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(71) Applicant and
(72) Inventor: **BERNREUTER, Peter** [DE/DE]; Hintere Str. 60, 73265 Dettingen u. Teck (DE).

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(54) Title: TISSUE OXIMETRY APPARATUS AND METHOD

(57) Abstract: An apparatus and method for determining tissue oxygenation such as arterial and venous oxygenation and cerebral oxygenation. In one embodiment, the optical properties of tissue are determined using measured light attenuations at a set of wavelengths. By choosing distinct wavelengths and using light attenuation information, the influence of variables such as light scattering, absorption and other optical tissue properties can be minimized.

TISSUE OXIMETRY APPARATUS AND METHOD

RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Patent Application No. 11/780,997, filed on July 20, 2007.

TECHNICAL FIELD

[0002] The present invention relates to a process and apparatus for improving accuracy of optical measurements of oxygenation of blood in tissue.

BACKGROUND OF THE INVENTION

[0003] A standard method to measure the arterial oxygenation of blood is known as pulse oximetry. Pulse oximeters function on the basis that at differing wavelengths, blood attenuates light very differently depending upon the level of oxygenation. Pulse waves starting from the heart cause in the arterial blood vessel system a periodic fluctuation in the arterial blood content in the tissue. As a consequence, a periodic change in the light absorption (Figure 1) can be registered between the light transmitter, whose radiation passes through the tissue, and the receivers, which are integrated in a pulse oximetry sensor. The evaluation of the sensor signals is normally carried out at light wavelengths of w1=660 and w2=940 nm by calculating the differential change of light absorption. It is possible to create a measured variable R which is obtained in the following manner or in a similar manner:

[0004] Eq: (1) $$R = Rw1,w2 = \frac{\Delta(LAw1) = \ln(Imax, w1) - \ln(Imin, w1)}{\Delta(LAw2) \quad \ln(Imax, w2) - \ln(Imin, w2)}$$

[0005] The light intensities described in the formula represent the light intensities received in the receiver of the sensors used in pulse oximetry. The measured variable R serves as a measurement for the oxygen saturation. The formation of a quotient in order to form the measured variable is intended to compensate for any possible influences the haemoglobin content of the tissue, the pigmentation of the skin or the pilosity may have on the measurement of the oxygen saturation of arterial blood. The difference of the light attenuations at a minimum and maximum value is the delta of the light attenuations for each of both wavelengths.

[0006] Measuring oxygen saturation of arterial blood in the tissue in a range of 70 to 100% using light of wavelength 940 nm and 660 nm most often produces for one single application site sufficiently accurate measured values. However, in order to measure lower oxygen saturation of arterial blood it is necessary to assume a strong influence on the measured variable R in particular caused by perfusion (i.e. blood content) (see: IEEE; Photon Diffusion Analysis of the Effects of Multiple Scattering on Pulse Oximetry by J. M. Schmitt; 1991) and other optical parameters of tissue.

[0007] US Patent No. 5,529,064 to Rall, describes a fetal pulse oximetry sensor. For this kind of application, a higher measurement precision is desirable because a fetus has a physiological lower oxygenation than adult human beings and measurement error of SaO2 increases at low oxygenations.

[0008] US Patent No. 6,226,540 to Bernreuter, incorporated by reference herein, improves the precision of pulse oximetry. However, in order to measure on different body sites with the same high resolution for the arterial oxygenation, additional precision to measure optical tissue properties is necessary. Another problem is that pulse oximetry alone does not provide sufficient diagnostic information to monitor critically ill patients (See: When Pulse Oximetry Monitoring of the Critically Ill is Not Enough by Brian F. Keogh in Anesth Analg (2002), 94:96-99).

[0009] Because of this it would be highly desirable to be able to additionally measure the mixed venous oxygenation of blood SvO2. Methods to measure SvO2 with NIR were described by Jöbsis in US Patent No. 4,223,680 and by Hirano et al in US Patent No. 5,057,695. A problem of those disclosed solutions is that hair, dirt or other optically non-transparent material on the surface of tissue can influence the measured results for SvO2.

[0010] To measure the metabolism of blood oxygenation, Anderson et al in US Patent No. 5,879,294 disclose an instrument in which the second derivative of the light spectrum used delivers information about the oxygenation. Hereby, the influence of light scattering in tissue is minimized, which can result in higher measurement precision. A disadvantage of this solution is that the calibration of the optical instruments is complicated and expensive, which makes it impractical to use such devices for sports activity applications, where light weight wearable devices would be of interest. Similar problems are known for frequency domain spectroscopy disclosed for example in Gratton, US Patent No. 4,840,485. Oximetry devices, which are described in the present specification and which simply measure light attenuations of tissue at different wavelengths, are more feasible, flexible and reliable in practice than complex time resolved methods..

BRIEF SUMMARY OF THE INVENTION

[0011] The present invention is directed to an apparatus and method which eliminate influences on calibration by subtracting and adding measured light attenuations, and a model-based calibration calculation to improve precision of measured output variables. In one embodiment, an apparatus utilizes a combination of light emitters and detectors with a light wavelength combination of more than two wavelengths, where the peak spectrum of a third wavelength is about the geometric mean value of the first and second wavelengths.

[0012] As a result, influences on the calibration of different tissue properties can be minimized in order to measure arterial or venous or the combination of arterial and venous oxygenation. It has been discovered that by choosing one of the wavelengths as a

geometric mean value of two other wavelengths, variations due to scattering can be reduced. Additional determination of light attenuation can reduce measurement errors because of variations of light absorption due to different tissue composition, i.e., variations of relative amounts of muscle, skin, fat, bone, etc.

[0013] The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawing, in which:

[0015] Figure 1 is a graph showing changes of light absorption by blood over time;

[0016] Figure 2 is a graph illustrating the dependency of arterial oxygen saturation on the measurement variable R for different optical tissue properties;

[0017] Figure 3 shows a reflectance oximetry sensor according to the invention in schematic cross-section;

[0018] Figure 4 shows a finger clip sensor according to the invention in schematic cross-section;

[0019] Figure 5 is a diagram of a multidimensional calibration of oxygenation for the two measuring variables R1, R2 vs. SaO2;

[0020] Figure 6 is a schematic diagram of an oximetry system in operation;

[0021] Figure 7 is a side view of a fetal scalp sensor according to the invention;

[0022] Figure 8 is a bottom view of the sensor of Figure 7;

[0023] Figure 9 is a bottom view of the sensor of Figure 3;

[0024] Figure 10 is a side cross-sectional view of a variation of the sensor of Figure 3;

[0025] Figure 11 is a side cross-sectional view of another variation of the sensor of Figure 3;

[0026] Figure 12, Figure 12A-12D is a bottom view of the sensor of Figure 11and several variations of emitter detector position on sensor interface;

[0027] Figures 13, 13B and 14 are side cross-sectional views of reflectance sensors fixed on the forehead;

[0028] Figure 15 shows a system for determining cardiac output;

[0029] Figure 16 shows person with wrist worn display and sensor interface with sensor applications on different sites of the body, two sensor interfaces for each hemnisphere of brain placed on the forehead;

[0030] Figure 17 is a schematic diagram of a hardware processing unit for an oximetry system according to the invention with detector ground shield and elastic isolating layer towards tissue;

[0031] Figure 18 is a diagram of a multidimensional calibration of oxygenation for the two measuring variables Rv1, Rv2 vs. SvO2; and

[0032] Figure 19 is a flow chart illustrating signal processing flow for a model-based determination of oxygen in blood.

DETAILED DESCRIPTION OF THE INVENTION

[0033] It is noted that as used in the present specification, "venous" and "mixed venous" may be synonyms, "attenuation" may refer to absolute or differential attenuation, "tissue oxygenation" may refer to arterial, mixed venous, or venous oxygenation or a combination of thereof, and the phrase "about" in reference to wavelengths may quantify in a band of +/- 80 nm and in reference to distances quantifies in a band of +/- 1 cm and that emitter corresponds to emitting point that means an area where light of at least one wavelength emitted by the sensor interface starts penetrating tissue, weighted values for light attenuations can have a value of one ore different values, the pulsatile part of a light attenuation corresponds to the AC signal of pulse oximetry and the non-pulsating part to the DC signal.

[0034] The diagram of Figure 1 shows the fundamental effect on which pulse oximetry and comparable methods to determine arterial blood oxygenation are based. When measuring light absorption of tissue in vivo light absorption changes synchronously with every heart cycle. The diagram illustrates the change of light absorption versus time, which is caused by arterial pulsations that can be measured while systole and diastole. During systole and diastole the pressure on the arterial vessel system varies from 80 mmHg to 120 mmHg. The change of light absorption is called the AC-signal. The DC-signal, the time-invariant part of light absorption, is caused by the non-pulsating part of the arterial blood, the

venous blood, bone, hair, tissue and other constant absorbing constituents versus time. The time-invariant signal is the basis for the calculation of the mixed venous oxygenation of tissue; thus, a major part of the absorption is caused by venous blood and a minor part by arterial blood.

[0035] Figure 2 shows two calibration curves in a diagram with SaO2 vs. R. Calibration line 42 is only valid for a first distinct set of optical properties. Calibration line 40 is only valid for a second distinct set of optical properties. The valid set of optical properties can be determined by an optical system illustrated in Figures 3 and 6 with a sensor 31S, which is placed on tissue 46 and connected via a plug 66 to a display device 64. Additionally, Figure 2 shows two horizontal lines at SaO2=0.6 and at SaO2=0.4 and one vertical line at R=1.4. If an optical system determines only R without registering the two different sets of optical properties, this would result in an error of 0.2 SaO2 (SaO2 at first set of optical properties - SaO2 at second set of optical properties). An analogous relation also exists for the mixed venous saturation of blood SvO2 and a measurement variable Rv1 and Rv2 for mixed venous oxygenation (Figure 18).

[0036] Figure 3 shows an oximetry sensor 31S on the upper part of the figure which is placed on tissue 46. The sensor 31S contains two light emitters 31E, 32E and two light detectors 31D, 32D. The arrows A1 through A4 show how light passes from emitters to detectors through tissue. A1 stands representative for light which is emitted in emitter 31E and received in detector 31D. A2 is light emitted in emitter 32E and detected in detector 31D. A3 is light emitted in 31E and received in 32D and A4 is light emitted in emitter 32E and detected in detector 32D.

[0037] Figure 4 shows a finger clip sensor 54 which is fixed on a finger 48. The finger clip sensor incorporates emitters 31E, 32E and detectors 31D, 32D. The electrical sensor signals of the finger clip sensor are transmitted via a sensor cable 60. The signals can also be conveniently transmitted wirelessly by means well known in the art (not shown).

[0038] Figure 5 illustrates a multidimensional calibration of SaO2 vs. R1 and R2. A certain combination of R1 and R2 corresponds to a data point on the calibration plane, which indicates the saturation level SaO2. An analogous relation also exists in Figure 18 for the mixed venous saturation of blood SvO2 and two related measurement variables Rv1 and Rv2 for mixed venous oxygenation.

[0039] Figures 7 and 8 show a fetal scalp sensor 74 with a set of emitters 31E, 32E, 33E and 34E and a set of detectors 31D, 32D, 33D and 34D from side and bottom views, respectively. The sensor can be fixed on the scalp of the fetus via a spiral needle 76 during labor. Additionally, an electrocardiogram (ECG) of the fetus can be transmitted via the needle 76.

[0040] Figure 9 is a bottom view of sensor 31S from Figure 3. Detectors 35D and 36D have a concentric form to maximize reception of light emitted by the emitters 31E and 32E.

[0041] Figures 10–12 show several modifications of sensor 31S. Figure 10 shows sensor in side view with a flat body where detectors 31D, 32D and the emitter 32D are grouped close together and emitter 32E is positioned far from this group. The sensor can be fixed via a band 108 on tissue. A light shield 110 minimizes the influence of ambient light.

[0042] Figure 11 shows a sensor with a sensor holder 122.

[0043] Figure 12 is a bottom view of sensor of Figure 11. The bottom side of sensor holder 122 can be covered with medical glue or adhesive. If sensor holder 122 is placed on sensor 31S according to Figure 11 and applied to tissue 46, fixation is possible by glue on sensor holder 122. Sensor holder 122 can be constructed as inexpensive and disposable. Alternatively, the bottom side of the sensor, which is applied to tissue, can be directly covered with glue. The disadvantage of this is that the sensor can not be reused. The heart rate is detected via ECG-electrode 123 which contacts the skin. Figure 12 A shows a sensor where the emitters 31E and 132E are placed close and a first detector 31D1 is

positioned near and a second 32D is positioned far towards the emitters. Figure 12B is a slight modification of Figure 12B showing a sensor where detector 31D1 is positioned in one line with the emitters 31E and 132E. In Figure 12C instead of detector 31D1 tow detectors 31D1 and 31D2 are illustrated. Figure 12D is a modification of Figure 12C showing that detectors 31D1 and 31D2 can be placed in various topologies on the sensor interface – here close to the emitters 31E and 132E.

[0044] Figures 13, 13B and 14 show variations of sensor 32S applied on the forehead of a person. In the first variation shown in Figure 13 and 13B, sensor 32S is fixed via a band 108 to the forehead. The arrows A32 and A42, which represent how light travels from the emitters 31E, 32E to the detectors 31 and 32D, pass through forehead tissue 152 and bone of skull 150 and pass or touch brain 148. The arrows A12 and A22 only pass through forehead tissue 152 and bone of skull 150. A difference of Figure 13 and Figure 13B is that in Figure 13 the detectors 31D and 32D are positioned in close proximity whereas in Figure 13B the emitters are placed in close proximity.

[0045] The second variation of sensor 32S also applied on the forehead is shown in Figure 14. The arrows A11, A21, A31 and A41 compared with arrows A12, A22, A32 and A42 of Figure 13 show that by variation of the position of light detectors and emitters, oxygen content can be sensed differently without changing the outline of the sensor variation used.

[0046] Figure 15 shows a patient lying on a bed being supplied with oxygen by an intubation tube 210, and an anesthesia machine 204. The anesthesia machine 204 is connected to the patient and has an inventive device for measuring oxygen consumption or carbon dioxide production of the patient. The sensor 32S is placed on the forehead of the patient, and is connected with oxygen extraction monitoring device 206, which calculates SaO2 and SvO2 and oxygen extraction. The monitoring device 206 and the anesthesia machine 204 are linked to a third device 202, which calculates cardiac output or trend of cardiac output.

[0047] Figure 16 illustrates the use of oxygen monitoring at different application sites e.g. for sports activity or other medical applications, in which a wrist worn display device 220 can receive oxygenation data from a forehead-band-sensor with sensor interfaces 214 and 215 for both hemispheres of brain, from a chest-band-sensor 224, from an arm-band-sensor 218 or a special variation of this the wrist band with sensor interface 221 or from a finger-glove-sensor 222.

[0048] Figure 17a shows the hardware for evaluating oxygenation by using two emitters 31E and 32E and two detectors 31D and 32D. The LED-drive 226 energizes the two emitters via lines 238, 248 which can incorporate coding hardware, to adjust calibration for the multidimensional calibration or to adjust calibration for varying emitter detector geometry. The amplifiers AMP1 232 and AMP2 234 are connected to detectors 31D and 32D. The demultiplexer DEMUX 320 selects each wavelength used in every emitter timed synchronously according to the switching state of the LED-DRIVE 226 and delivers the measured data via an AD-Converter AD-CONV 236 to the CPU 228. The sensor interfaces comprises an isolating layer 239 towards the patient which may consist of elastic material. The light detectors 31D and 32D are shielded with a grounded layer 233 which is connected to a ground line 235. The ground shield can consist for example of an electrical conductive layer or metallic grid. Figure 17b depicts a cross-sectional view of sensor 240.

[0049] Figure 19 illustrates the signal flow of a model-based calibration. An input processing circuit 260 is the first part of the signal flow. The processing circuit is connected with a circuit for calculating light attenuations 262 and a circuit calculating different measurement variables 264. The calculation for light attenuations 262 is a basis for a model-based determination circuit for mixed venous oxygenation 266 with a joint circuit to output a value for the mixed venous oxygenation SvO2 270. A model-based determination circuit for arterial oxygenation 268 is connected to the circuit for calculating light attenuations 262 and the circuit calculating different measurement variables 264. The output

value for a arterial oxygenation circuit for SaO2 272 is linked to the model-based calculation for SaO2 268.

[0050] By using three instead of two wavelengths to measure the arterial oxygenation, the following approximation can be derived with the help of diffusion theory. The result of this operation is:

[0051] eq. (2) $$R' = \frac{Rw2,w1}{Rw1,w0} * \frac{LAw2*LAw0 + Q}{LAw1*LAw1}$$

[0052] where Rw2,w1 and Rw1,w0 are calculated according to equation (1) using wavelengths w0, w1, and w2 and Q is a correction parameter.

[0053] Light attenuation LAwx can be calculated in the following or similar manner:

[0054] eq. (3) $$LAwx = \ln(Iwx/Iwxo)$$

[0055] LAwx corresponds to the logarithm of the ratio of light intensity Iwxo which is the emitted and light intensity Iwx the received light passing through tissue at wavelength wx. The index following suffix wx indicates the selected wavelength. Graaff et al showed that scattering in tissue decreases for higher wavelengths according to exponential functions (see: Applied Optics; Reduced Light-Scattering Properties for Mixtures of Spherical Particles: A Simple Approximation Derived from Mie Calculations by R. Graaff; 1992). LAwx corresponds to the logarithm of the ratio of light intensity Iwxo which is the emitted and light intensity Iwx the received light passing through tissue at wavelength wx. The index following suffix wx indicates the selected wavelength.

[0056] Graaff et al showed that scattering in tissue decreases for higher wavelengths according to exponential functions (see: Applied Optics; Reduced Light-Scattering Properties for Mixtures of Spherical Particles: A Simple Approximation Derived

from Mie Calculations by R. Graaff; 1992). Absorption variation may also be taken from other measures or approximations such as the ac/dc ratio. The amplitude may be any measure such as peak-to-peak, RMS, average, or cross correlation coefficient. It may also be derived from other techniques such as Kalman filtering or a measure of the time derivative of the signal. Also, while calculations utilizing ratios of absorptions at different wavelengths are shown, alternate calculations may be used to give the same or approximately the same results. For instance the absorptions could be used directly, without calculating the ratios.

[0057] A preferred selection of the wavelengths combination to reduce the influence of scattering is defined by the following equation, with wavelength w1 as the geometrical mean value of wavelength w0 and wavelength w2, defined as:

[0058] eq. (4) $w1 = SQRT(w0 * w2)$

[0059] This combination minimizes the variation band of correction parameter Q, which has a default value of about one. The measurement variable R' of equation (2) has minimized error related to variation of scattering and blood content of tissue.

[0060] EXAMPLE 1

[0061] The sensor 31S shown in Figure 3 is used to determine the arterial oxygenation and the mixed venous blood oxygenation of tissue with improved precision. Equation (2) is used to provide a measurement variable R' for the arterial oxygenation. For each of the emitters 31E and 32E, three wavelengths are defined. Initially, two measurement wavelengths w0 = 940 nm and w2 = 660 nm are selected. Using equation (4) the third wavelengths w1 is about 788 nm. Wavelength w1 = 805 nm is chosen because it is close to the calculated third wavelength and is additionally at an isobestic point of the blood absorption spectrum. The next step is to determine the resulting light attenuation LA for each of the three wavelengths w0, w1 and w3:

[0062] eq. (5) $LAw1 = LA(A3w1) + LA(A2w1) - LA(A1w1) - LA(A4w1)$

[0063] eq. (6) $LAw2 = LA(A3w2) + LA(A2w2) - LA(A1w2) - LA(A4w2)$

[0064] eq. (7) $LAw3 = LA(A3w3) + LA(A2w3) - LA(A1w3) - LA(A4w3)$

[0065] where LA(Axwy) is the logarithm of received light intensity in the detector related to light arrow Ax at wavelength wy. The suffix x for light arrows Ax represents the number of the selected light arrow and y the suffix for the selected wavelength. Instead of the logarithm of light intensities, light intensity itself can be used in eq. (5)-(7) and "+" is replaced by "*" and "-" is replaced by "/".

[0066] In the next step, Rw2,w1 and Rw1,w0 are calculated according to equation (1). As a result R' can be determined using equation (2) with Q as a correction factor which can be dependant on Rw2,w1 or Rw1,w0. The measured arterial oxygenation which is dependant on R' has minimized influence of scattering, blood content or other optical absorbing constituents in tissue.

[0067] The quotient in (8) which is part of (2) delivers a measurement variable Rv':

[0068] eq. (8) $$Rv' = \frac{LAw2 * LAw0}{LAw1 * LAw1}$$

[0069] Rv' is a measure of optical absorption of tissue with decreased influence of scattering. Therefore it can be used as a signal for mixed venous oxygenation SvO2.

[0070] A mathematically identical form of (2) is:

[0071] eq. (9) $$R' = \frac{w2,w0 * Rv' + Q}{Rw1,w0 * Rw1,w0}$$

[0072] According to eq. (9) the following equation can also be used to determine a measurement variable R1' for SaO2:

[0073] eq. (10) $$R1' = \frac{Rw2,w0 * f(1, Rv', Q)}{Rw1,w0 * Rw1,w0}$$

[0074] where f is an empirical function of optical tissue parameters with variables defined above.

[0075] An empirical calibration which reduces influence of absorption and scattering of tissue on the measured variables with the variables LAw1, LAw2, LAw3, Rw1,w2 and Rw2,w3 for the whole saturation range of blood is complex. An pure empirical calibration based on these parameters additionally for different application sites is probably impossible. The proposed model-based method reduces complexity of calibration. SaO2 can be determined with improved accuracy being only dependent on R'.

[0076] It is also possible to use this method for other light absorbing constituents of blood like carboxyhemoglobin, methemoglobin, bilirubin or glucose dissolved in blood. Light wavelength in the range from 600 nm – 1000 nm can be used for carboxyhemoglobin and methemoglobin. Glucose shows an absorption peek dissolved in blood at 1100 nm and bilirubin in the lower wavelengths range from 300 nm – 800 nm. For every additional constituent an additional wavelengths has to be chosen. That means that to measure SaO2 and methemoglobin at a time, four wavelength have to be selected and two different measurement variables R'1 and R'2 according equation (9) have to be defined. Accordingly, the resulting output for SaO2 is dependent on R'1 and methemoglobin on R'2.

[0077] As a result sensor 31S is able to measure arterial and mixed venous oxygenation and other blood constituents at a time with reduced influence of measurement errors due to scattering and absorption of tissue.

[0078] EXAMPLE 2

[0079] In Figure 4 finger clip sensor 54 is shown with the two emitters 31E, 32E and the two detectors 31D and 32D. The benefit of the finger clip sensor is that it is easy to apply. Equivalent to sensor 31S in Figure 3, four representative light paths between the two emitters and the two detectors are possible so that all calculations according example 1 can be performed in order to calculate the output variables R' and Rv' as a measure for mixed venous and arterial oxygenation in the finger 48. The corresponding calculations can also be performed using sensor of Figure 9. The difference here is the alternative form of detectors 35D and 36D, which are able to increase detected light intensity due to an enlarged, concentric detector area.

[0080] EXAMPLE 3

[0081] Figure 5 shows a multidimensional calibration of SaO2 vs. R1 and R2. R1 and R2 can be calculated according (1) by selecting two wavelengths pairs where for the first wavelengths pair the wavelengths wm1=660 nm and wm2 = 910 nm is chosen and for the second wavelengths pair wm3 = 810 nm and wm2 = 910 nm. The second wavelengths pair is less sensitive towards arterial oxygenation and is used to compensate errors due to optical tissue parameter variations. In order to guarantee that the multidimensional calibration delivers improved precision in presence of varying tissue parameters, it is important to select exactly the correspondent calibration which is specified for a distinct wavelengths set and a distinct detector emitter distance. Therefore additional information has to be coded to the selected sensor. The tissue oximeter device can read out this information and use the appropriate calibration. The coding of information can be achieved for example by a resistor implemented in the LED drive line of the sensor (see Figure 17: 248, 238). A grounded shield plane 233 between an isolating layer 239 and the light sensing elements 31D an 32D is useful to minimize the electrical interference and noise. The isolating layer can also be used to decouple forces e.g. for wrist worn devices 220 with and integrated sensor interface to control the forces of sensor interface on tissue which can have

influences on sensor precision. Also an elastic wrist band 221 can help to decrease this influence.

[0082] A variant of a multidimensional calibration (Figure 5) can be achieved by calculating R1 according to equation (2) and R2 according to equation (8). This minimizes the error of displayed arterial oxygenation SaO2 due to varying optical tissue absorption.

[0083] EXAMPLE 4

[0084] In Figure 7 a fetal pulse oximetry sensor 74 is shown, which punctures the skin on the head of the fetus with a spiral needle 76. The bottom view of Figure 8 shows sensor 74 with 4 emitters 31E, 32E, 33E, 34E and four detectors 31D, 32D, 33D, 34D. Apparently, more than four different light paths per selected wavelength between emitters and detectors (is) are possible. This additional information is used to calculate a whole set of resulting light attenuations Lax. For the different light paths it is also possible to compute a set of measurement variables Rx. Generating a weighted mean value (weight can depend on the noise of the related measurement signals) LAm and Rm of the variables LAx and Rx helps to reduce errors due to tissue inhomogenities. To achieve a stable measure for the optical tissue parameters, which are not influenced by locally varying tissue compositions, is important to minimize errors to precisely determine the inputs of model-based parameters.

[0085] EXAMPLE 5

[0086] A brain oximeter is shown in Figure 13 which is positioned on the right side of the forehead of a patient. The cross section of the brain illustrates how four light paths travel through tissue from emitters 31E, 32E to the detectors 31D and 32D, representative for one wavelength. A resulting light attenuation LA can be achieved for each wavelength by adding light attenuations of A32 and A22 and subtracting therefrom the light attentions which are related to A42 and A12. The resulting light attenuation LA is then independent on dirt on emitters or detectors or on degeneration of those parts, which is an

important feature since those sensors can be reused. Three wavelengths are chosen for each of the two emitters 31E and 32E of the sensor in Figure 13 of the brain oximeter: wb1 = 660 nm, wb2 = 740 nm and wb3 = 810 nm.

[0087] The ratio Rvb of the resulting light attentions LAwb2 and LAwb3 is used as a measure for the mixed venous oxygenation. The resulting light attenuation at wavelength wb3 = 810 nm can be used to eliminate the dependency of blood content in tissue of Rvb with a multidimensional calibration of SvO2 vs. Rvb and LAwb3.

[0088] A preferred emitter-detector distance between emitter 32E and detector 31D is greater than 2 cm. In order to contrast brain tissue and overlaying tissues one long light path should have an emitter detector distance of about 4 cm and a shorter one with an emitter detector distance of about 2 cm to distinguish the overlaying structures. The relation of noise on the signal and signal portion related mainly to brain is a good compromise for this application. The longer the distance the emitter detector distance is, the deeper is the penetration depth into the brain. In order to achieve maximum penetration depth at a minimum of sensor outline, the distance between an emitter and a detector should be the maximum distance between all emitters and detectors. Figure 14 shows an example where within the sensor, the two detectors have the maximum distance and the detector and emitter elements are grouped symmetrically with regard to the center of the sensor. The resulting maximum penetration depth of light of A31, A21 is here less than maximum penetration depth of light of A32 of the sensor which illustrated in Figure 13 because the maximum emitter detector distance is also less compared to sensor in Figure 13 at the same total outline of the sensors. Positioning emitters and detectors asymmetrically is therefore the best choice to achieve oxygenation measurements in deep layers of tissue. In Figure 13B emitter 31E is positioned close to emitter 32E. Detector 32D is positioned between detector 31D and emitter 32E. Adding the light attenuation A32 and A22 and subtracting A12 and A42 results in a signal where most of the brain overlaying structures can be contrasted versus brain tissue

and where oxygenation signals can be calculated which are originated for more than 80% from brain tissue and not overlaying structures.

[0089] Figure 12 shows a bottom view of a brain oximetry sensor, in which emitter 31E and detectors 31D and 32D are positioned in a triangle. The light paths between emitter 31E and 31D and between 31E and 32D using the wavelengths wb1 = 660 nm and wb3= 810 nm are determined to evaluate the measurement variables Rp1 and Rp2 which are calculated according to equation (1). The mean value of Rp1 and Rp2 is used as the output value for the arterial oxygenation SaO2. Alternatively, as shown in Figure 12A, the emitters 31E and 32E can be positioned where detectors 31D and 32D are located and detectors 31D and 32D are placed at the location of emitter 31E and 32E in Figure 12. In Figure 12B the detector 31D1 is positioned in between of the emitters 31E and 123E. Adding and subtracting light attenuations of the related light paths between 31D1 and 31E and the light path between 31D1 and 123E minimizes the influences of shallow tissue layers as they cancel out. Figure 12C shows a sensor analogous to Figure 12B. The difference here is that detector 31D1 is replaced by detector 31D1 and 31D2. Adding the light intensities of this two detectors before calculating the light attenuation thereof results that the related attenuation of detector 31D1 and 31D1 for further calculation can be handled like a single detector. According to this emitters 31E and 123D can be positioned closer by avoiding light shunting between detectors 31D1, 31D2 and emitters 31E and123E. Figure 12D shows an alternative position detectors 31D1 and 31D2. In order to monitor the oxygenation balance of brain for both hemispheres a sensor on the right and left side can be used according to the illustration in Figure 16 with sensor interfaces 214, 215.

[0090] EXAMPLE 6

[0091] Referring to Example 5, a brain oximetry sensor was described which is able to determine arterial and mixed venous oxygenation of tissue. These two parameters can be used to calculate the oxygen extraction of tissue. A measure therefore can be the difference of arterial and mixed venous oxygenation. Oxygen extraction reflects how well

tissue is supplied with oxygen, and can additionally be used to calculate the cardiac output or the trend of the cardiac output CaOut non-invasively. Figure 15 shows a patient being supplied with air via an intubation tube 210. The oxygen consumption or CO2 generation is determined within an anesthesia machine 204. Brain oximetry sensor 32S is connected to SaO2 and SvO2 display device 206. The information of device 204 and device 206 is evaluated in a cardiac output monitor 202 in the following or similar manner:

[0092] eq. (11) $$CaOut = \frac{\text{(oxygen consumption per time)}}{SaO2 - SvO2}$$

[0093] EXAMPLE 7

[0094] Knowledge of oxygenation of tissue of parts of the body is of high interest for sports activity monitoring. The oxygenation the muscles of the upper leg or upper arm can reflect the training level for different activities of sport. Figure 16 shows an athlete wearing various sensors which are connected by a line or wirelessly with a wrist-worn-display 220. A sports activity sensor can have the same topology as the above mentioned brain sensor of Figure 12. Emitter-detector distances however vary, depending on desired tissue monitoring depth. Preferred wavelengths to monitor the mixed venous oxygenation are ws1 = 700 nm, ws2 = 805 nm and ws3 = 870 nm. A resulting light attenuation LA is calculated for each wavelength: LWws1, LAws2 and LAws3 with ws1, ws2 and ws3 as index for the selected wavelengths. A measurement variable for the mixed venous oxygenation Rvs is obtained in the following or similar manner:

[0095] eq. (12) $$Rvs = \frac{LAws1 - LAws2}{LAws2 - LAws3}$$

[0096] Less influence of light scattering and absorption of tissue can be achieved for the determination of mixed venous oxygenation in this way.

[0097] A further improvement for better measurement precision can be achieved by generating an output value for the mixed venous oxygenation which is dependant on a multidimensional calibration of SvO2 vs. Rvs and Rv.

[0098] Although the description above contains many specificities, these should not be constructed as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. For example the shape of the emitters can be rectangular, emitters can include LEDs, detectors photodiodes; the shape of the brain sensor can be round; the proposed methods to calculate arterial and mixed venous oxygenation of tissue can be combined in different combinations, signals can be processed by Kalman filters in order to reduce influence of noise caused by motion or other unwanted sources, etc.

[0099] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

CLAIMS

What is claimed is:

1. Apparatus for measuring tissue oxygenation of a patient comprising:

a sensor interface adapted to be coupled to a patient tissue site and including at least one light emitter emitting light into tissue and at least one detector detecting light passing through tissue from said at least one emitter;

a processor for determining light attenuations LAwsj dependant on light detected at a selected wavelength, wsj;

a coupling device for coupling said sensor interface at said tissue site;

a data processor for generating a signal representative of tissue oxygenation based said determined light attenuations; and

a display device displaying a tissue oxygenation level.

2. The apparatus of claim 1 wherein said data processor includes means for generating a signal representative of tissue oxygenation and provides arterial oxygenation information based on pulsating changes of light attenuations.

3. The apparatus of claim 2 wherein said at least one emitter is an LED and said at least one detectors is a photodiode.

4. The apparatus of claim 2 wherein said means for generating a signal representative of tissue oxygenation uses a non-pulsating part of light attenuation in order to improve accuracy of said arterial oxygen information

5. The apparatus of claim 1 wherein said means for generating a signal representative of tissue oxygenation uses a non-pulsating part of light attenuation to determine tissue oxygenation.

6. The apparatus of claim 1 wherein said sensor interface is coupled to a chest band or head band.

7. The apparatus of claim 2 wherein said sensor coupling device is an arm band.

8. The apparatus of claim 7 wherein said armband is a wrist band.

9. The apparatus of claim 7 comprising:

elastic means for controlling a force applied to tissue through the sensor interface.

10. The apparatus of claim 2 wherein said at least one emitter emits light having at least three different wavelengths.

11. The apparatus of claim 2 wherein two determined light attenuations are added and two are subtracted to generate at least one measure related to oxygenation in tissue.

12. The apparatus of claim 2 wherein a pulse or heart rate is additionally determined.

13. The apparatus of claim 1 wherein said display device displays time.

14. An apparatus for measuring tissue oxygenation comprising:

a sensor interface including at least two emitters which emits light into tissue with at least two wavelengths, and at least one detector to receive light passing through said tissue;

a storage device for retaining information of sensor variation within said sensor interface; and

a processor for determining tissue oxygenation using said sensor variation information of said sensor interface.

15. Apparatus according to claim 14 wherein a wavelength emission intensity of at least one of said emitters is compensated for said by said means for calculating.

16. Apparatus according to claim 14 wherein a light emission intensity of at least one of said emitters is compensated for by said means for calculating.

17. Apparatus according to claim 14 wherein a light emission intensity of at least one of said emitters and a wavelength of at least one of said emitters is compensated for by said means for calculating.

18. Apparatus according to claim 17 wherein brain tissue oxygenation is determined using said sensor interface with at least one emitter/detector distance being greater than 3 cm and said sensor interface being provided at one side of a forehead, said apparatus measuring the oxygenation of one brain hemisphere.

19. Apparatus according to claim 18 wherein at least one emitter detector distance is about 1 cm long and a related path can be used to determine a light attenuation or additionally arterial oxygenation by evaluating a pulsatile part of detected light.

20. The apparatus of claim 17 wherein said apparatus performs calculation steps for at least one wavelength wsj of:

calculating light attenuation LA(A1,wsj) of light emitted in a first emitter and received at a first detector;

calculating light attenuation LA(A4,wsj) of light emitted in a second emitter and received at a second detector;

calculating light attenuation LA(A2,wsj) of light emitted in said first emitter and received at said second detector;

calculating light attenuation LA(A3,wsj) of light emitted in said second emitter and received at said first detector; and

computing the optical constitution of the tissue alone which corresponds to a resulting light attenuation LAwsj at said wavelength wsj by weighting and accumulating the light attenuations of LA(A2,wsj) and LA(A3,wsj) and subtracting therefrom the weighted and accumulated light attenuations LA(A1,wsj) and LA(A4,wsj).

21. Apparatus for measuring tissue oxygenation comprising:

a sensor adapted to be coupled to a forehead tissue including at least two light emitters placed apart from each other on said sensor with at least two different wavelengths for each emitter where each emitter has approximately the same wavelengths which emit light into said tissue and at least one detector for detecting light having passed through said tissue, whereby a distance of one said emitters and one of said at least one detector is chosen so that a light path penetrates through the tissue and whereby a distance between at least one emitter-detector pair is more than 20 millimeters;

means for calculating at least two signals which depend on detected light for selected wavelengths wsj for said at least one detector and said at least two emitters, wherein said at least two signals are calculated by adding or subtracting light attenuations;

calculating attenuation corresponding to ln(intensity of steady state light received at the detector) for at least two possible light paths between said at least two light emitters and said at least one detector; and

means for generating an output representative of tissue oxygenation based on the at least said two signals.

22. Apparatus of claim 21 using at least two emitters and at least two detectors whereby for at least two of said wavelengths for each of the wavelengths the corresponding light attenuations for two light paths are added and the corresponding light attenuation for two further light paths are subtracted to generate a measure for said at least two signals.

23. The apparatus of claim 22 comprising:

means for calculating a ratio R indicative of tissue oxygenation in brain whereby said two signals are used.

24. The apparatus of claim 22 comprising:

means for calculating a measure of tissue oxygenation level using three different wavelengths with a multidimensional calibration dependant on attenuations of said three wavelengths or two ratios R based on ratios of light attenuations versus oxygenation.

25. The apparatus of claim 22 comprising:

means for calculating a measure of tissue constituents using additional wavelengths of light.

26. The apparatus of claim 22 wherein a calibration is based on empirical data.

27. The apparatus of claim 22 wherein said sensor includes at least one emitter detector distance of at least 4 cm and a second emitter detector distance of at least 1.5 cm.

28. The apparatus of claim 21 wherein said sensor includes at least one emitter detector distance of at least 4 cm and a second emitter detector distance of at least 1.5 cm.

29. The apparatus of claim 21 wherein at least three of said at least one detector and said at least two emitters are approximately linearly aligned on the sensor.

30. The apparatus of claim 27 where at least 65% of a generated oxygenation signal is originated by brain tissue by adding and subtracting light paths through forehead tissue and brain tissue.

31. Apparatus of claim 28 for monitoring an oxygenation level of brain hemispheres of a subject with a pair of sensors placed on opposites side of the subject's forehead.

32. Apparatus of claim 28 for monitoring an oxygenation level of brain hemispheres of a subject with a pair of sensors placed on opposites side of the subject's forehead where the sensors include LEDs and photodetectors

33. Apparatus of claim 28 wherein an emitter-detector distance of the sensor placed on one side of the forehead to monitor a brain hemisphere is less than 20 mm long.

34. Apparatus of claim 28 having a means to calculate a measure for arterial oxygenation using a light signal related to an emitter-detector pair separated by a distance of no more than 20 mm.

35. The apparatus of claim 21 wherein for at least one wavelength wsj, said apparatus performs a method comprising:

determining a light attenuation LA(A1,wsj) of light emitted in a first emitter and received at a first detector;

determining a light attenuation LA(A4,wsj) of light emitted in a second emitter and received at a second detector;

determining a light attenuation LA(A2,wsj) of light emitted in said first emitter and received at said second detector;

determining a light attenuation LA(A3,wsj) of light emitted in said second emitter and received at said first detector; and

determining a optical constitution of the tissue which corresponds to a resulting light attenuation LAwsj at said wavelength wsj by weighting and accumulating light attenuations of LA(A2,wsj) and LA(A3,wsj) and subtracting therefrom the weighted and accumulated light attenuations LA(A1,wsj) and LA(A4,wsj)

36. The apparatus of claim 21 wherein at least one detector of said sensor includes an electrically isolated isolation layer and a grounded layer between said isolation layer and an area where said light intensity is detected.

37. The apparatus of claim 36 wherein said at least one detector is adapted for use to detect oxygenation of a brain hemisphere.

38. A method of determining tissue oxygenation comprising:

placing at least two detectors and at least two emitters on a tissue surface and determining a resulting light attenuation by adding a light attenuation measured at a first detector emitted by a first emitter, subtracting a light attenuation between said first emitter and a second detector, and further selecting pairs of detectors and emitters and adding or subtracting light attenuations;

subtracting a light attention from said resulting light attenuation for each detector and emitter pair having a light path which terminates at each detector for at least one light attenuation previously added to generate said resulting light attenuation; and

adding and subtracting light attenuations to determin a measure of tissue oxygenation.

39. The method of claim 38 wherein said detectors and emitters are rectangularly spaced.

40. The method of claim 38 wherein said detectors and emitters are spaced so that at least two light paths through tissue between said emitters and detectors are not crossing.

41. The method of claim 38 wherein said detectors and emitters are spaced to provide asymmetry in said light paths.

Fig. 1

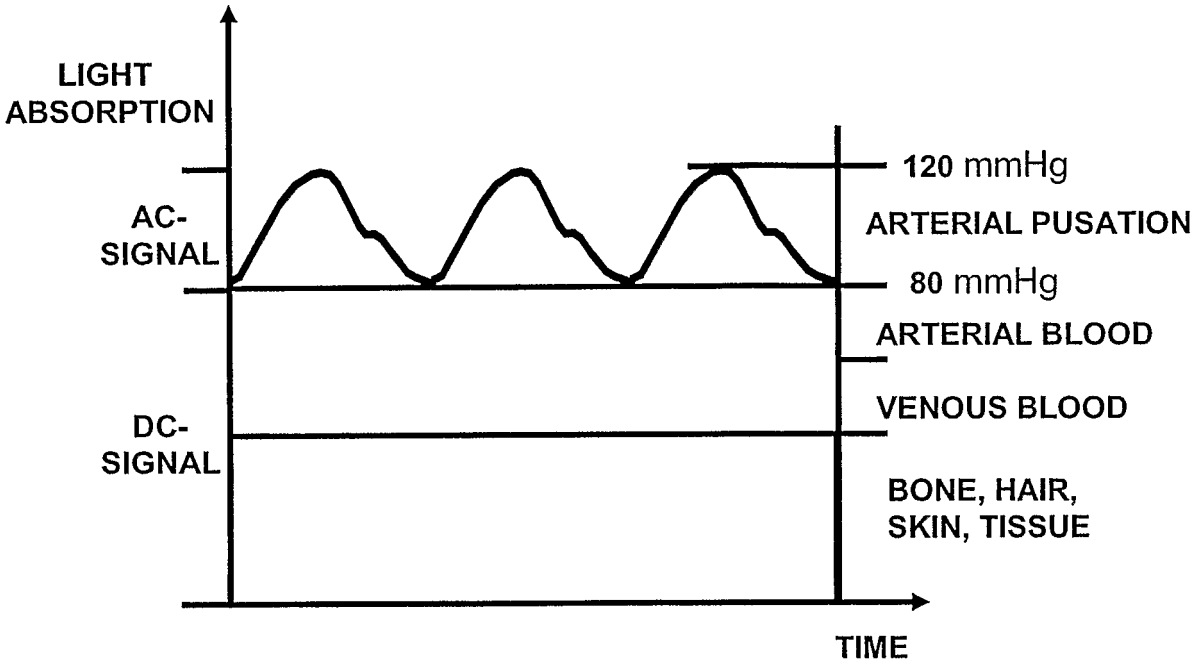

LIGHT ABSORPTION
AC-SIGNAL
DC-SIGNAL
120 mmHg
ARTERIAL PUSATION
80 mmHg
ARTERIAL BLOOD
VENOUS BLOOD
BONE, HAIR, SKIN, TISSUE
TIME

Fig. 2

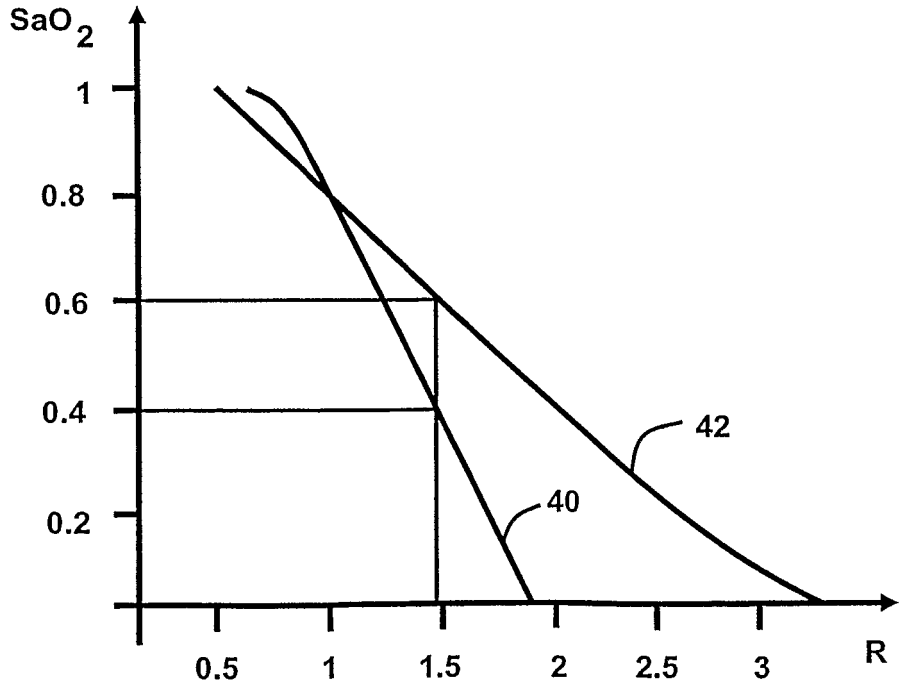

SaO2
1
0.8
0.6
0.4
0.2
42
40
0.5
1
1.5
2
2.5
3
R

Fig. 3

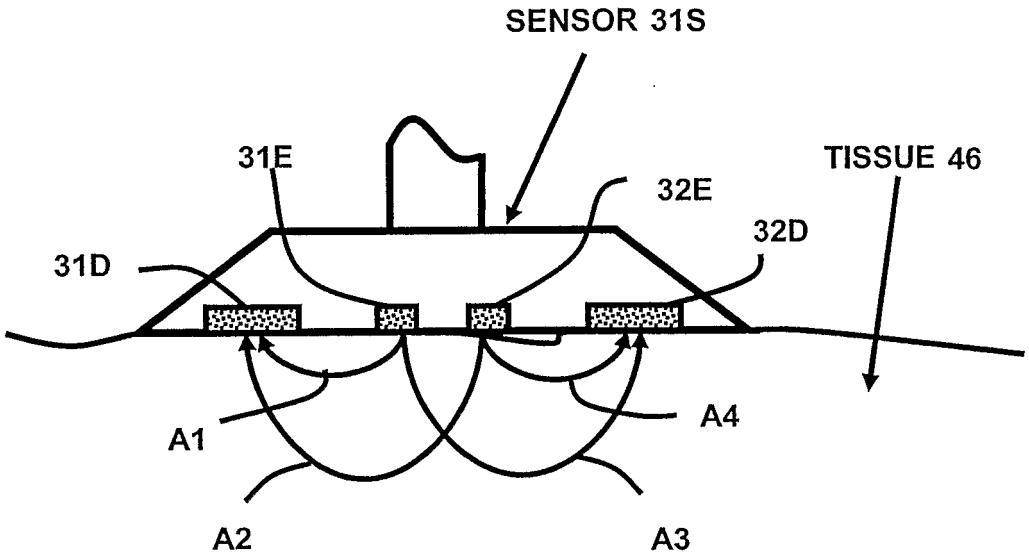

SENSOR 31S
31E
TISSUE 46
32E
32D
31D
A1
A4
A2
A3

Fig. 4

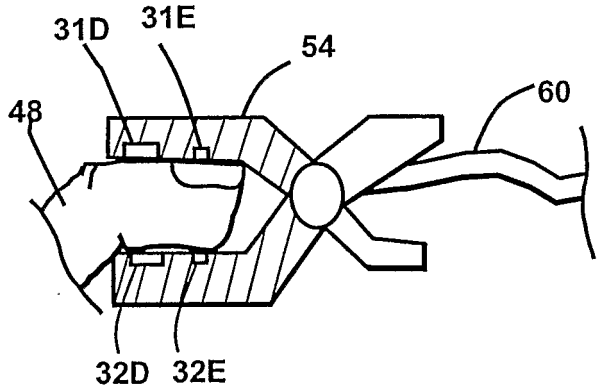

31D
31E
54
60
48
32D
32E

Fig. 5

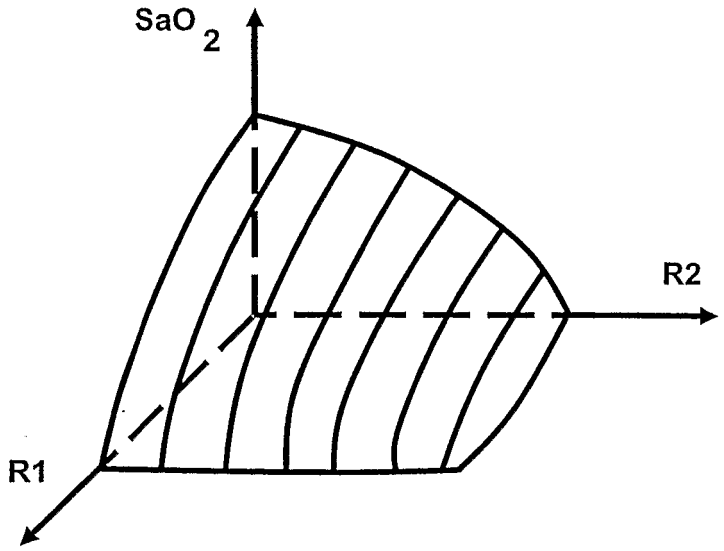


Fig. 6

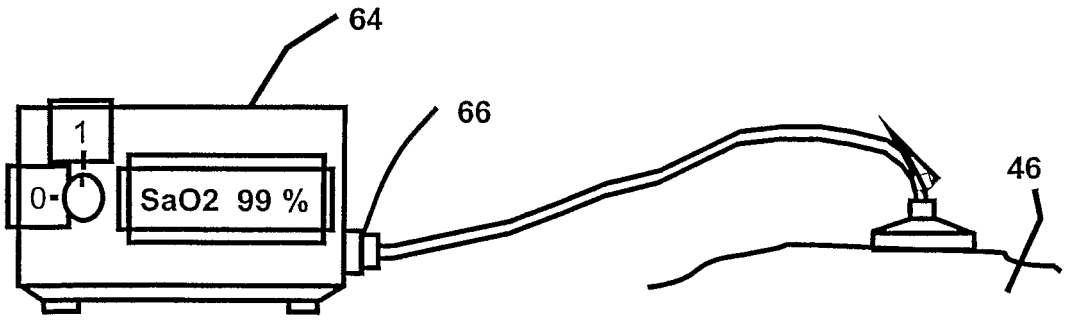


Fig. 7

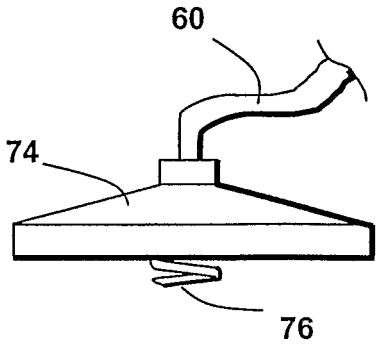


Fig. 8

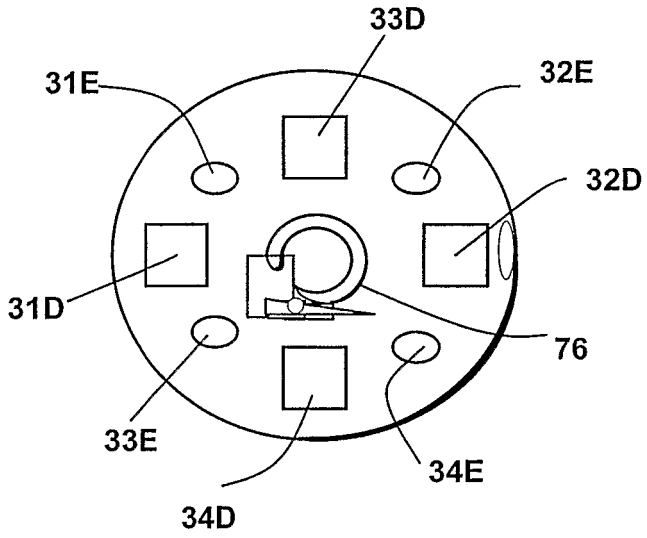


Fig. 9

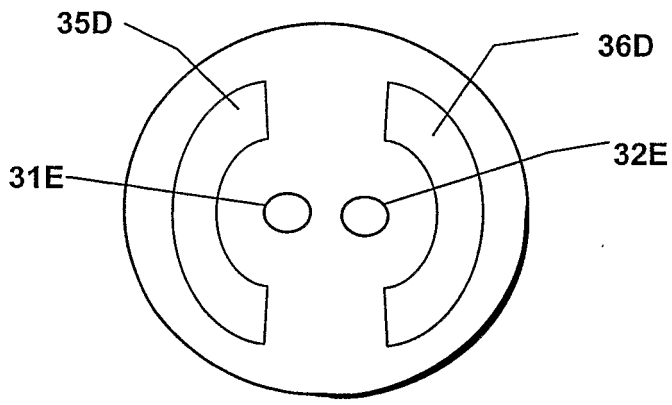


Fig. 10

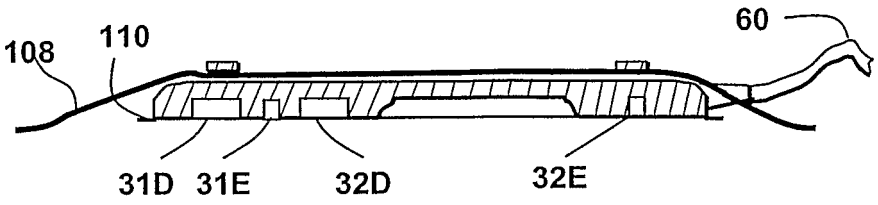


Fig. 11

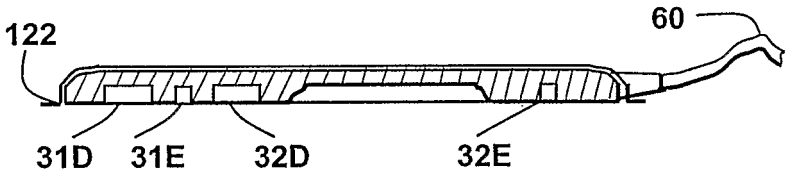


Fig. 12

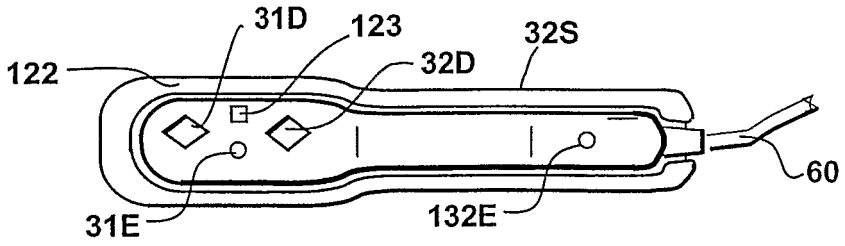


Fig. 12A

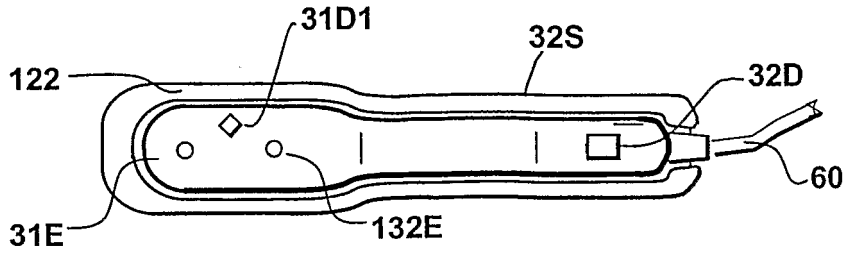


Fig. 12B

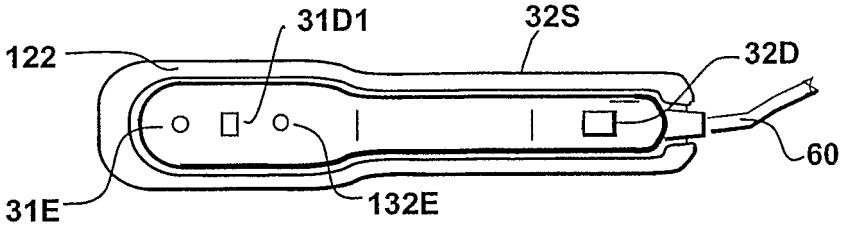


Fig. 12C

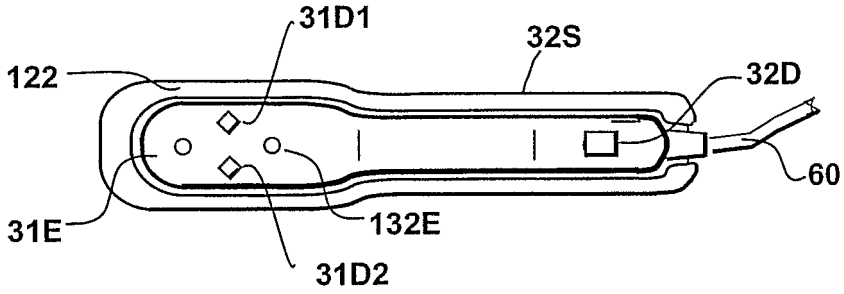


Fig. 12D

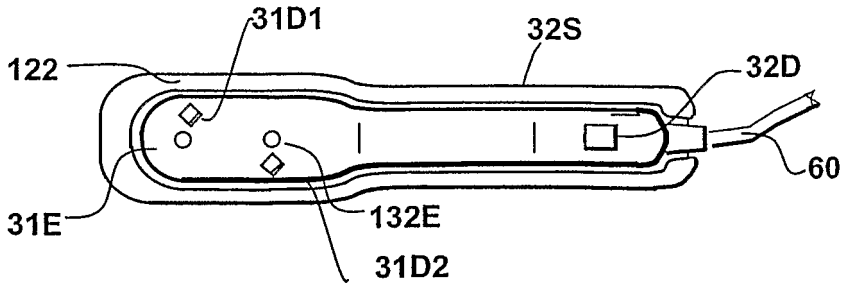


Fig. 13

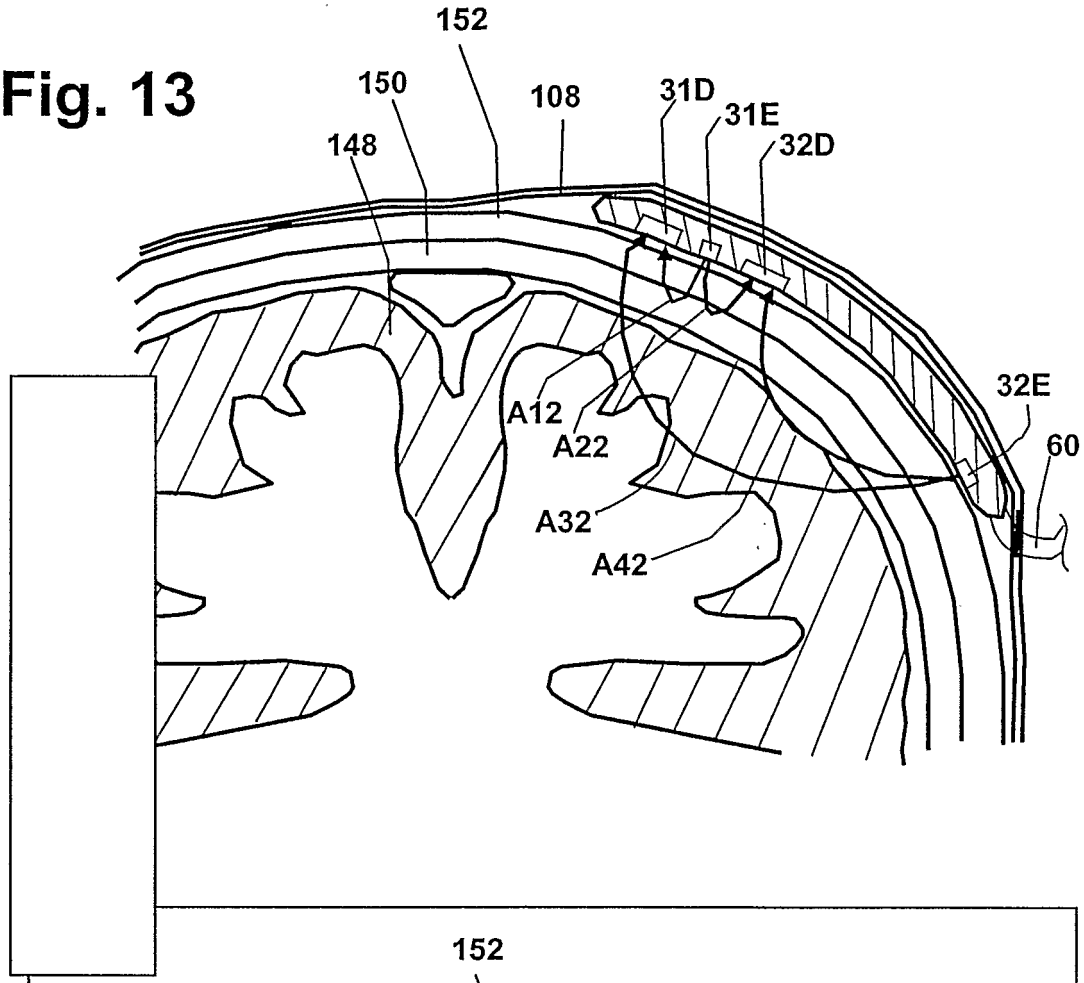


Fig. 13 B

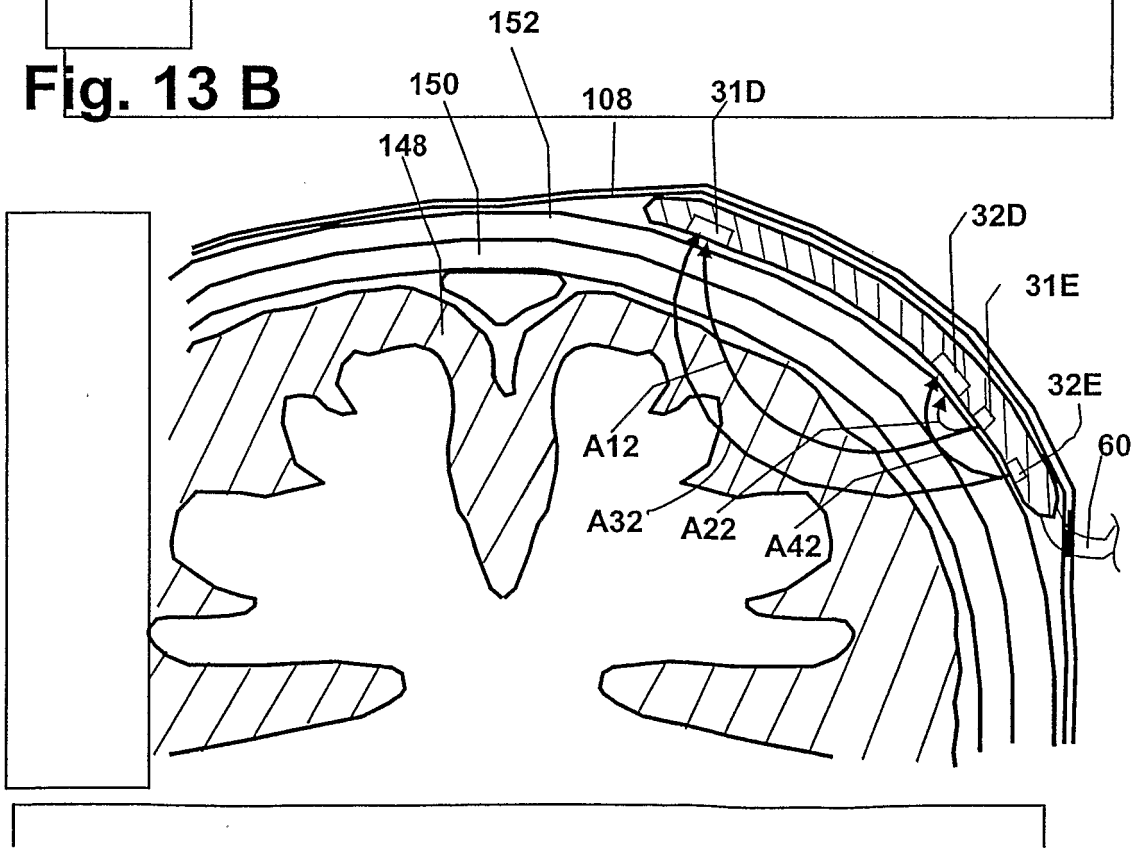


Fig. 14

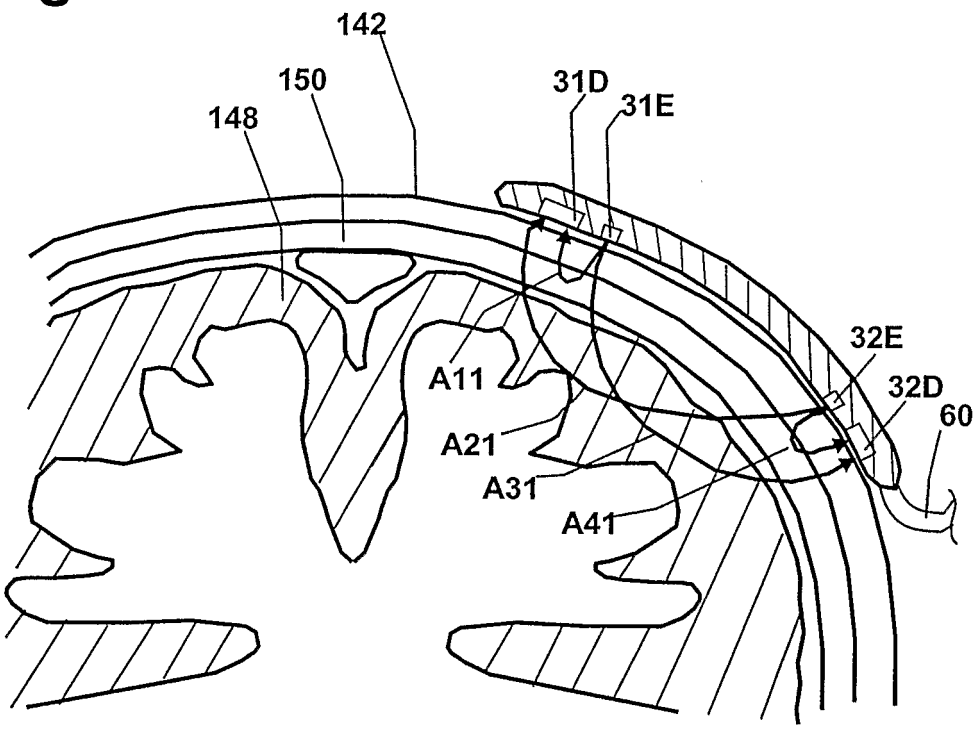


Fig. 15

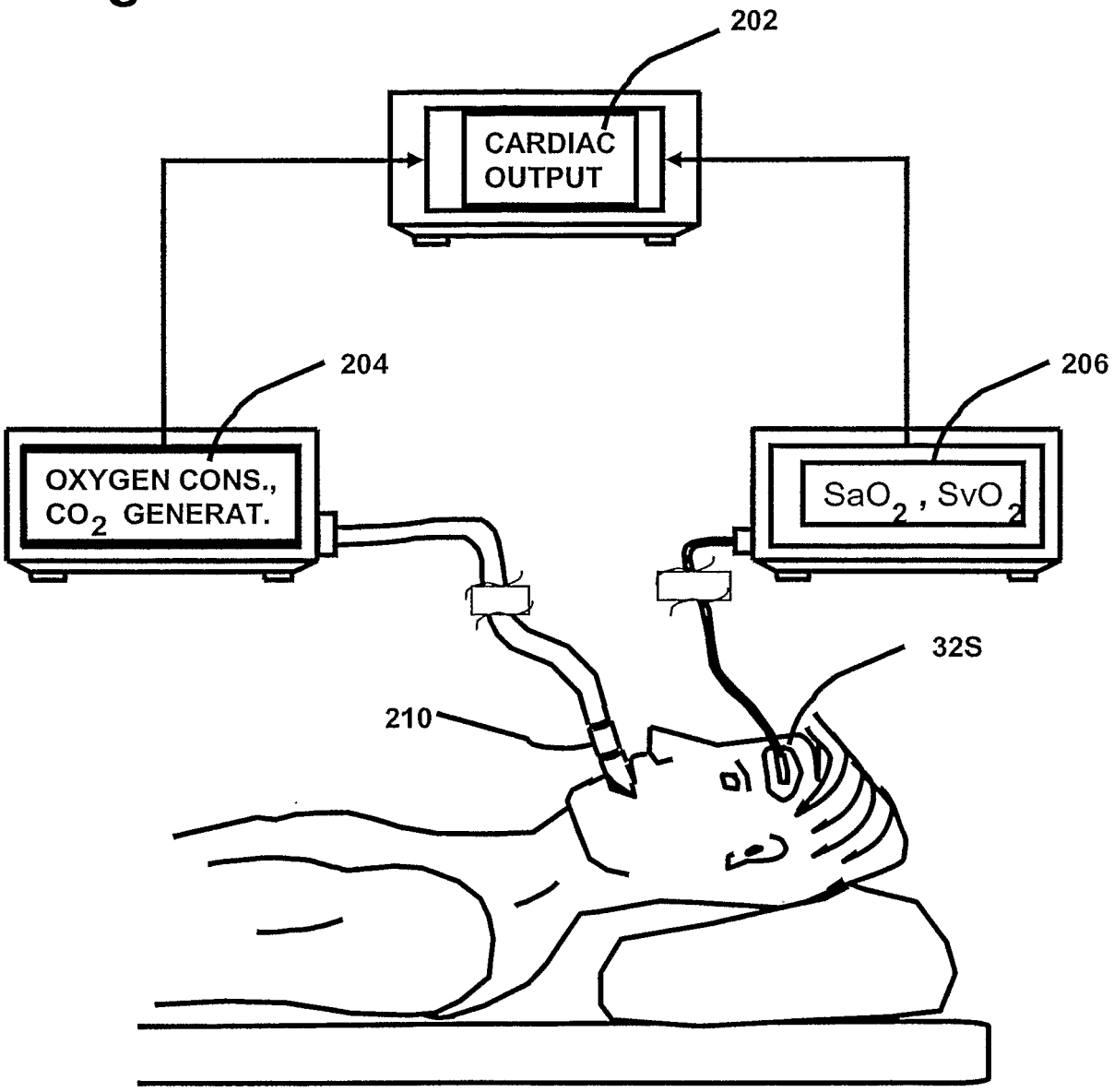

202
CARDIAC OUTPUT
204
206
OXYGEN CONS., CO_2 GENERAT.
SaO_2 , SvO_2
32S
210

Fig. 16

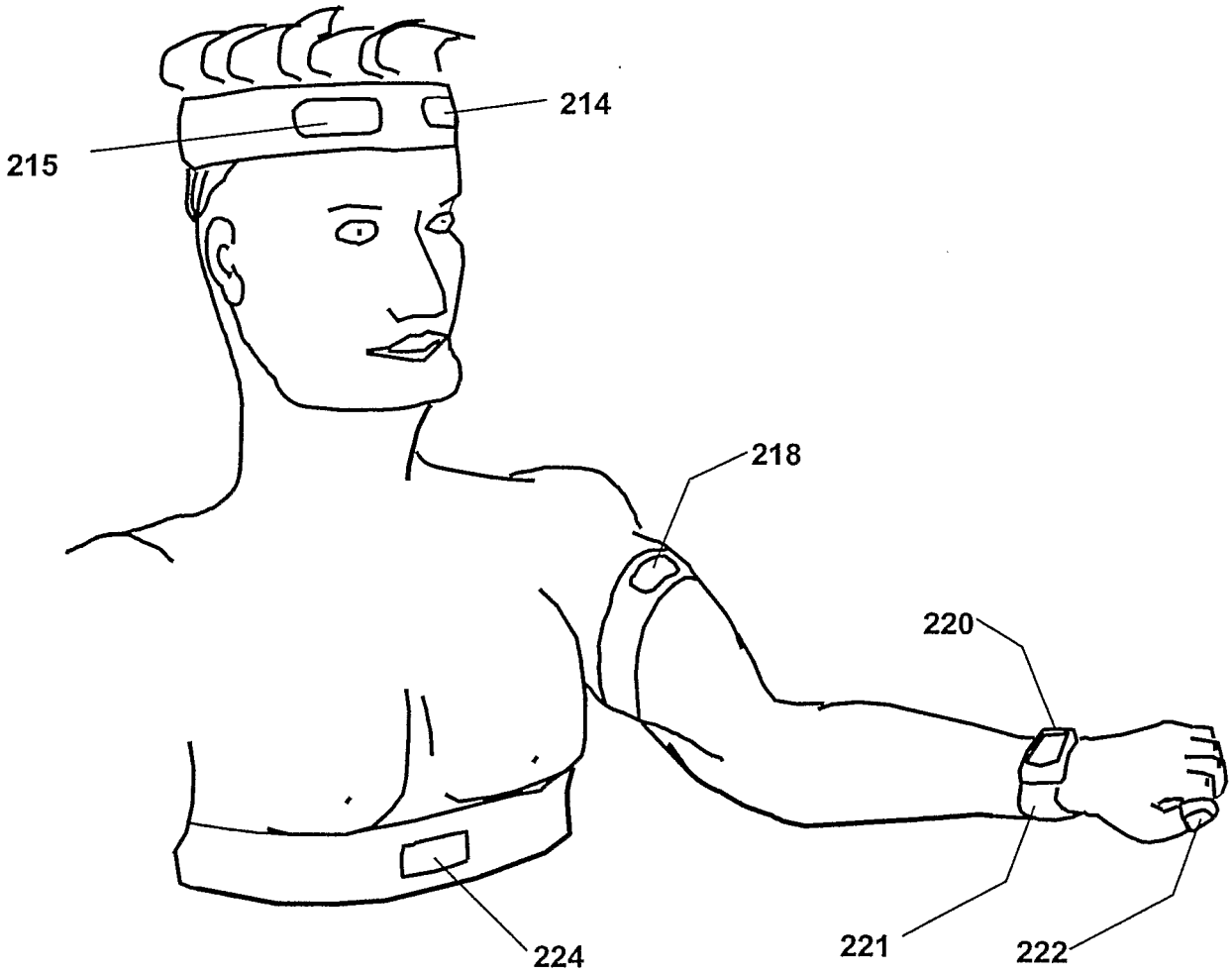


Fig. 17a

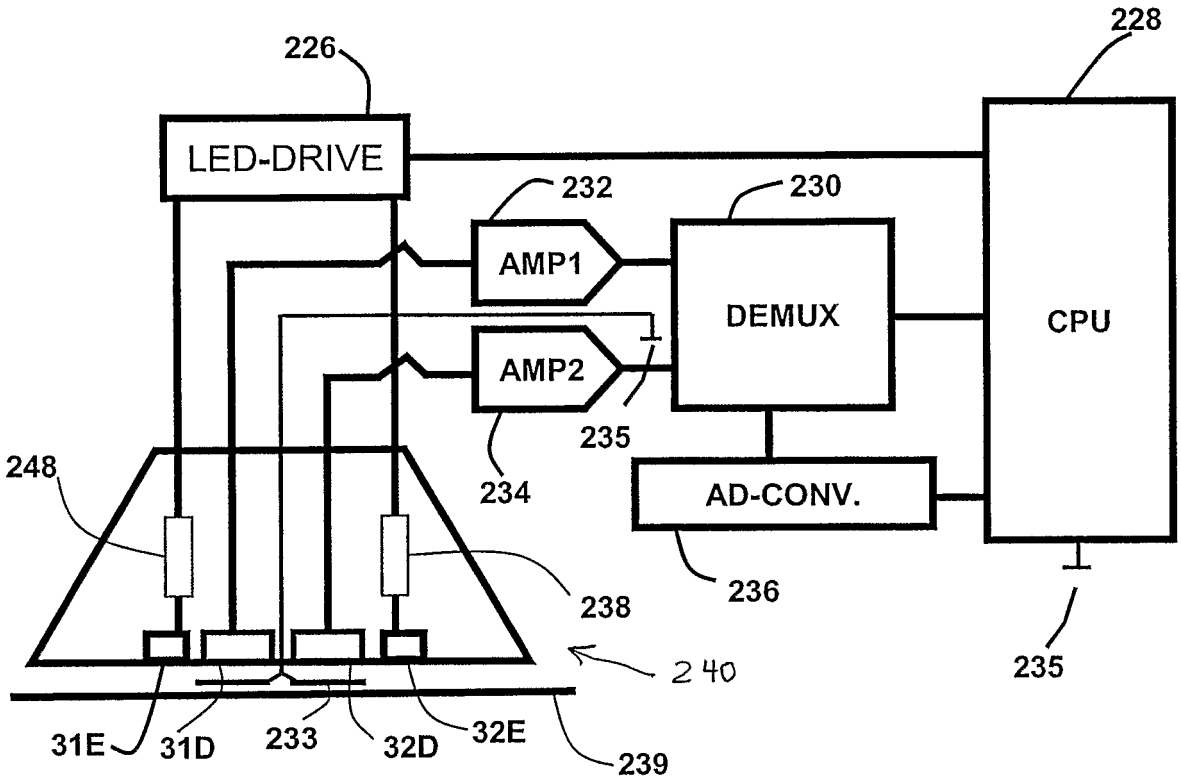


Fig. 18

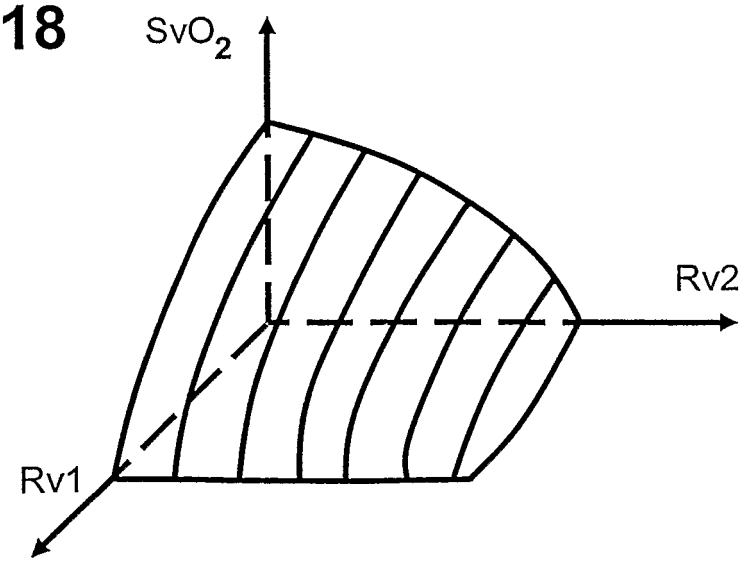


Fig. 17B (side view of sensorpart of Fig. 17)

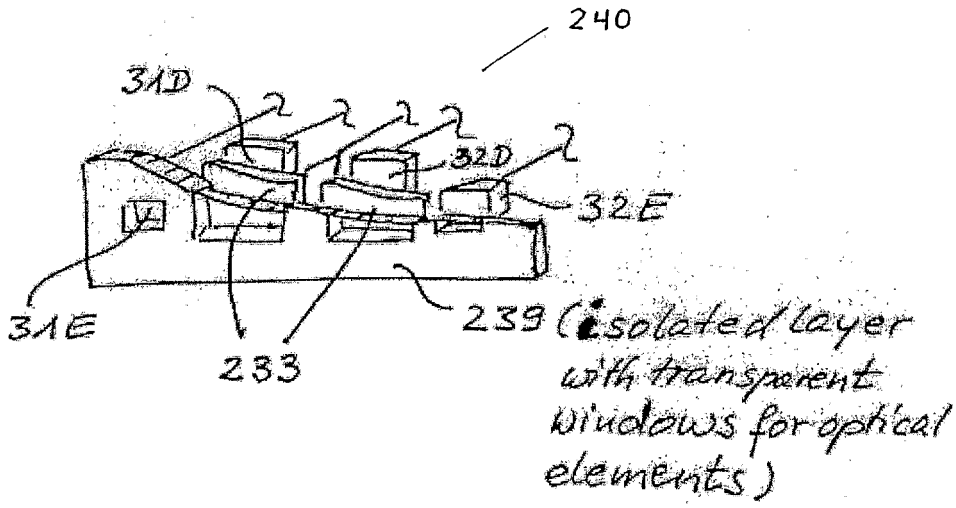
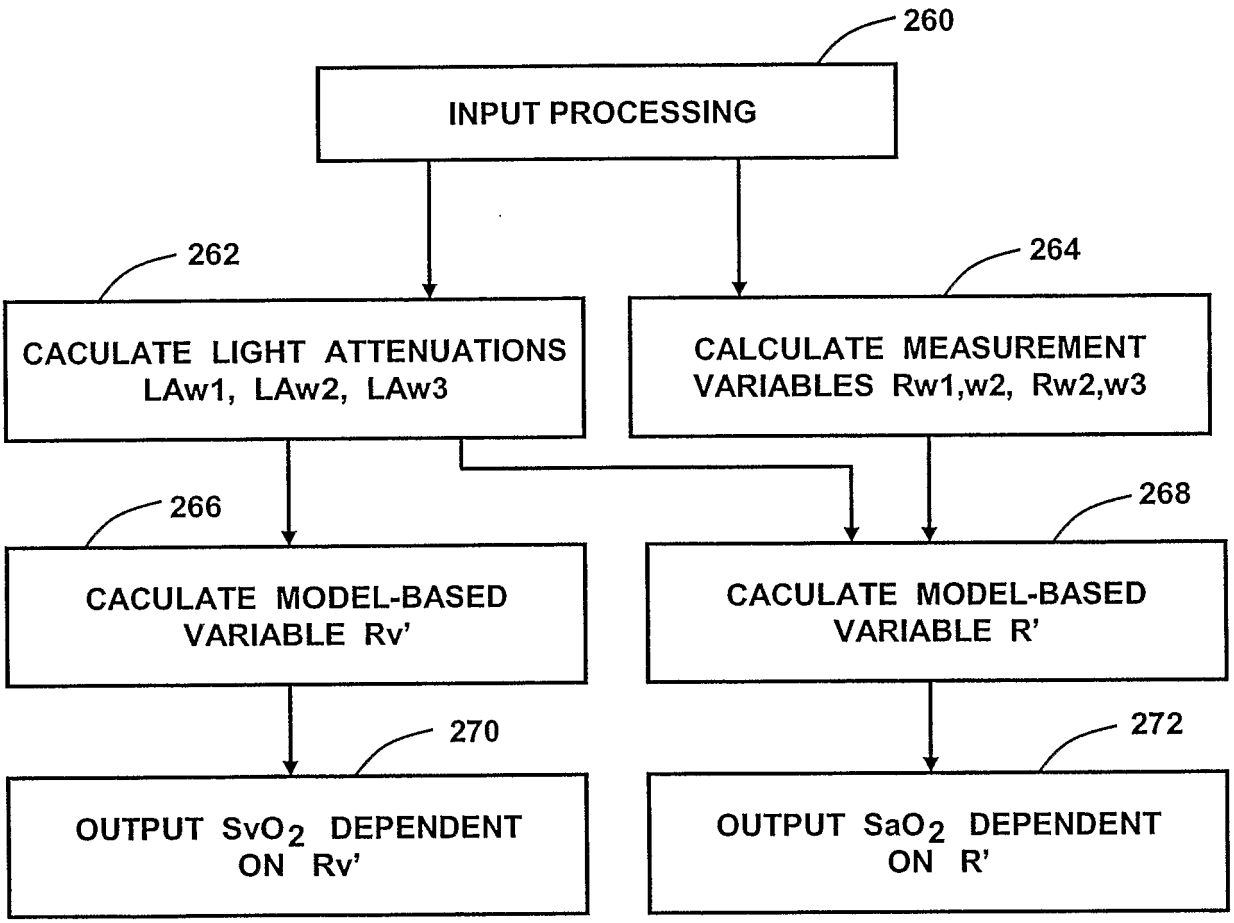


Fig. 19


260
INPUT PROCESSING
262
CACULATE LIGHT ATTENUATIONS LAw1, LAw2, LAw3
264
CALCULATE MEASUREMENT VARIABLES Rw1,w2, Rw2,w3
266
CACULATE MODEL-BASED VARIABLE Rv'
268
CACULATE MODEL-BASED VARIABLE R'
270
OUTPUT SvO2 DEPENDENT ON Rv'
272
OUTPUT SaO2 DEPENDENT ON R'

专利名称(译)	组织血氧测定装置和方法		
公开(公告)号	EP2178438A2	公开(公告)日	2010-04-28
申请号	EP2008788921	申请日	2008-07-21
[标]申请(专利权)人(译)	BERNREUTER PETER		
申请(专利权)人(译)	BERNREUTER，PETER		
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CPC分类号	A61B5/14552 A61B5/14551 A61B5/14553 A61B5/1495 A61B5/72 A61B5/7203 A61B5/742 A61B2560/0238 A61B2562/0238 A61B2562/0242		
优先权	11/780997 2007-07-20 US		
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摘要(译)

一种用于确定组织氧合的装置和方法，例如动脉和静脉氧合和脑氧合。在一个实施例中，使用在一组波长处测量的光衰减来确定组织的光学性质。通过选择不同的波长并使用光衰减信息，可以最小化诸如光散射，吸收和其他光学组织特性的变量的影响。