF THE INVENTION

[0002] In photoplethysmography, light signals corresponding with two or more different center wavelengths are utilized to non-invasively determine various blood analyte concentrations in a patient's blood and to obtain information regarding the patient's heart rate and the like. By way of primary example, blood oxygen saturation (SpO_2) levels of a patient's arterial blood are monitored in pulse oximeters by measuring the absorption of oxyhemoglobin (O2Hb) and reduced hemoglobin (RHb) using red and infrared light signals. The measured absorption data allows for the calculation of the relative concentrations of O2Hb and RHb, and therefore SPO_2 levels, since RHb absorbs more light than O2Hb in the red band and O2Hb absorbs more light than RHb in the infrared band, and since the absorption relationship of the two analytes in the red and infrared bands is known.

[0003] To obtain absorption data, pulse oximeters typically comprise a probe that is releaseably attached to a patient tissue site (e.g., finger, ear lobe, nasal septum, foot). The probe directs red and infrared light signals through the patient tissue site. The light signals are provided by one or more light signal sources (e.g., light emitting diodes or laser diodes) which are typically disposed in the probe. A portion of the red and infrared light signals is absorbed in the patient tissue site and the intensity of the transmitted light signals (light exiting the patient tissue site is referred to as transmitted) is detected by a detector that may also be located in the probe. The detector outputs a signal which includes information indicative of the intensities of the transmitted red and infrared light signals. The output signal from the detector may be processed to obtain separate signals associated with the red and infrared transmitted light signals (i.e., separate red and infrared plethysmographic signals or waveforms).

[0004] As will be appreciated, pulse oximeters rely on the time-varying absorption of light in the patient tissue site as it is supplied with pulsating arterial blood. The patient tissue site may contain a number of non-pulsatile light absorbers, including capillary and venous blood, as well as muscle, connective tissue and bone. Consequently, the red and infrared plethysmographic signals typically contain a large non-pulsatile, or DC, component, and a relatively small pulsatile, or AC, component. Patient heart rate can be determined by examining the time period between successive peaks in the small pulsatile AC component of the red or infrared plethysmographic signals. The small pulsatile AC component of the red or infrared plethysmographic signals can also be displayed on the monitor unit for further observation by persons involved in the treatment of the patient.

[0005] As noted, the pulsatile AC component of a pulse oximeter detector output signal is relatively small compared to the non-pulsatile DC component. Consequently, the accuracy of the heart rate determination and the information which can be obtained through visual perception of the plethysmographic signals on a display can be severely impacted by small amounts of noise. Noise may be introduced by factors such as, for example, motion of the patient tissue site, corruption of the transmitted light signals by ambient light, and noise inherent in the electronic and opto-electronic components of the pulse oximeter. Furthermore, in patients having high SpO_2 levels, the infrared plethysmographic signal typically has a better signal-to-noise (SIN) ratio and is preferred for visual display and heart rate determinations. However, in patients with low SpO_2 levels, the red plethysmographic signal typically has a better SIN ratio and is therefore preferred for visual display and heart rate determinations.

SUMMARY OF THE INVENTION

[0006] Accordingly, the present invention provides a plethysmographic signal processing method and system that achieves improved S/N ratios leading to improved patient heart rate estimates and improved plethysmographic waveform displays. The plethysmographic signal processing method and system generates a composite plethysmograhic signal from two or more plethysmographic signals (e.g., red and infrared). The composite plethysmographic signal has an improved S/N ratio over the full range of patient SpO_2 levels as compared to any of the separate plethysmographic signals from which it is generated.

[0007] According to one aspect of the present invention, a plethysmographic signal processing method includes the step of receiving at least two plethysmographic signals. Each plethysmographic signal received is associated with a particular wavelength. In this regard, where there are two plethysmographic signals (e.g., in pulse oximetry), a first one of the plethysmographic signals may be associated with infrared wavelengths (e.g., wavelengths from about 800 nm to about 950 nm), and a second one of the plethysmographic signals may be associated with red wavelengths (e.g., wavelengths from about 600 nm to 700 nm). Each plethysmographic signal received is multiplied by an associated scalar multiplication factor. A composite plethysmographic signal comprising a linear combination of the plethysmographic signals is then generated by adding the results of the multiplications. The plethysmographic signals may be analog signals or digital signals. Where the plethysmographic signals are digital signals, the multiplications and additions are performed for each temporally corresponding signal sample value (i.e., each corresponding-in-time sample instance).

[0008] In the plethysmographic signal processing method, the multiplication factors may be specifically chosen to provide an improved S/N ratio for the composite signal that is generated as compared to the S/N ratios of the separate plethysmographic signals that are received over a specified range of patient SpO_2 levels (e.g., from about 40% to about 100%). In this regard, the multiplication factors may be chosen to depend upon a ratio (e.g., an R value) wherein the ratio varies in accordance with the SpO_2 level in arterial blood circulated through a patient tissue site. By way of example, where there are first and second plethysmographic signals associated with an infrared wavelength and a red wavelength, respectively, first and second multiplication factors designated T_1 and T_2 and associated with the first and second plethysmographic signals, respectively, may be specified in accordance with the following equations:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

[0009] In the above equations, R may be the ratio of a first differential absorption value dA_1 obtained from the first plethysmographic signal and a second differential absorption value dA_2 obtained from the second plethysmographic signal calculated as follows:

$$R = \frac{dA_2}{dA_1}$$

[0010] Multiplication factors which depend upon the R value as described above may be obtained in a number of manners. For example, prior to multiplying the plethysmographic signals by their associated multiplication factors, the R value may be computed each time it is needed using the latest differential absorption values available (e.g., from another method or system utilized in a pulse oximeter) and the multiplication factors may be then be computed using the updated R value. As may be appreciated, this is fairly computationally intensive since computation of each multiplication factor requires a multiplication, addition, square root and division operation. As an alternative, the multiplication factors may be obtained from a look-up table. The look-up table includes sets of multiplication factors that are cross-referenced with corresponding incremental R values. The look-up table may, for example, include multiplication factors corresponding with incremental R values ranging from 40% to 100%. In this regard, the R values in the look-up table may, for example, be incremented in equal increments, with the increments being between about 0.001 and about 0.1 in size.

[0011] According to another aspect of the present invention, a signal processing method for use in plethysmography includes the step of receiving first and second plethysmographic signals S_1 and S_2. The first and second plethysmographic signals S_1 and S_2 are associated with first and second wavelengths, respectively (e.g., infrared and red). A complex signal vector $S=S_1+iS_2$ is formed by treating the first plethysmographic signal S_1 as the real component of the complex signal vector S and treating the second plethysmographic signal S_2 as the imaginary component of the complex signal vector S. A complex transformation vector T is also formed from first and second scalar multiplication factors T_1 and T_2. In this regard, the first scalar multiplication factor T_1 is treated as the real component of the complex transformation vector T and the second scalar multiplication factor T_2 is treated as the imaginary component of the complex transformation vector T (i.e. $T=T_1+iT_2$). The first and second scalar multiplication factors T_1 and T_2 may depend upon an R value comprising the ratio of a differential absorption value dA_2 obtained from the second plethysmographic signal S_2 to a differential absorption value dA_1 obtained from the first plethysmographic signal S_1. The complex signal vector S is then multiplied by the complex transformation vector T to generate a composite plethysmographic signal C. The composite plethysmographic signal C achieved has an improved signal strength as compared with either of the first and second plethysmographic signals S_1 and S_2.

[0012] According to a further aspect of the present invention, a plethysmographic signal processing system includes first and second input channels for receiving first and second plethysmographic signals thereon. The first and second plethysmographic signals are associated with first and second wavelengths, respectively (e.g., infrared and red). The system also includes first and second multipliers. The first multiplier is operable to receive the first plethysmographic signal and a first scalar multiplication factor as inputs and output a first product comprising the first plethysmographic signal multiplied by the first scalar multiplication factor. The second multiplier is operable to receive the second plethysmographic signal and a second scalar multiplication factor as inputs and output a second product comprising the second plethysmographic signal multiplied by the second scalar multiplication factor. The system also includes a summer. The summer is operable to receive the first and second products as inputs and add the first and second products to output a composite signal comprising the sum of the first and second products.

[0013] The first and second plethysmographic signals may comprise continuous time signals, in which case the system of the present invention may be implemented for processing the first and second plethysmographic signals in a continuous time fashion. In the regard, the first channel, second channel, first multiplier, second multiplier, and summer may all comprise analog components. The first and second plethysmographic signals may also comprise discretized-in-time (digital) signals, in which case the system of the present invention may be implemented in software executable by a digital processor.

[0014] The first and second scalar multiplication factors may be dependent upon a ratio (e.g., an R value) that varies in accordance with an SpO_2 level in arterial blood circulated through a patient tissue site. In this regard, the ratio may be computed as follows:

$$R = \frac{dA_2}{dA_1}$$

[0015] where dA_1 and dA_2 comprise differential absorption values associated with the first and second plethysmographic signals, respectively. The first and second scalar multiplication factors, designated T_1 and **T2**, may be specified in accordance with the following equations:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

[0016] The system may compute the first and second scalar multiplication factors when needed. Alternatively, the system may further include a look-up table that has multiple pairs of pre-computed first and second scalar multiplication factors cross-referenced with corresponding incremental R values. In this regard, the pairs of first and second scalar multiplication factors may correspond with incremental R values in the range of about 40% to about 100%, with the increments being equal and between about 0.001 and about 0.1 in size.

[0017] Where it is desirable to process additional plethysmographic signals (e.g., third and fourth plethysmographic signals associated with third and fourth wavelengths), the system may include additional input channels for receiving the additional plethysmographic signals. Additional multipliers are also included. The additional multipliers are operable to receive the additional plethysmographic signals and additional scalar multiplication factors as respective inputs and output additional products comprising the respective additional plethysmographic signals multiplied by the respective additional scalar multiplication factors. The summer is then operable to receive as inputs thereto not only the first and second products, but also the additional products as well, and compute the sum of all of the products to output the composite plethysmographic signal.

[0018] These and other aspects and advantages of the present invention will be apparent upon review of the following Detailed Description when taken in conjunction with the accompanying figures.

DESCRIPTION OF THE DRAWINGS

[0019] For a more complete understanding of the present invention and further advantages thereof, reference is now made to the following Detailed Description, taken in conjunction with the drawings, in which:

[0020] **FIG. 1** is a block diagram illustrating one embodiment of an exemplary pulse oximeter within which the plethysmographic signal processing method and system of the present invention may be implemented;

[0021] **FIG. 2** is a flow chart illustrating the steps of one embodiment of a plethysmographic signal processing method in accordance with the present invention;

[0022] FIGS. **3**A-B are plots of exemplary complex signal vectors and complex transformation vectors formed in the steps of the plethysmographic signal processing method of **FIG. 2**;

[0023] **FIG. 4** is a block diagram illustrating one embodiment of a plethysmographic signal processing system in accordance with the present invention;

[0024] **FIG. 5** shows an exemplary look-up table having pairs of first and second multiplication factors cross-referenced with corresponding incremental R values; and

[0025] **FIG. 6** is a plot of exemplary infrared plethysmographic and red plethysmographic signals and a composite signal obtained therefrom by a plethysmographic signal processing system in accordance with the present invention.

DETAILED DESCRIPTION

[0026] Referring to **FIG. 1**, there is shown an exemplary pulse oximeter **10** within which the plethysmographic signal processing method and system of the present invention may be implemented. The pulse oximeter **10** is configured for use in determining one or more blood analyte levels in a patient tissue site **12**. However, the plethysmographic signal processing method and system of the present invention may be implemented in any device wherein plethysmographic signals are utilized to obtain desired information therefrom.

[0027] The pulse oximeter **10** includes two light signal emitters **20***a-b* (e.g., light emitting diodes or laser diodes) for emitting two light signals **22***a-b* centered at different predetermined center wavelengths λ_1, λ_2 through the patient tissue site **12** and on to a detector **24** (e.g., a photo-sensitive diode). The center wavelengths λ_1, λ_2 required depend upon the blood analytes to be determined. For example, in order to determine the levels of O2Hb and RHb, λ_1 may be within the infrared region of the electromagnetic spectrum (e.g., about 800-950 nm) and λ_2 may within the red region of the electromagnetic spectrum (e.g., about 600-700 nm). If more blood analyte levels are to be measured, the pulse oximeter **10** may include additional light signal emitters for emitting light signals centered at additional wavelengths.

[0028] The light signal emitters **20***a-b* and detector **24** may be included in a positioning device **26** to facilitate alignment of the light signals **22***a-b* with the detector **24**. For example, the positioning device **26** may be of clip-type or flexible strip configuration adapted for selective attachment to the patient tissue site **12**. The positioning device **26** may be part of a probe cable unit **28** that is connectable with a separate monitor unit **30**.

[0029] The light signal emitters **20***a-b* are activated by a corresponding plurality of analog drive signals **32***a-b* to emit the light signals **22***a-b*. The drive signals **32***a-b* are supplied to the light signal emitters **20***a-b* by a corresponding plurality of drive signal sources **34***a-b*. The drive signal sources **34***a-b* may be connected with a digital processor **36**, which is driven with a clock signal **38** from a master clock **40**. The digital processor **36** may be programmed to define modulation waveforms, or drive patterns, for each of the light signal emitters **20***a-b*. More particularly, the digital processor **36** may provide separate digital trigger signals **42***a-b* to the drive signal sources **34***a-b*, which in turn generate the analog drive signals **32***a-b*. The drive signal sources **34***a-b*, processor **36** and clock **40** may all be housed in the monitor unit **30**.

[0030] Transmitted light signals **44***a-b* (i.e., the portions of light signals **22***a-b* exiting the patient tissue site **12**) are detected by the detector **24**. The detector **24** detects the intensities of the transmitted signals **44***a-b* and outputs a current signal **46** wherein the current level is indicative of the intensities of the transmitted signals **44***a-b*. As may be appreciated, the current signal **46** output by the detector **24** comprises a multiplexed signal in the sense that it is a composite signal including information about the intensity of each of the transmitted signals **44***a-b*. Depending upon the nature of the drive signals **32***a-b*, the current signal **46** may, for example, be time-division multiplexed, wavelength-division multiplexed, or code-division multiplexed.

[0031] The current signal **46** is directed to an amplifier **48**, which may be housed in the monitor unit **30** as is shown. The amplifier **48** converts the current signal **46** to a voltage signal **50** wherein a voltage level is indicative of the intensities of the transmitted signals **22***a-b*. The amplifier **48** may also be configured to filter the current signal **46** from the detector **24** to reduce noise and aliasing. By way of example, the amplifier **48** may include a bandpass filter to attenuate signal components outside of a predetermined frequency range encompassing modulation frequencies of the drive signals **32***a-b*.

[**0032**] Since the current signal **46** output by the detector **24** is a multiplexed signal, the voltage signal **50** is also a multiplexed signal, and thus, the voltage signal **50** must be demultiplexed in order to obtain signal portions corresponding with the intensities of the transmitted light signals **44***a-b*. In this regard, the digital processor **36** may be provided with demodulation software for demultiplexing the voltage signal **50**. In order for the digital processor **36** to demodulate the voltage signal **50**, it must first be converted from analog to digital. Conversion of the analog voltage signal **50** is accomplished with an analog-to-digital (A/D) converter **52**, which may also be included in the monitor unit **30**. The A/D converter **52** receives the analog voltage signal **50** from the amplifier **48**, samples the voltage signal **50**, and converts the samples into a series of digital words **54** (e.g., eight, sixteen or thirty-two bit words), wherein each digital word **54** is representative of the level of the voltage signal **50** (and hence the intensities of the transmitted light signals **44***a-b*) at a particular sample instance. In this regard, the A/D converter **52** should provide for sampling of the voltage signal **50** at a rate sufficient to provide for accurate tracking of the shape of the various signal portions comprising the analog voltage signal **50** being converted. For example, the A/D converter **52** may provide for a sampling frequency at least twice the frequency of the highest frequency drive signal **32***a-b*, and typically at an even greater sampling rate in order to more accurately represent the analog voltage signal **50**.

[**0033**] The series of digital words **54** is provided by the A/D converter **52** to the processor **36** to be demultiplexed. More particularly, the processor **36** may periodically send an interrupt signal **56** (e.g., once per every eight, sixteen or thirty-two clock cycles) to the A/D converter **52** that causes the A/D converter **52** to transmit one digital word **54** to the processor **36**. The demodulation software may then demultiplex the series of digital words **54** in accordance with an appropriate method (e.g., time, wavelength, or code) to obtain two digital signal portions indicative of the intensities of each of the transmitted light signals **44***a-b*.

[**0034**] The demultiplexed digital signal portions comprise first and second plethysmographic signals S_1 and S_2 associated with the two separate center wavelengths λ_1, λ_2 (e.g., infrared and red) of the transmitted light signals **44***a-b*. The first and second plethysmographic signals S_1 and S_2 may then be processed to obtain desired information therefrom such as O2Hb and RHb levels in the patient tissue site **12** as well as the patient's heart rate. In this regard, the first and second plethysmographic signals S_1 and S_2 may be processed in accordance with the steps of the plethysmographic signal processing method of the present invention in order to generate a composite plethysmographic signal C having an improved SIN ratio as compared to either of the first and second plethysmographic signals S_1 and S_2. The composite plethysmographic signal C may then be displayed on a display device **58** of the monitor unit **30** and processed further to obtain the patient's heart rate.

[**0035**] Referring now to **FIG. 2** the steps of one embodiment of a plethysmographic signal processing method in accordance with the present invention are shown. The method begins with step **100** wherein first and second plethysmographic signals S_1 and S_2 are received. In this regard, the plethysmographic signals S_1 and S_2 may be received from the detector of a pulse oximeter probe, either directly or after appropriate amplification and filtering. Typically, the plethysmographic signals S_1 and S_2 will be associated with infrared and red wavelength optical signals transmitted by the probe through a patient tissue site, although plethysmographic signals associated with other wavelength optical signals may be processed in accordance with the steps of the plethysmographic signal processing method described herein.

[**0036**] The infrared and red plethysmographic signals S_1 and S_2 are separately processed to obtain an R value associated therewith. The R value is defined as the ratio of red optical signal absorption in the patient tissue site to infrared optical signal absorption in the patient tissue site and provides information regarding oxygen saturation of hemoglobin in arterial blood circulated through the patient tissue site (higher R values indicate lower oxygen saturation levels). In this regard, the R value may computed as the ratio of a red delta absorption value dA_{Red} to an infrared delta absorption value $dA_{Infrared}$ (i.e. $R=dA_{Red}/dA_{Infrared}$). The delta absorption values dA_{Red}, $dA_{Infrared}$ and the R value depending thereon may, for example, be obtained from the infrared and red plethysmographic signals S_1 and S_2 as described in U.S. Pat. No. 5,934,277 entitled "SYSTEM FOR PULSE OXIMETRY SPO2 DETERMINATION", the disclosure of which is incorporated herein in its entirety.

[**0037**] In step **110**, a complex signal vector S is formed using the received plethysmographic signals S_1 and S_2. The complex signal vector S is formed by treating the first plethysmographic signal S_1 as the real component of the complex signal vector S and treating the second plethysmographic signal S_2 as the imaginary component of the complex signal vector S (i.e., $S=S_1+iS_2$). In this regard, exemplary complex signal vectors S formed from infrared and red plethysmographic signals S_1 and S_2 at a particular instant in time having respective R values of 0.5 (normal oxygen saturation) and 2.0 (low oxygen saturation) are illustrated in FIGS. **3**A-B. In FIGS. **3**A-B, the complex signal vectors S have been normalized to have magnitudes of 1.0 and plotted on a coordinate system where the infrared component of the complex signal vector S corresponds with the real axis and the red component of the complex signal vector S corresponds with the imaginary axis. The slopes of the complex signal vectors S correspond with their respective R values.

[**0038**] In step **120**, first and second scalar multiplication factors T_1 and T_2 are obtained. The first and second scalar multiplication factors T_1 and T_2 are chosen such that multiplication of the complex signal vector S (see step **140**) by a complex transformation vector T formed from the multiplication factors (see step **130**) rotates the complex signal vector S onto the real axis of the coordinate system. In this regard, the first and second scalar multiplication factors T_1 and T_2 depend upon the R value and are given by the following equations:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

[0039] Where the first and second plethysmographic signals S_1 and S_2 are associated with optical signal wavelengths other than infrared and red, the first and second multiplication factors T_1 and T_2 may be given by different equations and depend upon factors other than the R value.

[0040] The first and second scalar multiplication factors T_1 and T_2 may be obtained in several manners. They may be computed as needed using the most recently updated R value in accordance with above equations for T_1 and T_2. Alternatively, pairs of first and second scalar multiplication factors T_1 and T_2 corresponding with various incremental R values can be computed in advance in accordance with the above equations for T_1 and T_2 and stored in a lookup table. When needed, the first and second scalar multiplication factors T_1 and T_2 corresponding with the most recently updated R value are selected from the lookup table.

[0041] In step **130**, a complex transformation vector T is formed using the scalar multiplication factors T_1 and T_2 obtained in step **120**. In this regard, the complex transformation vector T is formed by treating the first scalar multiplication factor T_1 as the real component of the complex transformation vector T and treating the second scalar multiplication factor T_2 as the imaginary component of the complex transformation vector T (i.e., $T=T_1+iT_2$). Exemplary complex transformation vectors T formed using the scalar multiplication factors T_1 and T_2 obtained in accordance with the formulas for T_1 and T_2 described in connection with step **120** using respective R values of 0.5 (normal oxygen saturation) and 2.0 (low oxygen saturation) are illustrated in FIGS. **3**A-B.

[0042] In step **140**, the complex signal vector S is multiplied by the complex transformation vector T to generate a composite plethysmographic signal C. Multiplication of the complex signal vector S by the complex transformation vector T results in rotation of the complex signal vector S onto the real axis of the coordinate system because appropriate scalar multiplication factors T_1 and T_2 have been employed in forming the complex transformation vector T. In this regard, as can be seen for the exemplary complex signal vectors S and complex transformation vectors T illustrated in FIGS. **3**A-B, the complex transformation vectors T are the reflections of the complex signal vectors S across the real axis (i.e., they are the complex conjugates of the complex signal vectors S). Rotation of the complex signal vector S onto the real axis results in a composite plethysmographic signal C which has improved signal strength as compared with either of the first and second plethysmographic signals S_1 and S_2.

[0043] The following two examples illustrate the improvements in signal strength that are obtained by processing the red and infrared plethysmographic signals in accordance with the method of the present invention.

EXAMPLE 1

[0044] In the following example, it is assumed that R=0.5 and that the magnitude of the complex signal vector S is 1.0. Such a situation is representative of a normal (i.e., high SpO_2 saturation) patient. As is illustrated in **FIG. 3**A, the slope of the complex signal vector S formed by combining the infrared and red signals S_1, S_2 has a slope of 0.5 and a length of 1.0. The projection of the complex signal vector S onto the infrared axis is 0.894 and the projection of the complex signal vector S onto the red axis is 0.447. Thus, the infrared signal S_1 has a better S/N ratio than the red signal S_2. The complex signal vector S is rotated into the real axis by multiplying the complex signal vector S by the complex signal transformation vector:

$$\begin{aligned} T &= T_1 + iT_2 \\ &= \frac{1}{\sqrt{1+R^2}} - i\frac{R}{\sqrt{1+R^2}} \\ &= \frac{1}{\sqrt{1+0.5^2}} - i\frac{0.5}{\sqrt{1+0.5^2}} \\ &= 0.894 - 0.447i \end{aligned}$$

[0045] The following result is obtained:

$$\begin{aligned} S*T &= (0.894+0.447i)(0.894-0.447i) \\ &= 0.7992 - 0.3996i + 0.3996i - 0.1998i^2 \\ &= 1.0 \end{aligned}$$

[0046] The result obtained is nearly an 11% increase in signal strength as compared with using the infrared signal by itself.

EXAMPLE 2

[0047] In the following example, it is assumed that R=2.0 and that the magnitude of the complex signal vector S is 1.0. Such a situation is representative of a sick (i.e., low SpO_2 saturation) patient. As is illustrated in **FIG. 3**B, the slope of the complex signal vector S formed by combining the infrared and red signals S_1, S_2 has a slope of 2.0 and a length of 1.0. In this example, the projection of the complex signal vector S onto the infrared axis is now 0.447 and the projection of the complex signal vector S onto the red axis is now 0.894. Here, the red signal S_2 has a better S/N ratio than the infrared signal S_1. The complex signal vector S is rotated into the real axis by multiplying the complex signal vector S by the complex transformation vector:

$$\begin{aligned} T &= T_1 + iT_2 \\ &= \frac{1}{\sqrt{1+R^2}} - i\frac{R}{\sqrt{1+R^2}} \\ &= \frac{1}{\sqrt{1+2.0^2}} - i\frac{2.0}{\sqrt{1+2.0^2}} \\ &= 0.447 - 0.894i \end{aligned}$$

[0048] The following result is obtained:

$$\begin{aligned} S*T &= (0.447+0.894i)(0.447-0.894i) \\ &= 0.1998-0.3996i+0.3996i-0.7992i^2 \\ &= 1.0 \end{aligned}$$

[0049] Here, the result obtained is over a 123% increase in signal strength as compared with using the infrared signal by itself.

[0050] Exemplary System For Implementing Plethysmographic Signal Processing Method

[0051] Referring now to **FIG. 4**, there is shown a block diagram of one embodiment of a system **200** for implementing the plethysmographic signal processing method of the present invention. In configuring the system **200**, it has been recognized that the method of the present invention can be simplified. In this regard, assuming R is correct, it contains only noise and motion and therefore, only the real part of the result obtained when multiplying the complex signal vector S by the complex transformation vector T needs to be computed and the imaginary part of the result can be ignored.

[0052] The system **200** includes an infrared channel **210** for receiving an infrared plethysmographic signal S_1 thereon and a red channel **212** for receiving a red plethysmographic signal S_2 thereon. A first multiplier **214** takes as inputs the infrared signal S_1 received on the infrared channel **210** and a first multiplication factor T_1 and outputs the result of the first multiplication factor T_1 times the infrared signal S_1. A second multiplier **216** takes as inputs the red signal S_2 received on the red channel **212** and a second multiplication factor T_2 and outputs the result of the second multiplication factor T_2 times the red signal S_2. The results output by the first and second multipliers **214**, **216** are directed to a summer **218** which adds the multiplication results together and outputs the composite signal C on an output channel **220** of the system **200**.

[0053] The system **200** may be implemented in analog components, in which case the multiplication and summing operations are performed in continuous time. Alternatively, the system **200** may be implemented using digital technologies (e.g., in software executable by the processor **36** of the monitor unit of a pulse oximeter **10** such as described in connection with **FIG. 1**), in which case the multiplication and summing operations are performed on discrete time samples.

[0054] The first and second multiplication factors T_1, T_2 depend upon the R value and are computed in accordance with the previously described formulas. Since the R value typically changes infrequently, the first and second multiplication factors T_1, T_2 can be computed infrequently (e.g., only when the R value changes) to reduce the computational requirements of the system **200**. Further computational efficiencies can be achieved by computing first and second multiplication factors T_1, T_2 corresponding with a range of incremental R values in advance and storing the pre-computed multiplication factors T_1, T_2 in a lookup table **230** accessible to the system **200** (e.g., on an EPROM chip). In this regard, first and second multiplication factors T_1, T_2 may be pre-computed for R values ranging, for example, from 0.40 to 1.40 in, for example, 0.01 increments (i.e. for R=0.98, 0.99, 1.00, 1.01, 1.02, . . .). **FIG. 5** shows an exemplary look-up table **230** wherein the R values are incremented from 0.0 to 4.0 in equal 0.1 increments. Numerous other R value ranges and increments, equal or unequal, may be utilized depending upon factors such as the amount of precision desired and the amount of memory available for storing the lookup table. When needed, the first and second multiplication factors T_1, T_2 corresponding with the current R value are read from the lookup table. If there are no entries in the lookup table for the current R value, interpolation techniques may be employed or the current R value may be appropriately rounded to obtain the first and second multiplication factors T_1, T_2.

[0055] Plots of exemplary infrared plethysmographic and red plethysmographic signals S_1, S_2 and a composite signal C obtained using a system **200** such as described above implemented in computer software executable by a digital processor are shown in **FIG. 6**. In **FIG. 6** the DC portions (i.e., the non-pulsatile components) of the signals S_1, S_2 and C have been normalized (i.e., set equal to 1.0) to emphasize the AC portions (i.e., the small pulsatile components) of the signals S_1, S_2 and C. As can be seen from **FIG. 6**, the composite signal C generated by the system **200** has a significantly greater peak-to-peak (i.e., high point to low point) amplitude difference than either the infrared or red plethysmographic signals S_1 and S_2 making it easier to perform heart-rate calculations and the like using the composite signal S and making the composite signal S easier to perceive visually on a display.

[0056] While various embodiments of the present invention have been described in detail, further modifications and adaptations of the invention may occur to those skilled in the art. However, it is to be expressly understood that such modifications and adaptations are within the spirit and scope of the present invention.

What is claimed is:

1. A signal processing method for use in plethysmography, said method comprising the steps of:

receiving at least two plethysmographic signals, each plethysmographic signal being associated with a particular wavelength;

multiplying each plethysmographic signal by an associated multiplication factor; and

generating a composite plethysmographic signal comprising a linear combination of the plethysmographic signals by adding the results of the multiplications.

2. The method of claim 1 wherein the multiplication factors are chosen to provide an improved S/N ratio of the composite signal as compared with S/N ratios of the plethysmographic signals over a specified range of SpO_2 levels.

3. The method of claim 2 wherein the specified range of SpO_2 levels is from 40% to 100%.

4 The method of claim 2 wherein the multiplication factors are dependent upon an R value that varies in accordance with an SpO_2 level in arterial blood circulated through a patient tissue site.

5. The method of claim 4 further comprising the step of:

obtaining the multiplication factors from a look-up table comprising sets of multiplication factors cross-referenced with corresponding incremental R values.

6. The method of claim 5 wherein the look-up table includes multiplication factors corresponding with incremental R values ranging from 0.4 to 1.4.

7. The method of claim 6 wherein the R values in the look-up table are incremented in equal increments, the increments being between 0.001 and 0.1.

8. The method of claim 4 wherein there are first and second plethysmographic signals and the wavelength associated with the first plethysmographic signal is between 800 and 950 nm and the wavelength associated with the second plethysmographic signal is between 600 and 700 nm.

9. The method of claim 8 wherein a first multiplication factor designated T_1 associated with the first plethysmographic signal is given by the following formula:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

and wherein a second multiplication factor designated T_2 associated with the second plethysmographic signal is given by the following formula:

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

10. The method of claim 9 wherein R is given by the following formula:

$$R = \frac{dA_2}{dA_1}$$

wherein dA_1 and dA_2 comprise differential absorption values obtained from the first and second plethysmographic signals, respectively.

11. The method of claim 1 wherein the plethysmographic signals comprise digital signals including pluralities of signal sample values taken at sequential temporal instances and said steps of multiplying and generating are performed for each temporally corresponding signal sample value.

12. A signal processing method for use in plethysmography, said method comprising the steps of:

receiving first and a second plethysmographic signals S_1 and S_2, the first and second plethysmographic signals S_1 and S_2 being associated with first and second wavelengths, respectively;

forming a complex signal vector S, wherein S is given by $S=S_1+iS_2$;

forming a complex transformation vector T from first and second scalar multiplication factors T_1 and T_2, wherein T is given by $T=T_1+iTd_2$; and

multiplying the complex signal vector S by the complex transformation vector T to generate a composite plethysmographic signal C.

13. The method of claim 12 wherein the scalar multiplication factors T_1 and T_2 are dependent upon an R value, wherein the R value varies in accordance with an SpO_2 level in arterial blood circulated through a patient tissue site.

14. The method of claim 13 further comprising the step of:

obtaining the scalar multiplication factors T_1 and T_2 from a look-up table comprising a plurality of pairs of scalar multiplication factors T_1 and T_2 cross-referenced with corresponding incremental R values.

15. The method of claim 14 wherein the look-up table includes multiplication factors T_1 and T_2 corresponding with incremental R values ranging from 0.4 to 1.4.

16. The method of claim 15 wherein the R values in the look-up table are incremented in equal increments, the increments being between 0.0001 and 0.1.

17. The method of claim 13 wherein the first scalar multiplication factor T_1 is given by the following formula:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

and wherein the second scalar multiplication factor T_1 is given by the following formula:

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

18. The method of claim 17 wherein R is given by the following formula:

$$R = \frac{dA_2}{dA_1}$$

wherein dA_1 and dA_2 comprise differential absorption values obtained from the first and second plethysmographic signals S_1 and S_2, respectively.

19. The method of claim 12 wherein the first and second plethysmographic signals S_1 and S_2 are digital signals including pluralities of signal sample values taken at sequantial temporal instances and said steps of multiplying and generating are performed for each temporally corresponding signal sample value.

20. The method of claim 12 wherein the first and second plethysmographic signals S_1 and S_2 are associated with infrared and red wavelengths, respectively.

21. A plethysmographic signal processing system comprising:

a first input channel for receiving a first plethysmographic signal thereon, said first plethysmographic signal being associated with a first wavelength;

a second input channel for receiving a second plethysmographic signal thereon, said second plethysmographic signal being associated with a second wavelength;

a first multiplier operable to receive the first plethysmographic signal and a first scalar multiplication factor as inputs and output a first product comprising the first plethysmographic signal multiplied by the first scalar multiplication factor;

a second multiplier operable to receive the second plethysmographic signal and a second scalar multiplication factor as inputs and output a second product comprising the second plethysmographic signal multiplied by the second scalar multiplication factor;

a summer operable to receive the first and second products as inputs and add the first and second products to output a composite signal comprising the sum of the first and second products.

22. The system of claim 21 wherein said first channel, said second channel, said first multiplier, said second multiplier, and said summer are implemented in software executable by a digital processor.

23. The system of claim 21 wherein said first channel, said second channel, said first multiplier, said second multiplier, and said summer comprise analog components.

24. The system of claim 21 wherein the first and second scalar multiplication factors are dependent upon an R value, wherein the R value varies in accordance with an SpO_2 level in arterial blood circulated through a patient tissue site.

25. The system of claim 24 further comprising:

a look-up table including a plurality of pairs of first and second scalar multiplication factors cross-referenced with corresponding incremental R values.

26. The system of claim 25 wherein said look-up table includes pairs of first and second multiplication factors corresponding with incremental R values ranging from 0.4 to 1.4.

27. The system of claim 26 wherein the R values in said look-up table are incremented in equal increments, said increments being between 0.001 and 0.1.

28. The system of claim 25 wherein the first scalar multiplication factor designated T_1 is given by the following formula:

$$T_1 = \frac{1}{\sqrt{1+R^2}}$$

and wherein the second multiplication factor designated T_2 is given by the following formula:

$$T_2 = -\frac{R}{\sqrt{1+R^2}}$$

29. The system of claim 28 wherein R is given by the following formula:

$$R = \frac{dA_2}{dA_1}$$

wherein dA_1 and dA_2 comprise differential absorption values obtained from with the first and second plethysmographic signals, respectively.

30. The system of claim 21 wherein the first and second plethysmographic signals are associated with infrared and red wavelengths, respectively.

31. The system of claim 21 further comprising:

at least one additional input channel for receiving at least one additional plethysmographic signal thereon, said at least one additional plethysmographic signal being associated with at least one additional wavelength; and

at least one additional multiplier operable to receive said at least one additional plethysmographic signal and at least one additional scalar multiplication factor as inputs and output at least one additional product comprising said at least one additional plethysmographic signal multiplied by said at least one additional scalar multiplication factor;

said summer being operable to receive the first, second, and at least one additional products as inputs and add the first, second, and at least one additional products together to output a composite signal comprising the sum of the first, second, and at least one additional products.

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专利名称(译)	体积描记信号处理方法和系统		
公开(公告)号	US20030073890A1	公开(公告)日	2003-04-17
申请号	US09/975289	申请日	2001-10-10
[标]申请(专利权)人(译)	HANNAĐALAN		
申请(专利权)人(译)	HANNA D. ALAN		
当前申请(专利权)人(译)	HANNA D. ALAN		
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发明人	HANNA, D. ALAN		
IPC分类号	A61B5/00 A61B5/024		
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摘要(译)

本发明提供了一种体积描记信号处理方法和系统，其实现了改善的S / N比，从而改善了患者心率估计并改善了体积描记波形显示。可以使用脉冲血氧计内的模拟和/或数字组件来实现本发明的体积描记信号处理方法和系统。在一个实施例中，分别与第一和第二波长（例如，红外和红色）相关联的第一和第二体积描记信号S1，S2在第一和第二通道210,212上被接收。第一和第二乘法器214,216将第一和第二乘法器214,216相乘。第二和第二乘法因子T1，T2的第二体积描记信号S1，S2。求和器218对来自第一和第二乘法器214,216的乘积求和，以在输出通道220上输出复合体积描记信号C.然后可以显示和/或利用复合体积描记信号C来进行心率确定等。