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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
21 August 2003 (21.08.2003)

PCT

(10) International Publication Number
WO 03/068060 A1

(51) International Patent Classification[7]: A61B 5/00

(21) International Application Number: PCT/FI03/00089

(22) International Filing Date: 4 February 2003 (04.02.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/077,196 15 February 2002 (15.02.2002) US

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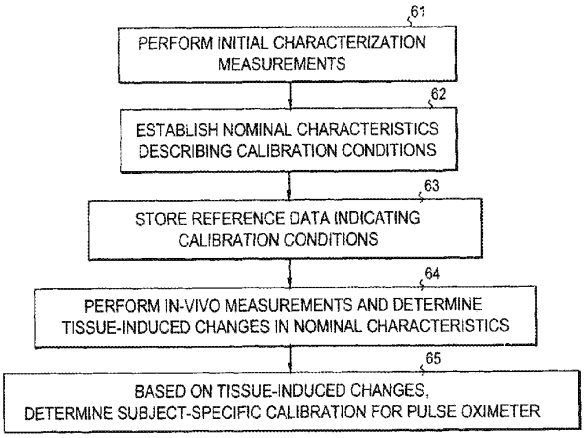
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) **Title:** COMPENSATION OF HUMAN VARIABILITY IN PULSE OXIMETRY



(57) **Abstract:** The invention relates to the calibration of a pulse oximeter intended for non-invasively determining the amount of at least two light-absorbing substances in the blood of a subject. In order to bring about a solution by means of which the effects caused by the tissue of the subject can be taken into account in connection with the calibration of a pulse oximeter, initial characterization measurements are carried out for a pulse oximeter calibrated under nominal conditions. Based on the characterization measurements, nominal characteristics are established describing the conditions under which nominal calibration has been defined, and reference data indicating the nominal characteristics are stored. In-vivo measurements are then performed on living tissue and based on the in-vivo measurements and the reference data stored, tissue-induced changes in the nominal characteristics are determined. Subject-specific variation in the in-vivo measurements is compensated for by correcting the nominal calibration on the basis of the tissue-induced changes.

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COMPENSATION OF HUMAN VARIABILITY IN PULSE OXIMETRY

Field of the Invention

The invention relates generally to pulse oximeters used to detect blood oxygenation. More specifically, the invention relates to a method for taking into account human variability in pulse oximeters. The invention further relates to a sensor allowing compensation for the inaccuracies caused by human variability, the sensor being an integral part of the pulse oximeter.

Background of the Invention

Pulse oximetry is at present the standard of care for continuous monitoring of arterial oxygen saturation (SpO_2). Pulse oximeters provide instantaneous in-vivo measurements of arterial oxygenation, and thereby an early warning of arterial hypoxemia, for example.

A pulse oximeter comprises a computerized measuring unit and a probe attached to the patient, typically to a finger or ear lobe. The probe includes a light source for sending an optical signal through the tissue and a photo detector for receiving the signal after transmission through the tissue. On the basis of the transmitted and received signals, light absorption by the tissue can be determined. During each cardiac cycle, light absorption by the tissue varies cyclically. During the diastolic phase, absorption is caused by venous blood, tissue, bone, and pigments, whereas during the systolic phase there is an increase in absorption, which is caused by the influx of arterial blood into the tissue. Pulse oximeters focus the measurement on this arterial blood portion by determining the difference between the peak absorption during the systolic phase and the constant absorption during the diastolic phase. Pulse oximetry is thus based on the assumption that the pulsatile component of the absorption is due to arterial blood only.

Light transmission through an ideal absorbing sample is determined by the known Lambert-Beer equation as follows:

$$I_{out} = I_{in} e^{-\varepsilon DC}, \quad (1)$$

where I_{in} is the light intensity entering the sample, I_{out} is the light intensity received from the sample, D is the path length through the sample, ε is the extinction coefficient of the analyte in the sample at a specific wavelength, and C is the concentration of the analyte. When I_{in}, D, and ε are known, and I_{out} is measured, the concentration C can be calculated.

In pulse oximetry, in order to distinguish between two species of hemoglobin, oxyhemoglobin (HbO_2), and deoxyhemoglobin (RHb), absorption must be measured at two different wavelengths, i.e. the probe includes two different light emitting diodes (LEDs). The wavelength values widely used are 660 nm (red) and 940 nm (infrared), since the said two species of hemoglobin have substantially different absorption values at these wavelengths. Each LED is illuminated in turn at a frequency which is typically several hundred Hz.

The accuracy of a pulse oximeter is affected by several factors. This is discussed briefly in the following.

Firstly, the dyshemoglobins which do not participate in oxygen transport, i.e. methemoglobin (MetHb) and carboxyhemoglobin (COHb), absorb light at the wavelengths used in the measurement. Pulse oximeters are set up to measure oxygen saturation on the assumption that the patient's blood composition is the same as that of a healthy, non-smoking individual. Therefore, if these species of hemoglobin are present in higher concentrations than normal, a pulse oximeter may display erroneous data.

Secondly, intravenous dyes used for diagnostic purposes may cause considerable deviation in pulse oximeter readings. However, the effect of these dyes is short-lived since the liver purifies blood efficiently.

Thirdly, coatings like nail polish may in practice impair the accuracy of a pulse oximeter, even though the absorption caused by them is constant, not pulsatile, and thus in theory it should not have an effect on the accuracy.

Fourthly, the optical signal may be degraded by both noise and motion artifacts. One source of noise is the ambient light received by the photodetector. Many solutions have been devised with the aim of minimizing or eliminating the effect of the movement of the patient on the signal, and the ability of a pulse oximeter to function correctly in the presence of patient motion depends on the design of the pulse oximeter. One way of canceling out the motion artefact is to use an extra wavelength for this purpose.

A further factor affecting the accuracy of a pulse oximeter is the method used to calibrate the pulse oximeter. Usually the calibration is based on extensive empirical studies in which an average calibration curve is determined based on a high number of persons. By means of this calibration curve, which relates the oxygen saturation of blood to pulse oximeter signals, the average difference between the theory and practice (i.e. in-vivo

measurements) is taken into account. The calibration curve typically maps the measured in-vivo signal to a corresponding SpO_2 value.

Pulse oximeters, however, can also utilize the Lambert-Beer model for calculating the concentrations of the different Hb species. In this method of calibration, the measurement signals must first be transformed into signals applicable to the Lambert-Beer model for calculation. This transformation constitutes the calibration of the pulse oximeter, since it is the step which adapts the in-vivo signals to the Lambert-Beer theory, according to which the pulse oximeter is designed to operate. Thus, the calibration curves can also be in the form of transformations used to adapt the actual in-vivo measurements to the Lambert-Beer model.

Transformations are discussed for example in U.S. Patent 6,104,938, which discloses a calibration method based on the absorption properties of each hemoglobin component, i.e. on the extinction coefficients of blood. In this method, the effective extinction coefficients are determined for each light signal via a mathematical transformation from the extinction coefficients according to the Lambert-Beer theory.

However, each patient (i.e. subject of the measurement) has a calibration curve of his or her own, which deviates from the average calibration curve calculated on the basis of a high number of patients. This is due to the fact that for each patient the characteristics of the tissue through which light is transmitted deviate from those of an average patient. One drawback of the current pulse oximeters is that they are incapable of taking this human variability into account. Human variability here refers to any and all factors causing patient-specific variation in the calibration curve, including time-dependent changes in the calibration curve of a single patient. As discussed in the above-mentioned U.S. Patent, subject-dependent variation can also be seen as an effect of a third substance, such as a third hemoglobin species in the blood. However, the variation can also be interpreted as a subject-dependent change in the calibration curve of the pulse oximeter.

Without compensation for human variability, the accuracy of current pulse oximeters is about ±2%SpO2. However, in multi-wavelength applications in general, and especially if weak absorbers, such as COHb, are to be measured, the human variability represents a much more serious problem. Therefore, techniques of compensation for these inaccuracies are called for.

It is an objective of the invention to bring about a solution by means of which the effects caused by the tissue of the subject can be taken into account when a pulse oximeter is calibrated. In other words, it is an objective of the present invention to create a pulse oximeter which can take into account the differences caused by an individual subject as compared to the average calibration or transformation curve which the current pulse oximeter relies on.

A further objective of the invention is to bring about a general-purpose solution for the compensation of inaccuracies caused by human variability in pulse oximetry, a solution which is not limited to the particular general calibration method employed in the pulse oximeter, but which can be applied to any pulse oximeter regardless of its current built-in calibration method.

Summary of the Invention

These and other objectives of the invention are accomplished in accordance with the principles of the present invention by providing a mechanism by means of which the subject-specific deviation in the tissue-induced effects on the accuracy of the pulse oximeter can be taken into account.

In the method of the invention, the effect of tissue is taken into account and the inaccuracies caused by subject-specific variation in that effect are compensated for. This is implemented by defining a nominal calibration for the apparatus and making off-line measurements, also termed "initial characterization measurements", in order to define the characteristics which describe the conditions under which the nominal calibration has been defined. Reference data indicating the characteristics are stored for subsequent on-line measurements in which light transmission through the actual tissue is measured. (Off-line here refers to measurements performed before the apparatus is taken into use, whereas on-line refers to the actual in-vivo measurements.) Subject-specific calibration is then defined based on the nominal calibration, the on-line measurements, and the reference data created in connection with the off-line measurements. Thus, the inaccuracies are eliminated by means of on-line measurements, which indicate the effect of the tissue. Off-line measurements are used to create the reference data so that light transmission measured subsequently through the tissue of a subject can be used to correct the nominal calibration for that particular subject.

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