Abstract: A non-invasive apparatus and method for monitoring the blood pressure of a subject detects a blood pressure pulse signal at both a first and second location on the subject's body. The elapsed time between the arrival of corresponding points of the blood pressure pulse signal at the first and second locations is determined, and the estimated blood pressure determined by performing the following calculation: \( P = a + b \ln(T) \), where \( a \) and \( b \) are constants dependent upon the nature of the subject and the signal detecting devices. The system is calibrated before the blood pressure calculation is made.
patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

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CONTINUOUS BLOOD PRESSURE MONITORING
METHOD AND APPARATUS

Reference to Related Application
This application claims the benefit of the filing date of U.S. provisional patent application No. 60/178,027 filed on 26 January 2000.

Field of the Invention
This invention relates to blood pressure monitoring devices of the type which measure transit times of pressure pulses in a patient’s circulatory system and compute an estimated blood pressure from the measured transit times.

Background of the Invention
Various approaches have been tried for monitoring the blood pressure of patients. One approach is to insert a pressure sensor directly into a suitable artery in the patient. The sensor can be connected to a suitable monitoring device by a lead which passes through the patient’s skin. This approach provides accurate and instantaneous blood pressure measurements. A disadvantage of this approach is that it is invasive. A surgical procedure is required to introduce the pressure sensor. The fistula through which the lead exits the patient’s body can provide a pathway for infection.

Another approach to measuring blood pressure uses a sphygmomanometer. A typical sphygmomanometer has an occluding cuff capable of being wrapped around a patient’s arm; a pump for inflating the cuff; either an aneroid or
mercury gravity sphygmomanometer to measure pressure in
the cuff; and a stethoscope or other system for detecting
Korotkoff sounds. Such devices are widely used in
hospitals and doctors' offices for making routine blood
pressure measurements but are not well adapted to
providing continuous blood pressure monitoring.

Another method for measuring blood pressure is the
oscillometric method. Oscillometric blood pressure
measurements are made by using a transducer to detect and
measure pressure waves in a pressure cuff as blood surges
through an artery constricted by the pressure cuff. Many
currently available digital blood pressure monitors use
the oscillometric method for determining blood pressure.
The oscillometric method is not ideal for continuous blood
pressure monitoring because it typically cannot produce an
updated blood pressure reading more frequently than about
once every 30 seconds. Further, the cuff compresses
underlying tissues. Over an extended period of time this
can cause tissue damage.

There has been significant research directed toward
the development of new non-invasive techniques for
monitoring blood pressure. One approach exploits the
correlation between blood pressure and the time taken for
a pulse to propagate from a patient's heart to a selected
point on a patient's artery. This approach is possible
because the speed at which pressure pulse waves travel
from the heart to points downstream in a patient's
circulatory system varies with blood pressure. As blood
pressure rises the propagation velocity of arterial pulse
waves decreases. In general, such methods may be called
Pulse Transit Time (or "PTT") methods.
Typically a signal from an electrocardiogram (EKG) is used to detect a heart beat and a pressure sensor is used to detect the arrival of a pressure pulse wave generated by the heart beat at a downstream location. This approach is described, for example, by Inukai et al., U.S. patent No. 5,921,936. The Inukai et al. system uses an electrocardiogram to detect the start of a heart beat and uses a cuff equipped with a pressure sensor to detect pressure pulse waves. Other similar systems are described in Orr et al., European Patent application No. EP0181067. A variation of this approach is described in Golub, U.S. patent No. 5,857,975.

One difficulty with PTT blood pressure measurement systems which measure blood pressure as a function of the time between the pulse of an EKG signal and a detected pressure pulse is that there is a delay between the onset of an EKG pulse and the time that the heart actually begins to pump blood. This delay can vary significantly in a random way, even in healthy subjects. Hatschek, U.S. patent No. 5,309,916 discloses a method for measuring blood pressure by determining the time taken for a pressure pulse to propagate downstream along a single arterial branch. This approach eliminates uncertainties caused by the imperfect correlation between EKG signals and the delivery of blood by the heart. However, it has the disadvantage that it can be difficult to arrange two sensors so that they can detect a pressure pulse at each of two widely spaced apart locations along a single arterial branch.

Another difficulty with prior art PTT blood pressure measurements is that the relationship between blood
pressure and the time taken for pulses to transit a portion of the circulatory system is different for every patient. Thus, it is necessary to calibrate a PTT blood pressure measurement system for each patient.

The book entitled *Monitoring in Anesthesia and Critical Care Medicine*, 3rd Edition, edited by Blitt and Hines, Churchill Livingstone, 1995, mentions a blood pressure monitor having the trade name, ARTRAC™ 7000, which used two photometric sensors, one on the ear and another on a finger, to measure diastolic blood pressure. This device apparently used the difference in arrived times of pulses at the ear and finger to measure the pulse transit time. The diastolic pressure was estimated based on an assumed linear relationship of pressure and pulse wave velocity. This device apparently computed systolic pressure from the pulse volume. Further information about this device is provided in a FDA 510(k) Notification entitled, "ARTRAC™ Vital Sign Monitor, Models 7000 and 5000 (K904888)," submitted by Sentinel Monitoring, Inc., 1990.

A relationship between blood pressure and pulse transit time can be developed by assuming that an artery behaves as if it were a thin-walled elastic tube. This relationship, which is known as the Moens-Korteweg-Hughes equation is described in more detail below. The Moens-Korteweg-Hughes equation depends on the nature and geometry of blood vessels and is highly nonlinear.

Inventors Aso et al., U.S. patent No. 5,564,427, proposed the use of a linear equation to calculate blood pressure using the EKG based pulse transit time. This method was further developed by Hosaka et al., U.S. patent
No. 5,649,543. To calibrate the linear measurement system, Sugo et al., U.S. patent No. 5,709,212, introduced a multi-parameter approach to determine the parameters at deferent blood pressure levels for systolic and diastolic pressures respectively. Shirasaki patented another method to calibrate the parameters based on the multiple blood pressure reference inputs in Japan patent No. 10-151118.

Despite progress that has been made in the field of blood pressure measurement, there remains a need for devices for blood pressure measurement which have acceptable accuracy and do not require complicated calibration steps.

Summary of the Invention

This invention provides blood pressure measurement methods and apparatus which avoid some of the disadvantages of the prior art. Preferred embodiments of the invention are suitable for continuous non-invasive blood pressure ("CNIBP") monitoring.

One aspect of the invention provides a method for monitoring blood pressure. The method comprises detecting a first blood pressure pulse signal at a first location on a patient and detecting a second blood pressure pulse signal at a second location on the patient; measuring a time difference between corresponding points on the first and second blood pressure pulse signals; and, computing an estimated blood pressure from the time difference.

In preferred embodiments of the invention, computing an estimated blood pressure comprises performing the calculation: \( P = a + b \ln(T) \) where \( P \) is the estimated blood pressure, \( a \) is a constant, \( b \) is a constant, and \( T \) is the
time difference. Most preferably, the constants $a$ and $b$ for a particular patient are determined by performing a calibration by taking a reference blood pressure reading to obtain a reference blood pressure $P_0$, measuring the elapsed time $T_0$ corresponding to the reference blood pressure and determining values for both of the constants $a$ and $b$ from $P_0$ and $T_0$.

Brief Description of the Drawings

In drawings which illustrate non-limiting embodiments of the invention:

Figure 1 is a block diagram of apparatus according to the invention;

Figure 2 is a diagram illustrating first and second pulse signals detected by the apparatus of Figure 1;

Figure 3 is a block diagram of apparatus according to one specific embodiment of the invention;

Figure 4 is a schematic diagram of a possible sensor and signal-conditioning circuit for use in the invention;

Figure 5 is a plot of two constants $a$ and $b$ in a formula for estimating systolic blood pressure used in a preferred embodiment of the invention;

Figure 6 is a plot of two constants $a$ and $b$ in a formula for estimating diastolic blood pressure used in a preferred embodiment of the invention;

Figure 7 is a flow chart illustrating a computer-implemented method for estimating blood pressure according to the invention;

Figure 8 illustrates a possible organization for software for use in the invention; and,
Figure 9 is a view of a possible user interface display for use in the invention.

Detailed Description

Figure 1 shows a blood pressure monitoring system 10 according to the invention. System 10 has first and second sensors 12 and 14 which are each capable of detecting a pulse signal at a location on a patient. Sensors 12 and 14 can advantageously be photoelectric pulse wave sensors of the type used for pulse oximetry. An example of such a sensor is the model SAS-F FingerSat™ sensor available from Datex-Ohmeda (Canada) Incorporated. Sensors of this type are easy to obtain, reasonable in cost, light weight and familiar to medical professionals. Other types of sensor capable of detecting the arrival of pressure pulse waves at a location on a patient may also be used within the broad scheme of the invention. For example, Figure 4 is a schematic diagram of a specific sensor implementation in which an OP140A light emitting diode available from Optech Technology Inc. is used to generate light. The light is reflected back to a model OP550A phototransistor also available from Optech Technology Inc. The remaining circuitry shown in Figure 4 is an example of one possible embodiment for signal conditioning circuitry which could be used in the practise of this invention.

Sensors 12 and 14 are applied to first and second locations L1 and L2 on a patient P. In the example illustrated in Figure 1, L1 is an earlobe of the patient and L2 is a finger of the patient. L1 and L2 may be any places on a patient where a blood pressure pulse wave can be readily detected by sensors 12 and 14 respectively. L1
and \( \textbf{L2} \) should be chosen so that a pressure pulse wave from the patient's heart takes a different amount of time to propagate to \( \textbf{L1} \) than the pulse takes to propagate to \( \textbf{L2} \). \( \textbf{L1} \) and \( \textbf{L2} \) can conveniently each be any of a finger, a toe, a wrist, an earlobe, an ankle, a nose, a lip, or any other part of the body where blood vessels are close to the surface of the skin. Most preferably, \( \textbf{L1} \) and \( \textbf{L2} \) are the paired combination of:

- an earlobe and a finger;
- an earlobe and a toe; or,
- a finger and a toe.

In preferred embodiments of the invention, \( \textbf{L1} \) and \( \textbf{L2} \) are supplied by blood from different branches of the patient's arterial system so that \( \textbf{L1} \) is not directly downstream from \( \textbf{L2} \) and \( \textbf{L2} \) is not directly downstream from \( \textbf{L1} \).

Since locations \( \textbf{L1} \) and \( \textbf{L2} \) do not need to be supplied by blood by the same branch of a patient's arterial system, this invention provides a much wider and more convenient range of locations for the application of sensors \( 12 \) and \( 14 \) than would be the case if sensor \( 12 \) was required to be directly upstream or downstream from sensor \( 14 \).

First and second electrical signals \( 16 \) and \( 18 \) are generated at sensors \( 12 \) and \( 14 \) respectively. Signals \( 16 \) and \( 18 \) are respectively conditioned by signal conditioning circuits \( 20 \) and \( 22 \). Signal conditioning circuits \( 20 \) and \( 22 \) preferably include low-pass filters to eliminate spurious spikes, noise filters to eliminate interference from power supplies and other noise sources, and gain amplifiers.

After being conditioned, first and second signals \( 16 \) and \( 18 \) are digitized by an analog-to-digital converter ("ADC")
24. Preferably each of signals 16 and 18 is sampled at a frequency of about 1 kHz, or greater. Most preferably the sampling frequency is 2kHz or greater. ADC 24 can conveniently be an ADC integrated with a processor capable of forwarding digitized signals 16 and 18 to a processing device for further analysis. For example, ADC 24 may be the 8/10 bit ADC portion of a Motorola MC68HC916X1 microcontroller.

Figure 2 shows first and second signals 16 and 18 after they have been digitized. The digitized signals are then processed in a processor 26 to yield an estimated blood pressure. Processor 26 may be a computer connected to ADC 24 by a suitable interface 25. Figure 3 illustrates a specific embodiment of the invention wherein interface 25 comprises an RS-232 serial interface which receives digitized data from a Motorola MC68HC916X1 microcontroller and transmits that data over a standard RS-232 serial cable to the serial port of a standard personal computer. In the embodiment of Figure 3, the personal computer is programmed to perform the necessary processing of the digitized signals 16 and 18.

Processor 26 determines the time separating selected corresponding locations on the first and second signals 16 and 18. Preferably, processor 26 determines both the time difference T1 between the peaks of signals 16 and 18 (e.g. the systolic points on first and second signals 16 and 18) and the time difference T2 between the valleys of the first and second signals 16 and 18 (e.g. the diastolic points on first and second signals 16 and 18).

There are numerous ways in which T1 and T2 can be measured. One way is to use a cross correlation technique.
Where two signals are respectively given by \( p_1(t) \) and \( p_2(t) \) the correlation between the two signals for a time difference of \( N \) sample points can be expressed as follows:

\[
C_{p_1p_2}(m) = \frac{1}{N} \sum_{n=0}^{N-m-1} p_1(n)p_2(n+m)
\]

(1)

The time difference between corresponding points on the two signals is determined by finding the value of \( m \) for which the correlation is maximized and then multiplying by the sample time (e.g. the time between subsequent samples of each signal) as follows:

\[
T = m \left| \frac{\Delta t}{c_{\text{max}}} \right|
\]

(2)

The sample time may be, for example, 1 millisecond.

One way to separately measure the time differences \( T_1 \) and \( T_2 \) which, in general, are different, is to create from signals 16 and 18 a first set of signals \( p_1(t) \) and \( p_2(t) \) which include the systolic peaks of signals 16 and 18 but do not include the diastolic valleys of signals 16 and 18. The cross-correlation between the first set of signals can then be used to obtain a value for \( T_1 \). Similarly, a second set of signals \( p_1(t) \) and \( p_2(t) \) which include the diastolic valleys of signals 16 and 18 but do not include the systolic peaks of signals 16 and 18 can be cross-correlated to obtain a value for \( T_2 \). The values for \( T_1 \) and \( T_2 \) can be used as described below to compute systolic and diastolic blood pressures.

The first set of signals can be created from signals 16 and 18, for example, by selecting a threshold for each of signals 16 and 18 with each threshold being lower than
the peak values of the signal and setting to zero all data points having values lower than the threshold. A suitable threshold may be derived, for example, by computing the average values of the data points of each of signals 16 and 18 and using the average values as thresholds.

The second set of signals can be created from signals 16 and 18, for example, by selecting a threshold for each of signals 16 and 18 with each threshold being higher than the minimum values of the signal and setting to zero all data points having values greater than the threshold. A suitable threshold may be derived, for example, by computing the average values of the data points of each of signals 16 and 18 and using the average values as thresholds. The same or different thresholds may be used in obtaining the first and second sets of signals.

Times T1 and T2 may be used to compute an estimate of a patient's blood pressure. The speed at which pressure pulse waves propagate through a patient's arterial system is related to blood pressure by an equation known as the Moens-Kortweg-Hughes Equation. L.A. Geddes Handbook of Blood Pressure Measurement, Human Press, Clifton, New Jersey, 1990 describes the theoretical basis for the variation in pulse propagation speed with blood pressure.

The Moens-Kortweg-Hughes Equation can be expressed as follows:

\[
v = \sqrt{(tE_0 / \rho d)E_p} = \frac{L}{T}
\]  

where \(v\) is the pulse wave velocity; \(t\) is the thickness of the vessel wall; \(E_0\) is the zero-pressure modulus of the
vessel wall; \( d \) is the diameter of the vessel; \( \lambda \) is a constant that depends on the geometry of the vessel; \( P \) is a blood pressure within the vessel; \( L \) is the distance travelled by a pulse between two points at which a pulse is detected; and \( T \) is the time elapsed between detecting the pulse at a first measurement point and detecting the pulse at a second measurement point.

The Moens-Kortweg-Hughes Equation includes a large number of factors which depend upon the nature and geometry of a patient’s blood vessels. Many of those who have attempted to measure blood pressure by measuring the propagation times of pressure pulse waves have assumed that, over a relevant range, the Moens-Kortweg-Hughes Equation could be expressed as a linear equation. That is, they have assumed that blood pressure and time are related by the following equation over a relevant range of propagation times:

\[
P = AT + B
\]

(4)

where \( P \) and \( T \) are as defined above and \( A \) and \( B \) are parameters which are specific to each individual patient. While the relationship of equation (4) may be used in certain embodiments of this invention, it is not preferred. One problem is that equation (4) will generally lead to inaccurate blood pressure estimates in cases where a patient experiences large dynamic fluctuations in blood pressure as can occur in operating room situations.

The inventors have discovered that, for purposes of estimating blood pressure, it is desirable to express the relationship between blood pressure and elapsed time
between detecting a pressure pulse wave at two locations $L_1$ and $L_2$ as follows:

$$P = a + b \ln(T)$$

(5)

where $a$ and $b$ are parameters to be determined for each patient.

The inventors have discovered that the use of equation (5) for estimating blood pressure provides unanticipated advantages over methods which use equation (4) for calculating an estimated blood pressure.

In order to use either of equations (4) and (5) to estimate the blood pressure of a patient from a time difference $T$ it is necessary to obtain values for the constants which are appropriate to the individual in question. One way to calibrate system 10 for a specific individual is to measure both $T$ and the patient's blood pressure at two times when the patient's blood pressure is different. This is inconvenient because, in general, a patient's blood pressure will not predictably fluctuate significantly enough to obtain measurements of $T$ at two different blood pressures.

Various techniques can be used to deliberately alter a patient's blood pressure to obtain two points from which values for the constants $a$ and $b$ (or $A$ and $B$) can be determined. These include: administering drugs to the patient which have the effect of raising or lowering the patient's blood pressure; taking measurements both when a limb of the patient is in a raised position (so that the base hydrostatic pressure within the patient's circulatory system is increased) and in a lowered position (so that the base hydrostatic pressure within the patient's circulatory system is decreased); or causing the patient
to increase the pressure within his or her thoracic cavity by attempting to exhale against a resistance, as described by Inukai et al., U.S. patent No. 5,921,936. While all of these techniques may be used in some embodiments of the invention, none is ideal.

The inventors have conducted trials in which the values $a$ and $b$ were experimentally determined for a number of patients. This can be done, for example, by measuring the patient's blood pressure and pulse transit time at a number of different times as the patient's blood pressure varies. Then one can fit a curve to Equation (5) to directly obtain values for $a$ and $b$. The inventors have discovered that surprisingly $a$ and $b$ are related linearly to one another by the equation:

$$a = c_1 + c_2 b$$

where $c_1$ and $c_2$ are constants. $c_1$ and $c_2$ are different for systolic and diastolic blood pressure measurements. A plot of the values of $a$ and $b$ for systolic blood pressure measurements made on a number of patients is shown in Figure 5. A plot of the values of $a$ and $b$ for diastolic blood pressure measurements made on a number of patients is shown in Figure 6.

For systolic blood pressure it has been determined that $c_{1s}$ and $c_{2s}$ are respectively about 85.41 and -4.73 whereas, for diastolic blood pressure, $c_{1d}$ and $c_{2d}$ are respectively about 49.36 and -4.3. Although it is considered best to use the foregoing values, in methods and apparatus of the invention the specific values used for the constants $c_{1s}$ and $c_{2s}$, $c_{1d}$ and $c_{2d}$ may be varied somewhat from these preferred values without departing from the invention. Preferably $c_{1s}$ is in the range of 85±10
and $c_{2s}$ is in the range of $-4\pm1$. Preferably $c_{2d}$ is in the range $50\pm10$ and $c_{2d}$ is in the range of $-4\pm1$.

It will appreciated that the particular values of $a$ and $b$ will vary depending upon the equipment used for measuring $a$ and $b$. By taking advantage of the unexpected linear relationship between $a$ and $b$, a blood pressure measurement apparatus according to this invention may be calibrated for a specific person using only one set of measurements.

Combining equations (5) and (6) gives the relationships:

$$P_{\text{systolic}} = c_{1s} + c_{2s} b_s + b_s \ln(T1)$$

(7)

where $P_{\text{systolic}}$ is estimated systolic blood pressure; and,

$$P_{\text{diastolic}} = c_1 + c_2 b_D + b_D \ln(T2)$$

(8)

$P_{\text{diastolic}}$ is estimated diastolic blood pressure. The constants $b_s, b_D, c_{1s}, c_{1d}, c_{2s}$ and $c_{2d}$ in equations (7) and (8) are those given above for systolic and diastolic blood pressure respectively. It can be seen that the unexpected correlation between $a$ and $b$ of equation (5) permits system $10$ to be calibrated for either systolic or diastolic blood pressure measurements with a single blood pressure measurement made by any alternative reliable method. This can be done by measuring the patient's blood pressure and $T$ and calculating the values of $a$ and $b$ for the patient as follows:

$$a = c_1 + \frac{c_2 (P_0 - c_1)}{(\ln(T_0) + c_2)}$$

(9)
\[ b = \frac{(P_0 - c_1)}{(\ln(T_0) + c_2)} \] (10)

where \( P_0 \) is the measured reference blood pressure; \( T_0 \) is the measured elapsed time (either \( T_1 \) or \( T_2 \)) between the detection of a pressure pulse at \( L_1 \) and the detection of the pressure pulse at \( L_2 \) and \( c_1 \) and \( c_2 \) are as given above.

System 10 may include an input (not shown) for receiving a signal indicative of the reference blood pressure or \( P_0 \) may be measured using a separate device and entered into system 10 by way of a keyboard or other manual interface.

After system 10 has been calibrated for a particular patient and for a particular pair \( L_1 \) and \( L_2 \) of sensor locations then the patient’s blood pressure can be continuously estimated by frequently measuring \( T_1 \) and \( T_2 \), as described above, and computing an estimated blood pressure through the use of the following equation:

\[
P = \left\{ c_1 + c_2 \frac{(P_0 - c_1)}{[\ln(T_0) + c_2]} \right\} + \left\{ \frac{(P_0 - c_1)}{[\ln(T_0) + c_2]} \right\} \ln(T)
\] (11)

System 10 can then display the patient’s estimated blood pressure on a suitable display 54 (Fig. 9), can compare the patient’s estimated blood pressure to one or more stored alarm limits and trigger an alarm signal if the estimated blood pressure exceeds or is less than a particular alarm limit, can periodically record the estimated blood pressure(s) for the patient and so on.

Figure 7 illustrates a method 100 that may be implemented in processor 26 for deriving an estimated blood pressure.
blood pressure from first and second signals 16 and 18. Processor 26 runs computer instructions which direct processor 26 to request digitized signals 16 and 18. s1 may involve processor 26 sending a request via interface 25 to ADC system 24 requesting that ADC system 24 obtain and forward by way of interface 25 digitized signals 16 and 18.

In block s2 processor 26 is directed to determine T1 and T2 by comparing digitized signals 16 and 18. Block s2 preferably involves computing cross-correlations from signals 16 and 18 as described above.

In block s3, processor 26 is directed to determine whether it has calibration information for the current patient. If so then method 100 continues at block s5. If not then method 100 proceeds to block s4 in which processor 26 runs computer instructions which cause processor 26 to obtain calibration information for the current patient. Such calibration information may be obtained, for example, by requesting and obtaining information identifying a file accessible to processor 26 in which calibration information for the patient in question has been stored previously or may be obtained by requesting input values for measured systolic and diastolic blood pressure from which the values for b can be calculated as described above.

In block s5 processor 26 runs computer instructions which cause it to calculate systolic and diastolic blood pressure estimates using equation (10) above and the values for b determined in block s4. In block s6 processor 26 is directed to display computed blood pressure estimates on a suitable display connected to processor 26,
save the blood pressure estimates in a file, and/or otherwise make the blood pressure estimates available for use.

In block **s7** processor **26** runs computer instructions which determine whether the blood pressure monitoring should continue. Block **s7** may include a user selectable delay so that a user can decide how frequently a new blood pressure estimate will be obtained. If processor **26** determines in block **s7** that a further blood pressure estimate should be obtained then method **100** continues to block **s1**. If processor **26** determines in block **s7** that a further blood pressure estimate should not be obtained then method **100** terminates and processor **26** awaits further user instructions.

Method **100** may be implemented by running suitable computer software on a personal computer, microcontroller, or other suitable computer device. Method **100** could also be completely implemented in hardware although a hardware implementation would be less versatile than the preferred embodiments described above.

Figure 8 illustrates a possible software architecture for software **50** to be run on a processor **26** in the practice of this invention. A form view object **52** provides a graphical display **54** which may, for example, have the appearance shown in Figure 9. Display **54** provides a graphical user interface by way of which a user can control the operation of system **10** and see the blood pressure estimates developed by system **10**. Display **54** may include a portion **55A** for displaying estimated systolic blood pressure, a portion **55B** for displaying estimated diastolic blood pressure; a portion **55C** for displaying the
patient's measured heart rate; and a portion 55D for displaying the number of elapsed blood pressure measurement cycles. Portions 55E and 55F show digitized signals 16 and 18. Portion 55G displays status information. Portion 55H displays the current system date and time.

Display 54 may include a number of user controls including a control 56A for setting the cycle time; a control 56B for starting a sequence of blood pressure estimations; a control 56C for reviewing previously recorded blood pressure estimates for the same patient; a portion 57 for setting and displaying the name of the patient being monitored.

A serial communication object 55 sends commands to ADC unit 24 and receives data from ADC unit 24 via interface 25.

A blood pressure calculation object 56 processes digitized signals 16 and 18 to derive blood pressure estimates, as described above.

A calibration object 58 receives measured blood pressure information and computes values for b for a patient as described above.

A file management object 59 moderates the storage of data in files and the retrieval of data from files accessible to processor 26.

A data pre-processing object 60 formats the data to be presented in a predefined format, for example a format compatible with application software such as Microsoft™ EXCEI™.

Preferred implementations of the invention comprise a computer processor running software instructions which
cause the computer processor to perform a method of the invention. The invention may also be provided in the form of a program product. The program product may comprise any medium which carries a set of computer-readable signals containing to instructions which, when run by a computer, cause the computer to execute a method of the invention. The program product may be in any of a wide variety of forms. The program product may comprise, for example, physical media such as magnetic data storage media including floppy diskettes, hard disk drives, optical data storage media including CD ROMs, DVDs, electronic data storage media including ROMs, flash RAM, or the like or transmission-type media such as digital or analog communication links.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example, Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.
We claim:

1. A method for monitoring blood pressure, the method comprising:
   a) detecting (s1) a first blood pressure pulse signal at a first location (L1) on a patient and detecting (s1) a second blood pressure pulse signal at a second location (L2) on the patient;
   b) measuring (s2) a time difference (T) between corresponding points on the first and second blood pressure pulse signals; and,
   d) computing (s5) an estimated blood pressure from the time difference (T).

2. The method of claim 1 wherein computing an estimated blood pressure comprises performing the calculation:

   \[ P = a + b \ln(T) \]

   where \( P \) is the estimated blood pressure, \( a \) is a constant, \( b \) is a constant, and \( T \) is the time difference.

3. The method of claim 1 wherein the first and second locations are locations supplied with blood by separate streams.

4. The method of claim 1 wherein the first location is selected from the group consisting of: a finger, an ear lobe, a toe, and a wrist.
5. The method of claim 4 wherein the second location is not the same as the first location but is selected from the group consisting of: a finger not on the same arm as the first location, an ear lobe, a toe, and a wrist.

6. The method of any one of claims 1-5 wherein the first blood pressure pulse signal and the second blood pressure pulse signal are both detected by photoelectric pulse wave sensors.

7. A method for estimating a blood pressure of a subject, the method comprising:
   a) detecting a blood pressure pulse signal at a first location (L1);
   b) detecting the blood pressure pulse signal at a second location (L2);
   c) determining an elapsed time, T, between the arrival of corresponding points of the blood pressure pulse signal at the first and second locations; and,
   d) computing an estimated blood pressure, P, from the elapsed time by performing the calculation:
      \[ P = a + b \ln(T) \]
      where a and b are constants.

8. The method of claim 7 wherein the corresponding points correspond to a systolic peak of the blood pressure pulse signal.
9. The method of claim 7 wherein the corresponding points are diastolic valleys of the blood pressure pulse signals.

10. The method of claim 7 wherein determining the elapsed time comprises computing a cross-correlation of a first blood pressure pulse signal detected at the first location (L1) and a second blood pressure pulse signal detected at the second location (L2).

11. The method of claim 10 comprising performing a calibration by taking a reference blood pressure reading to obtain a reference blood pressure $P_o$ and measuring the elapsed time $T_o$ corresponding to the reference blood pressure and performing the calculations:

$$a = c_1 + c_2 (P_o - c_1) / (\ln(T_o) + c_2)$$

and,

$$b = (P_o - c_1) / (\ln(T_o) + c_2)$$

to obtain values for the constants $a$ and $b$.

12. A method for estimating the blood pressure, $P$, of a subject, the method comprising:

a) detecting (s1) a first blood pressure pulse signal at a first location (L1);

b) detecting (s1) the first blood pressure pulse signal at a second location (L2);
c) determining an elapsed time, $T$, between the arrival of corresponding points of the first blood pressure pulse signal at the first and second locations;

d) performing a calibration by detecting a reference blood pressure pulse signal at a first location and at a second location and determining an elapsed time, $T_0$, between the arrival of corresponding points of the reference blood pressure pulse signal at the first and second locations;

e) taking a reference blood pressure reading to obtain a reference blood pressure $P_0$ corresponding to the reference blood pressure pulse; and

f) performing the following calculation:

$$P = \{c_1 + c_2(P_0 - c_1)/[\ln(T_0) + c_2]\}$$

$$+ \{(P_0 - c_1)/[\ln(T_0) + c_2]\}\ln(T)$$

where $c_1$ and $c_2$ are constants.

13. The method of claim 12 wherein $c_1$ is about 85.41 and $c_2$ is about -4.73 for systolic pressure measurements.

14. The method of claim 12 wherein $c_1$ is about 49.36 and $c_2$ is about -4.3 for diastolic pressure measurements.

15. The method of claim 12 wherein $c_1$ is in the range of 85±10 and $c_2$ is in the range of -4±1 for systolic pressure measurements.
16. The method of claim 12 wherein \( c_1 \) is in the range of 50±10 and \( c_2 \) is in the range of -4±1 for diastolic pressure measurements.

17. The method of claim 12 where \( c_1 \) and \( c_2 \) are derived by:
for several patients, at each of two or more times, measuring a reference blood pressure value \( P \) and an elapsed time, \( T \), between the arrival of corresponding points of a blood pressure pulse signal at first and second locations on the patient;
for each of the patients determining best fit values for \( a \) and \( b \) such that:
\[
P = a + b \ln(T)
\]
for the measured reference blood pressure values and elapsed times;
based upon the values for \( a \) and \( b \) determining best fit values for \( c_1 \) and \( c_2 \) such that:
\[
a = c_1 + c_2 b.
\]

18. Apparatus for estimating a blood pressure of a subject, the apparatus comprising:
a) a computer processor;
b) an input for receiving a first signal corresponding to a blood pressure pulse signal detected at a first location (L1);
c) an input for receiving a second signal corresponding to the blood pressure pulse signal detected at a second location (L2);
d) a clock;
e) a program store containing computer software comprising instructions which, when run on the processor cause the processor to measure an
elapsed time, $T$, between corresponding points on the first and second signals and compute an estimated blood pressure, $P$, from the elapsed time by performing the calculation:

$$P = a + b \ln(T)$$

where $a$ and $b$ are constants.

19. The apparatus of claim 18 wherein the corresponding points correspond to a systolic peak of the blood pressure pulse signal.

20. The apparatus of claim 18 wherein the corresponding points correspond to a diastolic valley of the blood pressure pulse signal.

21. The apparatus of any one of claims 18 to 20 wherein the software comprises instructions which cause the computer processor to compute a cross-correlation of the first and second signals.

22. The apparatus of any one of claims 18 to 21 comprising an input for receiving a reference signal indicative of a reference blood pressure value.

23. A program product comprising a medium bearing computer readable instructions which, when executed on a computer processor, cause the computer processor to perform a method according to any one of claims 1 to 17.
Figure 2

T1 - Systolic DPTT
T2 - Diastolic DPTT

Pulse - 1
Pulse - 2
Figure 7

Start

Data acquisition from sensors

Use correlation technique to calculate systolic DPTT (T1) and diastolic DPTT (T2)

Is system calibrated?

Yes

No

BP-DPTT calibration

Calculate systolic and diastolic BP from T1 and T2 respectively

Update/save/display results

Continue?

Yes

No

End
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A61B5/0225 A61B5/0285

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61B

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

Electronica database consulted during the international search (name of data base and, where practical, search terms used)

PAJ, EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Patent family members are listed in annex.

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Date of the actual completion of the international search: 11 May 2001

Date of mailing of the international search report: 18/05/2001

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