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(54) **CONTINUOUS NON-INVASIVE BLOOD PRESSURE MONITORING METHOD AND APPARATUS**

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Related U.S. Application Data

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(60) Provisional application No. 60/178,027, filed on Jan. 26, 2000.

(51) **Int. Cl.**[7] **A61B 5/02**
(52) **U.S. Cl.** **600/485**; 600/500; 600/481
(58) **Field of Search** 600/481, 485, 600/486, 490, 500, 501, 502, 503

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,790,910	A	*	2/1974	McCormack
3,908,640	A		9/1975	Page
4,245,648	A		1/1981	Trimmer et al.
4,303,984	A	*	12/1981	Houvig
4,404,974	A	*	9/1983	Titus
4,492,877	A	*	1/1985	Staerzl
4,718,427	A	*	1/1988	Russell
4,718,428	A	*	1/1988	Russell
4,873,987	A		10/1989	Djordjevich et al.
4,907,596	A		3/1990	Schmid et al.

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

CA	2341416	2/2001
EP	0 181 067	5/1986
EP	0 443 267 A1	8/1990
EP	0456844 A1	11/1991
EP	0 821 910 A2	2/1998
EP	0 829 227 A2	3/1998
EP	0852126 A2	7/1998
EP	0 875 200 A1	11/1998
EP	0852126 A3	12/1998

(List continued on next page.)

OTHER PUBLICATIONS

A short article and a copy of a 510(k) Notification regarding Sentinel Monitoring, Inc.'s Artac™ 7000 Vital Signs Device, 1990 (a re–typed copy of pp. 8 through 11 of the 510(k) Notification is enclosed).
A copy of *Monitoring in Anesthesia and Critical Care Medicine*, 1995, pp. 117–130.

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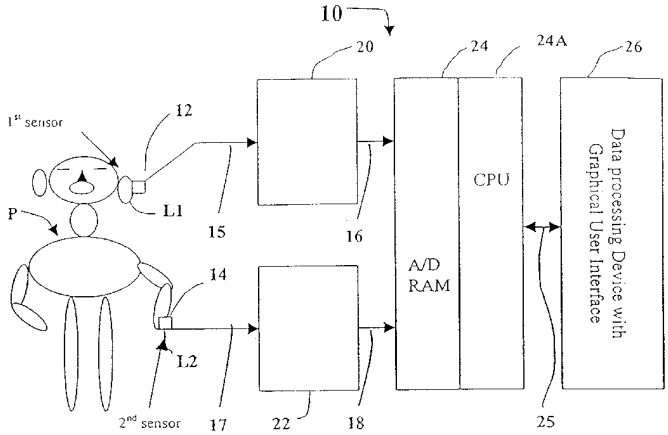
(57) **ABSTRACT**

A non-invasive apparatus and method for monitoring the blood pressure of a subject detects a 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 pulse signal at the first and second locations is determined. Blood pressure is related to the elapsed time by relationships such as:

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

where a and b are constants dependent upon the nature of the subject and the signal detecting devices. The system can be calibrated by measuring a single pair of reference blood pressure and corresponding elapsed time.

63 Claims, 11 Drawing Sheets



U.S. PATENT DOCUMENTS

5,033,472	A	*	7/1991	Sato et al.
5,072,736	A	*	12/1991	Ogawa et al.
5,237,997	A		8/1993	Greubel et al.
5,255,686	A	*	10/1993	Takeda et al.
5,293,874	A		3/1994	Takahashi et al.
5,309,916	A		5/1994	Hatschek
5,485,838	A		1/1996	Ukawa et al.
5,485,848	A		1/1996	Jackson et al.
5,533,511	A		7/1996	Kaspari et al.
5,564,427	A		10/1996	Aso et al.
5,584,299	A		12/1996	Sakai et al.
5,590,649	A		1/1997	Caro et al.
5,603,329	A		2/1997	Hosaka et al.
5,649,543	A		7/1997	Hosaka et al.
5,676,140	A		10/1997	Ukawa et al.
5,699,807	A		12/1997	Motogi et al.
5,709,212	A		1/1998	Sugo et al.
5,743,856	A		4/1998	Oka et al.
5,743,857	A		4/1998	Shinoda et al.
5,752,920	A		5/1998	Ogura et al.
5,755,669	A		5/1998	Ono et al.
5,772,602	A		6/1998	Sakai et al.
5,776,071	A		7/1998	Inukai et al.
5,810,734	A		9/1998	Caro et al.
5,833,618	A		11/1998	Caro et al.
5,857,975	A		1/1999	Golub
5,865,755	A		2/1999	Golub
5,873,834	A		2/1999	Yanagi et al.
5,876,348	A		3/1999	Sugo et al.
5,882,311	A		3/1999	O'Rourke
5,921,936	A		7/1999	Inukai et al.
6,004,274	A		12/1999	Nolan et al.
6,010,457	A		1/2000	O'Rourke
6,083,171	A		7/2000	Ono et al.
6,129,677	A		10/2000	Sohma et al.
6,190,325	B1		2/2001	Narimatsu
2002/0002339	A1		1/2002	Sugo et al.

FOREIGN PATENT DOCUMENTS

EP	0 956 813	A1	11/1999
EP	0 956 815	A1	11/1999
EP	0 956 816	A1	11/1999
JP	07136136		5/1995
JP	08131410		5/1996
JP	9122087	A	5/1997
JP	10 151 118		6/1998
JP	2000107141		4/2000
WO	WO 89 08424	A	9/1989
WO	WO 00/10453		3/2000

* cited by examiner

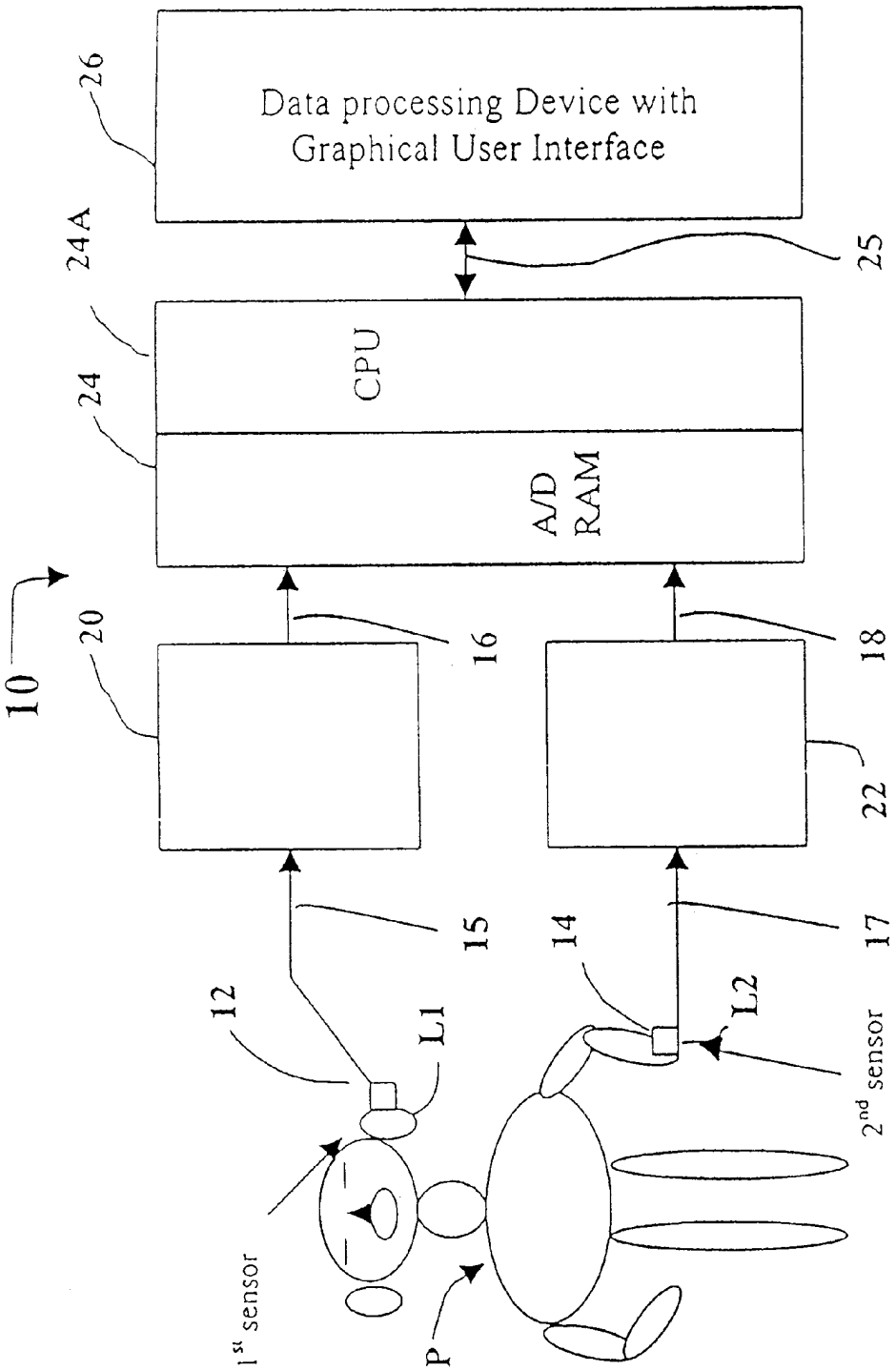

Data processing Device with Graphical User Interface
26
24A
25
CPU
24
A/D RAM
10
20
16
18
22
15
14
17
12
L1
L2
1st sensor
2nd sensor
P

Figure 1

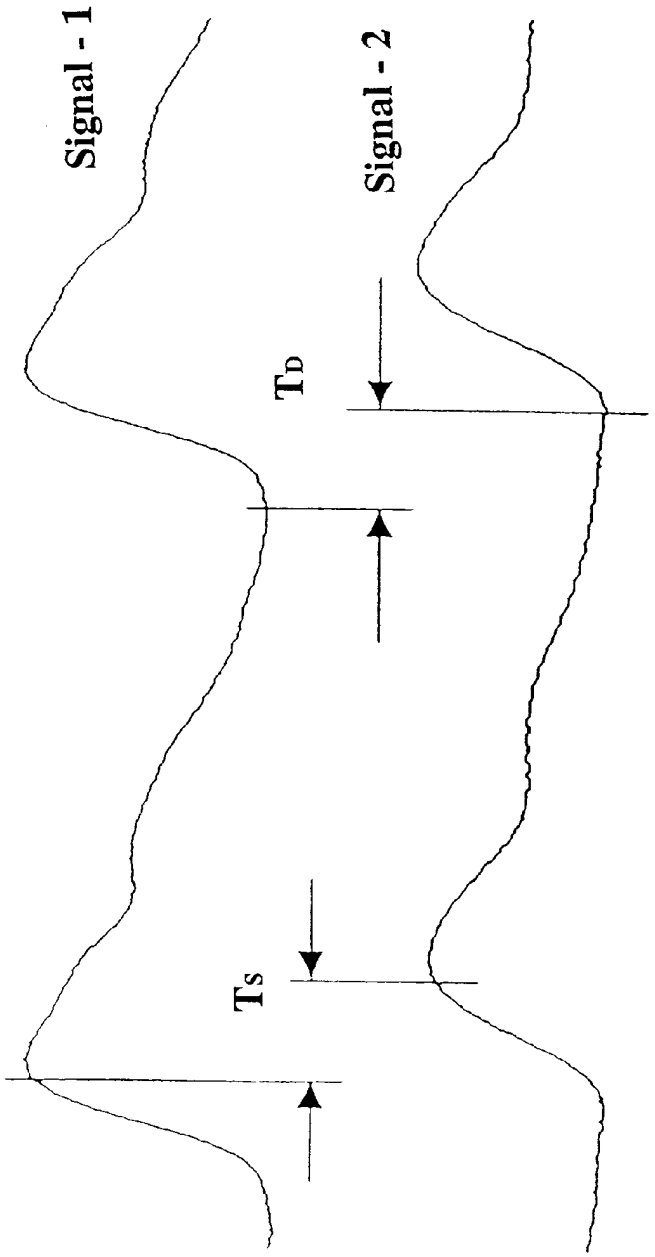


Figure 2

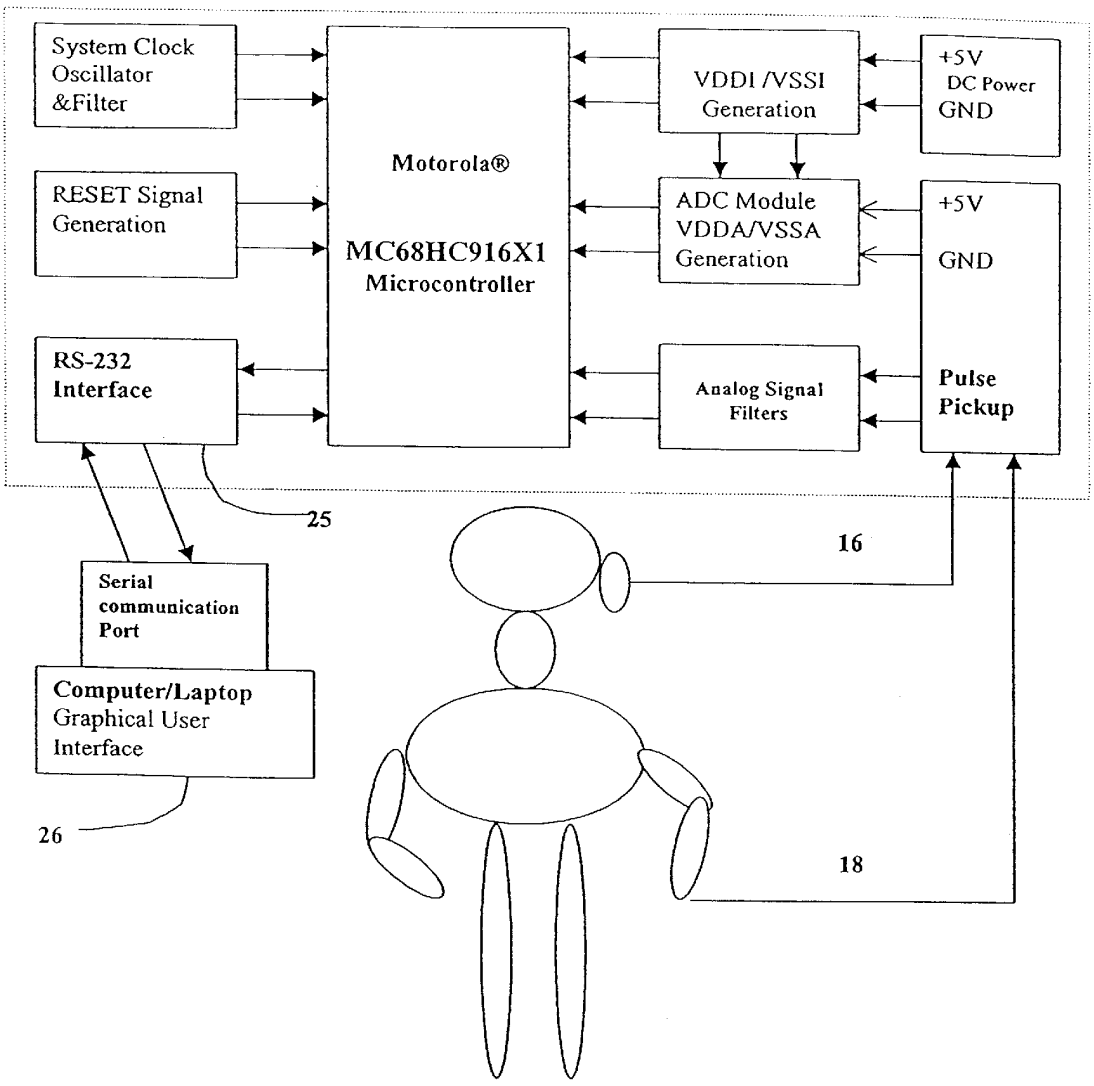

System Clock Oscillator &Filter
RESET Signal Generation
RS-232 Interface
Motorola®
MC68HC916X1
Microcontroller
VDDI /VSSI Generation
ADC Module VDDA/VSSA Generation
Analog Signal Filters
+5V DC Power
GND
+5V
GND
Pulse Pickup
25
16
18
Serial communication Port
Computer/Laptop Graphical User Interface
26

Figure 3

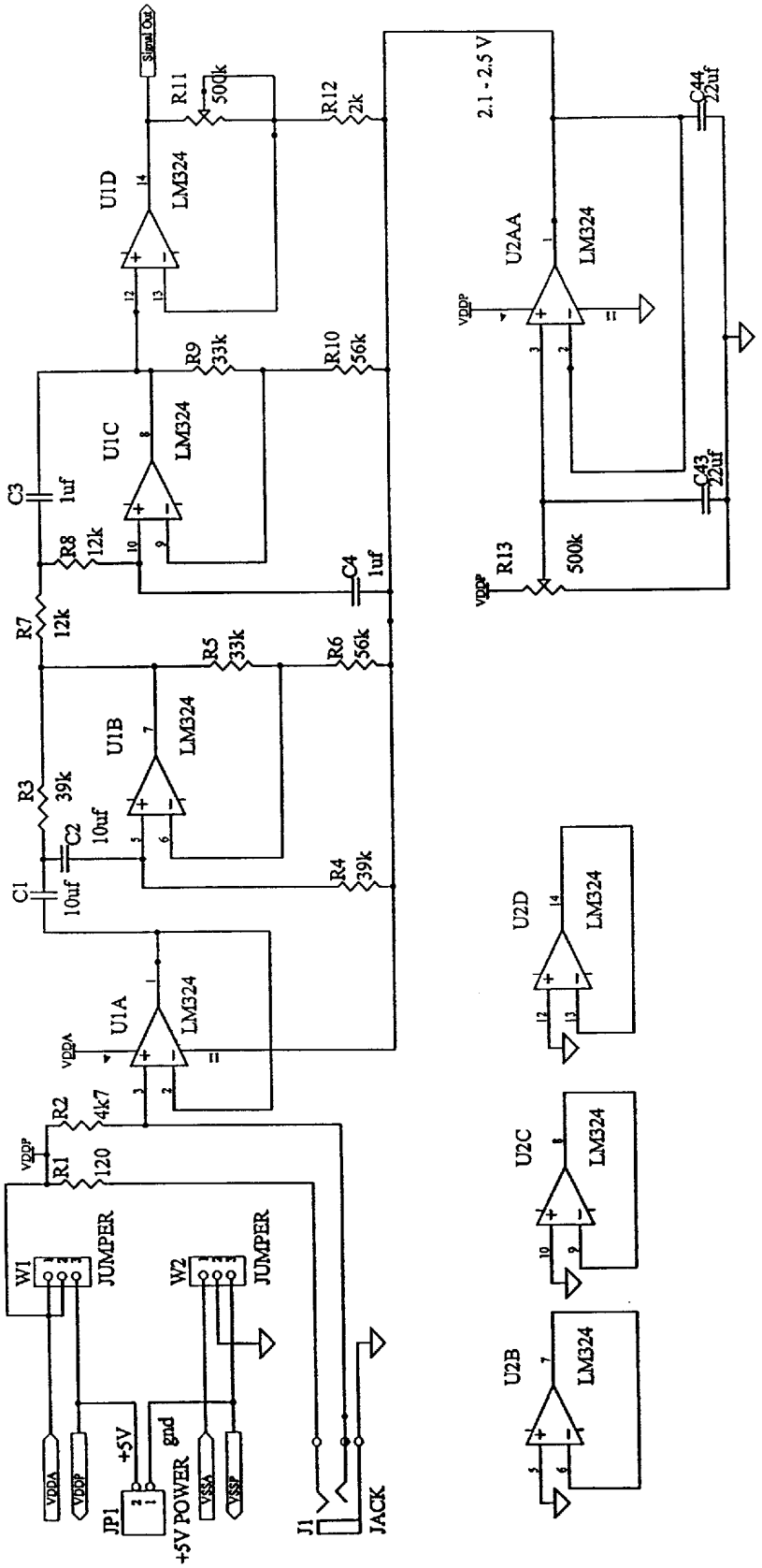

Signal Out
R11
500k
R12
2k
U1D
LM324
R9
33k
R10
56k
U1C
LM324
C3
1uf
R8
12k
C4
1uf
R7
12k
R5
33k
R6
56k
U1B
LM324
R3
39k
C2
10uf
C1
10uf
R4
39k
U1A
LM324
VDDA
R2
4k7
VDDP
R1
120
W1
JUMPER
W2
JUMPER
VDDA
VDDP
+5V
gnd
JP1
+5V POWER
VSSA
VSSP
J1
JACK
2.1 - 2.5 V
U2AA
LM324
VDDP
R13
500k
C44
22uf
C43
22uf
U2D
LM324
U2C
LM324
U2B
LM324

Figure 4

Figure 5

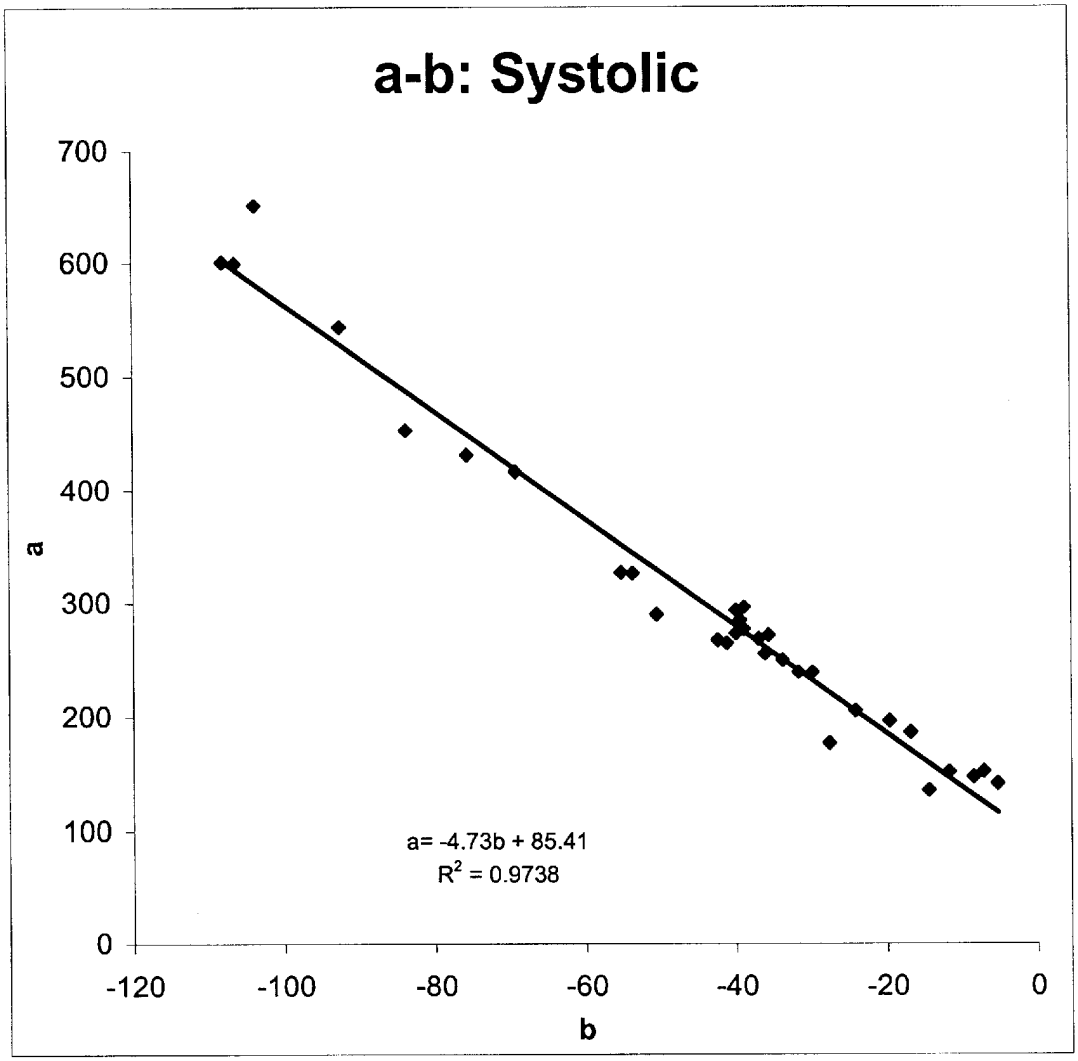

a-b: Systolic
700
600
500
400
300
200
100
0
a
-120
-100
-80
-60
-40
-20
0
b
a= -4.73b + 85.41
R2 = 0.9738

Figure 6

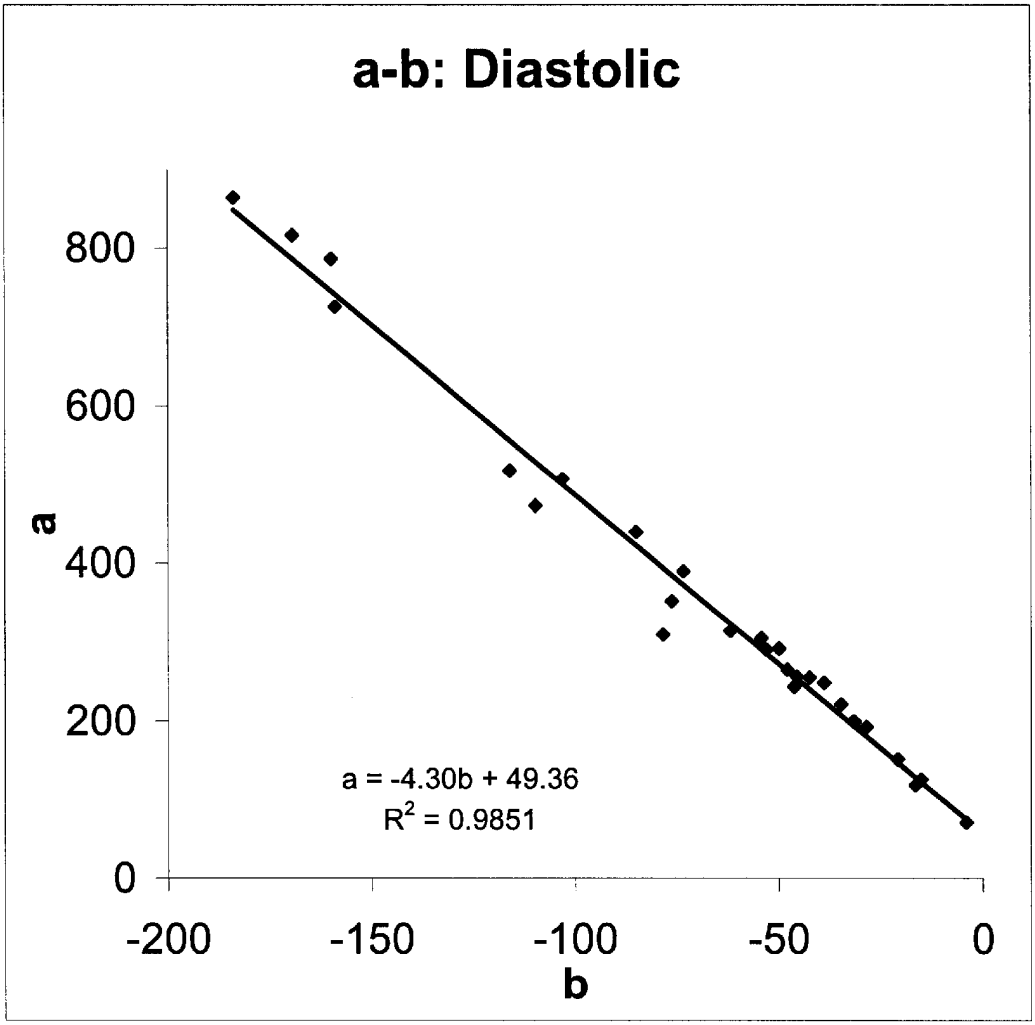

a-b: Diastolic
800
600
400
200
0
a
-200
-150
-100
-50
0
b
a = -4.30b + 49.36
R2 = 0.9851

Figure 7

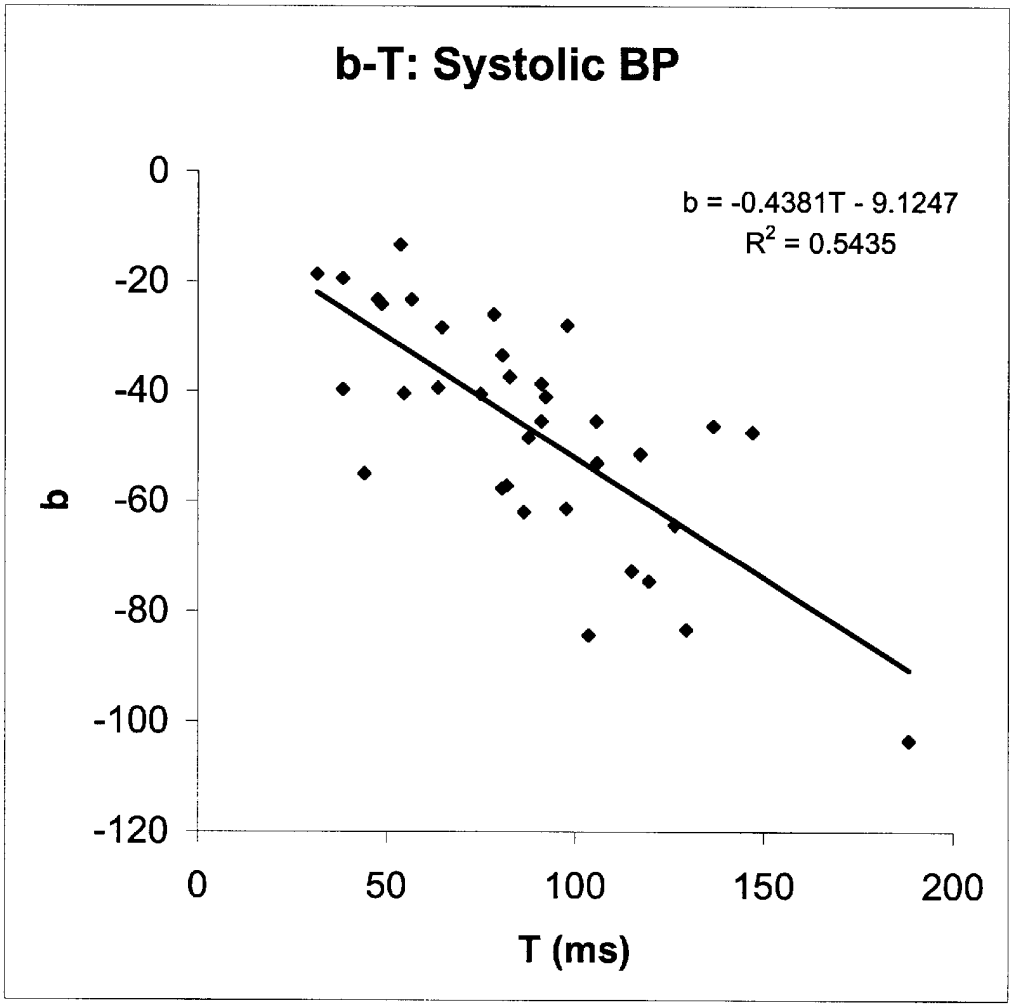

b-T: Systolic BP
b = -0.4381T - 9.1247
R2 = 0.5435
0
-20
-40
-60
-80
-100
-120
b
0
50
100
150
200
T (ms)

Figure 8

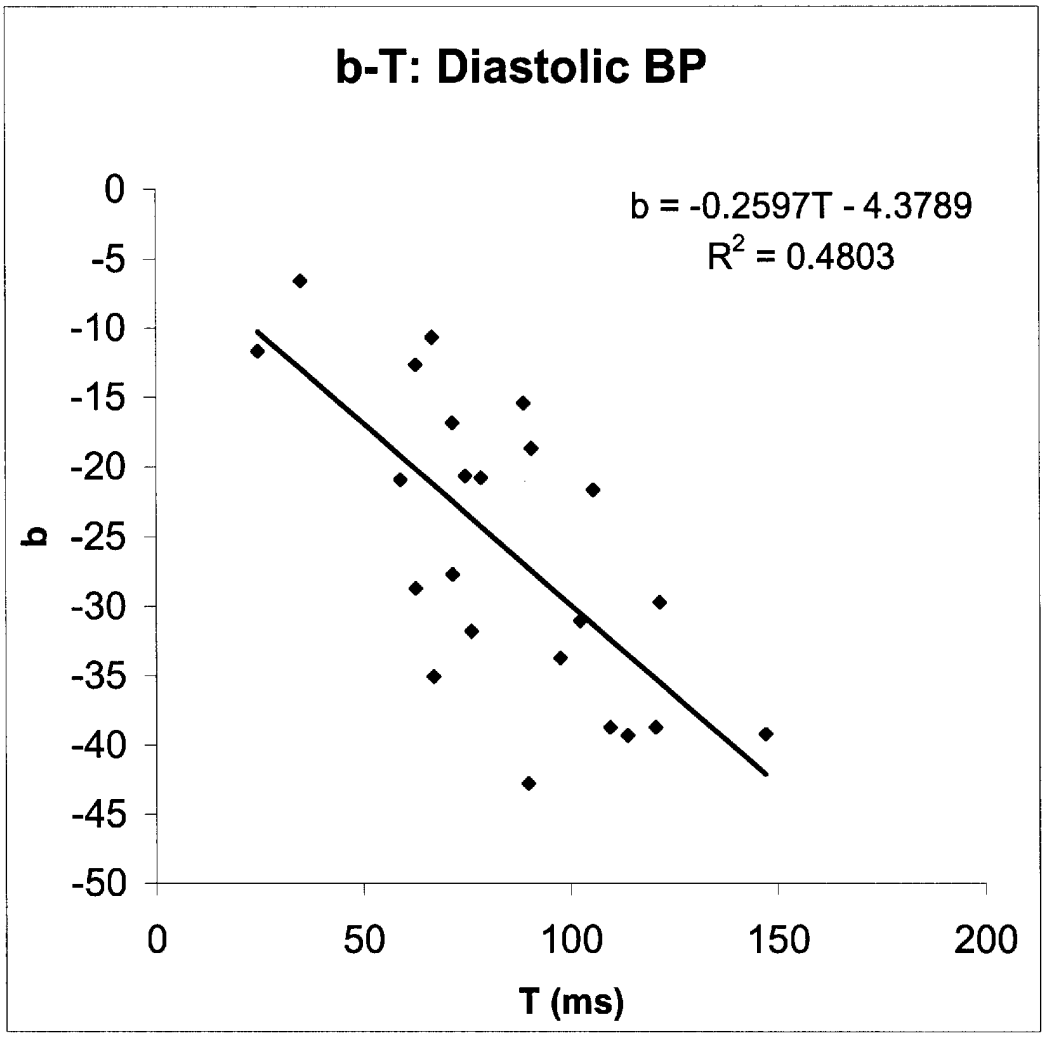
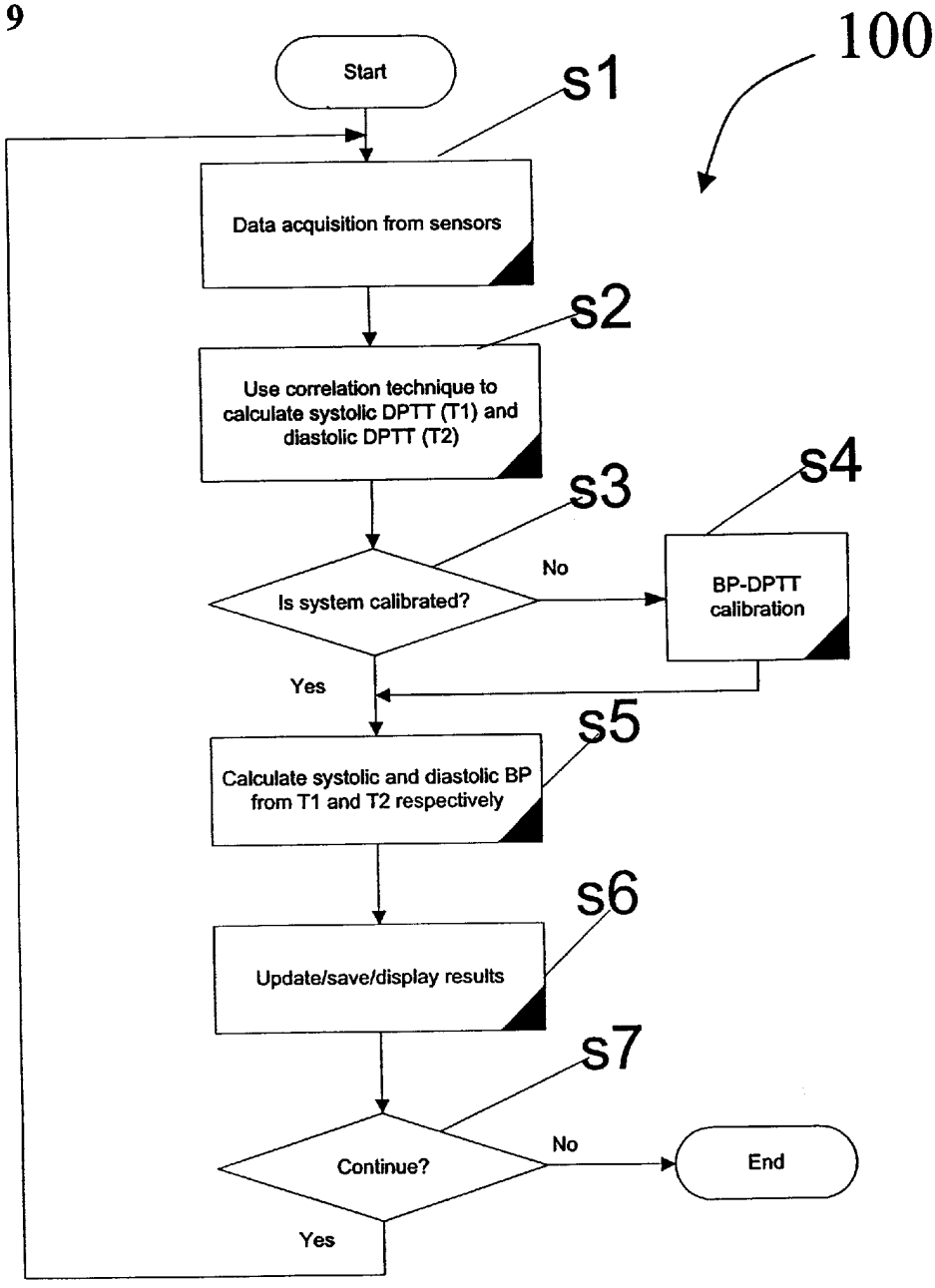

b-T: Diastolic BP
b = -0.2597T - 4.3789
R2 = 0.4803
b
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
0
50
100
150
200
T (ms)

Figure 9


100
Start
s1
Data acquisition from sensors
s2
Use correlation technique to calculate systolic DPTT (T1) and diastolic DPTT (T2)
s3
Is system calibrated?
No
s4
BP-DPTT calibration
Yes
s5
Calculate systolic and diastolic BP from T1 and T2 respectively
s6
Update/save/display results
s7
Continue?
No
End
Yes

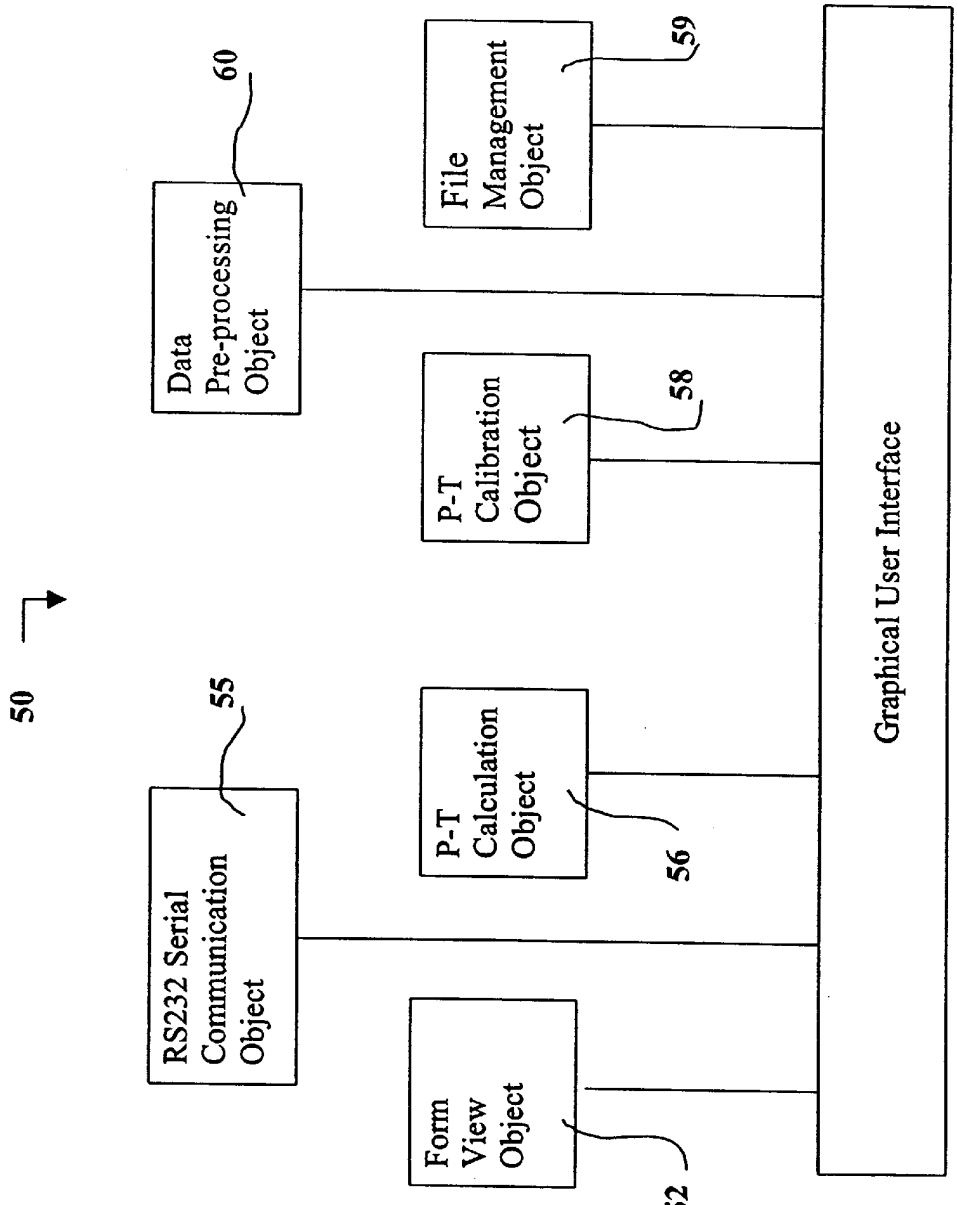

50
Graphical User Interface
Form View Object
52
RS232 Serial Communication Object
55
P-T Calculation Object
56
P-T Calibration Object
58
Data Pre-processing Object
60
File Management Object
59

Figure 10

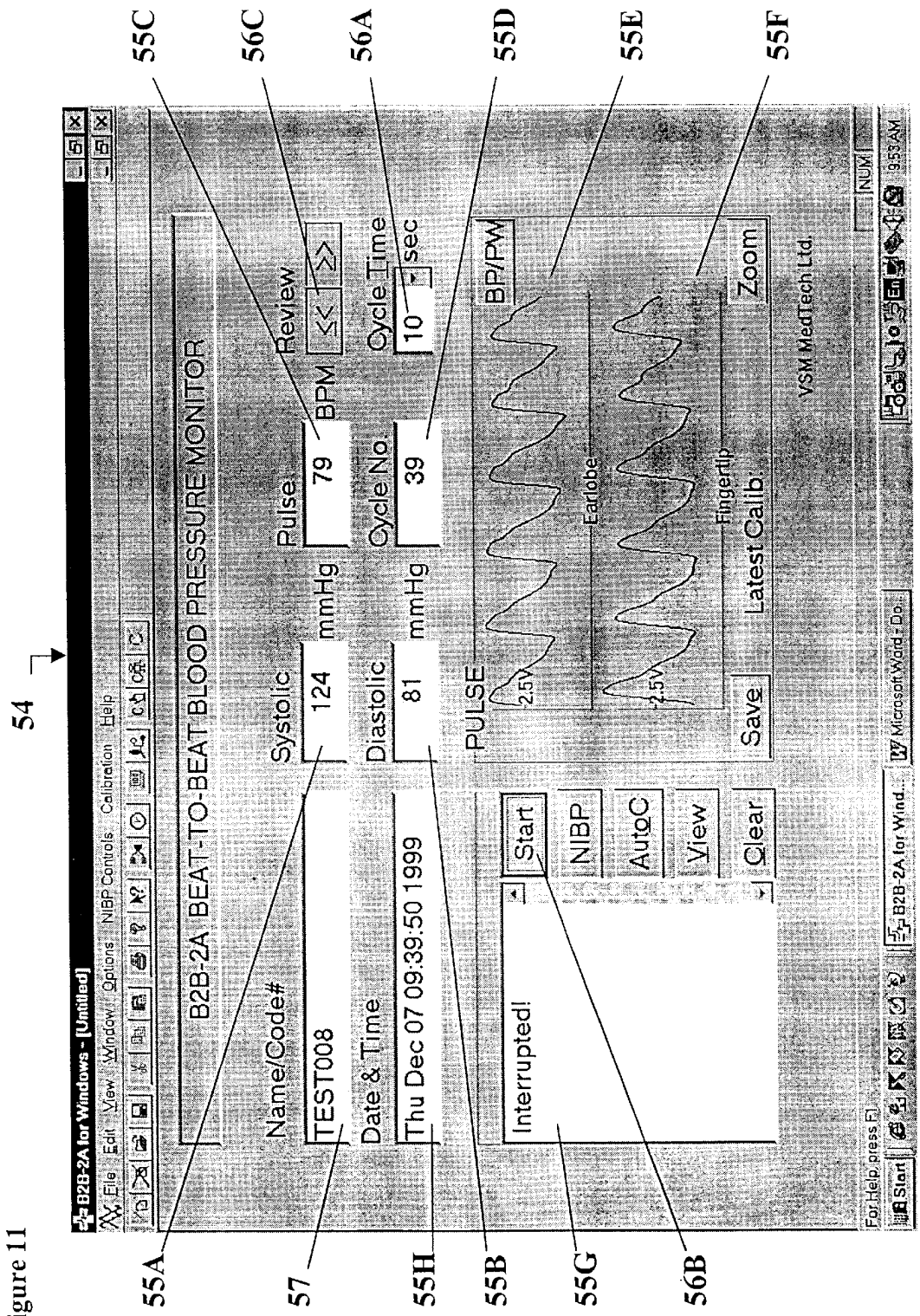

54
55C
56C
56A
55D
55E
55F
B2B-2A for Windows - [Untitled]
File Edit View Window Options NIBP Controls Calibration Help
B2B-2A BEAT-TO-BEAT BLOOD PRESSURE MONITOR
Review
<< >>
Pulse
79
BPM
Cycle Time
10
sec
Cycle No.
39
Systolic
124
mmHg
Diastolic
81
mmHg
Name/Code#
TEST008
Date & Time
Thu Dec 07 09:39:50 1999
PULSE
BP/PW
2.5V
Earlobe
2.5V
Fingertip
Zoom
Latest Calib:
VSM MedTech Ltd.
Interrupted!
Start
NIBP
AutoC
View
Clear
Save
55A
57
55H
55B
55G
56B
For Help, press F1
Start
B2B-2A for Wind...
Microsoft Word - Do...
NUM
9:53 AM

Figure 11

CONTINUOUS NON-INVASIVE BLOOD PRESSURE MONITORING METHOD AND APPARATUS

REFERENCE TO RELATED APPLICATION

This application claims the benefit of the filing dates of U.S. provisional patent application No. 60/178,027 filed on Jan. 26, 2000 and a continuation of PCT international application No. PCT/CA00/0152 filed on Dec. 22, 2000 and entitled CONTINUOUS BLOOD PRESSURE MONITORING METHOD AND APPARATUS.

FIELD OF THE INVENTION

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

BACKGROUND OF THE INVENTION

Various approaches have been tried for monitoring the blood pressure of living subjects. One approach is to insert a pressure sensor directly into a suitable artery in the subject. The sensor can be connected to a suitable monitoring device by a lead which passes through the subject'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 subject'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 subject'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 subject's heart to a selected point on a subject's artery. This approach is possible because the speed at which pulse waves travel from the heart to points downstream in a subject's blood circulatory system varies with blood pressure. As blood pressure rises the propagation velocity of arterial pulse waves increases and the pulse transit time 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 pulse wave generated by the heart beat at a downstream location. This approach is described, for example, by Inukai et al., U.S. Pat. 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 pulse waves. Other similar systems are described in Orr at al., European Patent application No. EP0181067. A variation of this approach is described in Golub, U.S. Pat. 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 pulse wave 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. Pat. No. 5,309,916 discloses a method for measuring blood pressure by determining the time taken for a 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 he difficult to arrange two sensors so that they can detect a 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 transmit a portion of the blood circulatory system is different for every subject. Thus, it is necessary to calibrate a PTT blood pressure measurement system for each subject.

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 a 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 elasticity and geometry of blood vessels and is highly nonlinear.

Inventors Aso et al., U.S. Pat. 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. Pat. No. 5,649,543. To calibrate the linear measurement system, Sugo et al., U.S. Pat. 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 Japanese 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 methods for monitoring blood pressure. The method comprises detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject; measuring a time difference between corresponding points on the first and second 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 subject 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.

Accordingly, a method for monitoring blood pressure according to one aspect of the invention comprises; detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject; measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals; from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference; monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters.

The multi-parameter equation may be the calculation:

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

or a mathematical equivalent thereof where a and b are constants.

In some specific embodiments, determining the plurality of constant parameters in the multi-parameter equation comprises performing calculations mathematically equivalent to:

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

and,

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

to obtain values for the constants a and b, where c_1 and c_2 are predetermined constants.

In other specific embodiments of the invention determining the plurality of constant parameters in the multi-parameter equation comprises performing calculations mathematically equivalent to:

$$a=P_0-(c_3T_0+c_4)\ln(T_0),$$

and

$$b=c_3T_0+c_4$$

where a and b are first and second parameters and c_3 and c_4 are predetermined constants.

In preferred embodiments of the invention the multi-parameter equation comprises a non-linear function which is monotonically decreasing and concave upward in a manner specified by the constant parameters.

The invention may be applied to measuring systolic blood pressures of subjects. In preferred embodiments of the invention measuring the time difference T comprises measuring a first time difference T_S for higher portions (ie portions corresponding generally to the parts of the signals associated with systolic blood pressure) of the first and second signals. Measuring the first time difference may comprise maximizing a cross-correlation between the first and second pulse signals. Preferably, in such measurements portions of the first and second pulse signals below a first threshold are not considered. The first threshold may be an average value for the signal (or equivalently a mean value for the signal).

Another aspect of the invention provides a method for estimating a blood pressure of a subject. The method comprises detecting a pulse signal at a first location; detecting the pulse signal at a second location; determining an elapsed time, T, between the arrival of corresponding points of the pulse signal at the first and second locations; and, 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.

Yet another aspect of the invention provides a method for estimating the blood pressure, P, of a subject. The method comprises: detecting a first pulse signal at a first location; detecting a second pulse signal at a second location; performing a calibration by measuring the subject's blood pressure P_0 and measuring a corresponding elapsed time, T_0, between the arrival of corresponding points of the first and second pulse signals; subsequently monitoring the subject's blood pressure by determining an elapsed time, T, between the corresponding points of the first and second pulse signals; and, calculating an estimated blood pressure, P, based on the value:

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

where c_1 and c_2 are constants.

A still further aspect of the invention provides a method for estimating the blood pressure, P, of a subject. The method comprises: detecting a first pulse signal at a first location; detecting a second pulse signal at a second location; performing a calibration by measuring the subject's blood pressure P_0 and measuring a corresponding elapsed time, T_0, between corresponding points of the first and second pulse signals; subsequently monitoring the subject's blood pressure by determining an elapsed time, T, between corresponding points of the first and second pulse signals; and, calculating an estimated blood pressure, P, substantially according to the equation:

$$P=P_0=(c_3T_0+c_4)\ln(T/T_0)$$

where c_3 and c_4 are constants.

Yet another aspect of the invention provides a method for estimating the blood pressure, P, of a subject. The method comprises: detecting a first pulse signal at a first location; detecting a second pulse signal at a second location; measuring a reference blood pressure P_0 and measuring a corresponding time difference, T_0, between corresponding points of the first and second pulse signals; from the reference blood pressure and corresponding time difference, determining a plurality of constant parameters in a multi-parameter equation relating blood pressure and the time difference by: determining a first parameter of the plurality of parameters as a predetermined function of the corresponding time difference; and, determining a second parameter of the plurality of parameters as a predetermined function of the reference blood pressure and the time difference; and, subsequently monitoring the subject's blood pressure by determining a time difference, T, between corresponding points of the first and second pulse signals and computing an estimated blood pressure from the time difference T using the multi-parameter equation and the first and second parameters.

Other aspects of the invention provide apparatus for making blood pressure measurements. One such aspect of the invention provides apparatus for estimating a blood pressure of a subject. The apparatus comprises a computer processor; an input for receiving a first signal corresponding to a pulse signal detected at a first location; an input for receiving a second signal corresponding to the pulse signal detected at a second location; 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.

Another apparatus-related aspect of the invention provides apparatus for estimating a blood pressure of a subject. The apparatus comprises: signal detection means for detecting first and second pulse signals; correlation means for determining an elapsed time, T, between the first and second pulse signals; computation means for computing an estimated blood pressure, P, from the elapsed time according to a non-linear function which is generally decreasing and concave upward in a manner specified by two or more settable parameters; calibration means for receiving a reference blood pressure and associating the reference blood pressure with an elapsed time determined by the correlation means; and, means responsive to the calibration means for establishing values for the two or more settable parameters from the reference blood pressure and elapsed time.

A still further aspect of the invention provides a program product comprising a medium bearing computer-readable signals. The signals contain instructions which, when executed on a computer processor, cause the computer processor to perform a method according to the invention.

Further advantages and features of the invention are described below.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. **1** is a block diagram of apparatus according to the invention;

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

FIG. **3** is a block diagram of apparatus according to one specific embodiment of the invention;

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

FIG. **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;

FIG. **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;

FIG. **7** is a plot illustrating a relationship between the constant b and T which may be taken advantage of in calibrating apparatus according to the invention for measuring systolic blood pressures;

FIG. **8** is a plot illustrating a relationship between the constant b and T which may be taken advantage of in calibrating apparatus according to the invention for measuring diastolic blood pressures;

FIG. **9** is a flow chart illustrating a computer-implemented method for estimating blood pressure according to the invention;

FIG. **10** illustrates a possible organization for software for use in the invention; and,

FIG. **11** is a view of a possible user interface display for use in the invention.

DETAILED DESCRIPTION

The methods of the invention use the difference in transit times of pulse waves to different points on a subject's anatomy to measure blood pressure As such, such methods may be called differential pulse transit time ("DPTT") methods FIG. **1** shows a blood pressure monitoring system **10** according to the invention. System **10** has an input sub-system comprising first and second sensors **12** and **14** which are each capable of detecting a pulse signal at a location on a subject. FIG. **2** depicts typical pulse signals **16** and **18**. Sensors **12** and **14** can advantageously be photoelectric pulse wave sensors on a 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 in weight and familiar to medical professionals.

Other types of sensor capable of detecting the arrivals of pulse waves at a location on a subject may also be used within the broad scheme of the invention. For example, FIG. **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 FIG. **4** is an example of one possible embodiment for signal conditioning circuitry which could be used in the practice of this invention.

Other types of sensors which are capable of generating a signal representing the arrivals of pulses at different locations on a subject's body could also be used. Some examples of such other types of sensors are ultrasound sensors, tonometric sensors, and oscillometric cuffs.

Sensors **12** and **14** are applied to first and second locations L1 and L2 on a subject P. In the example illustrated in FIG. **1**, L1 is an earlobe of the subject and L2 is a finger of the subject. L1 and L2 may be any places on a subject where

pulse signals can be readily detected by sensors **12** and **14** respectively L1 and L2 should be chosen so that a pulse wave (which originates at the subject's heart) takes a different amount of time to propagate to L1 than the pulse wave takes to propagate to L2. L1 and 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, L1 and 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, L1 and L2 are supplied by blood from different branches of the subject's arterial system so that L1 is not directly downstream from L2 and L2 is not directly downstream from L1.

Since locations L1 and L2 do not need to be supplied by blood by the same branch of a subject'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 **15** and **17** are generated at sensors **12** and **14** respectively. Signals **15** and **17** 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**. A single ADC **24** may be used to digitize both signals **16** and **18**. Separate ADC's could also be used for signals **16** and **18**.

Preferably each of signals **16** and **18** is sampled at a frequency of about 1 kHz, or greater. Most preferably the sampling frequency is 2 kHz or greater. If a sampling frequency of less than 1 kHz is used, interpolation of the sampled data is preferred used to achieve an effective sampling resolution of 1 millisecond or higher. ADC **24** can conveniently comprise an ADC integrated with a processor **24**A capable of forwarding digitized signals **16** and **18** to data processing device **26** through a suitable data communication interface **25** for further analysis. For example, ADC **24** may comprise the 8/10 bit ADC portion of a Motorola MC68HC916X1 microcontroller.

FIG. **2** shows first and second signals **16** and **18**. The digitized signals are provided to a data processing device **26**. Data processing device **26** may comprise, for example, a programmable device which obtains an estimated blood pressure from characteristics of first and second signals **16** and **18**. Data processing device **26** may comprise a computer/microcontroller/microprocessor/DSP or the like connected to ADC **24** by a suitable interface **25**.

FIG. **3** illustrates apparatus according to 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 data connection, which may comprise, for example, a standard RS-232 serial cable to the serial port of a data processing device **26**. Data processing device **26** may comprise a standard personal computer. In the embodiment of FIG. **3**, the personal computer is programmed to perform the steps necessary to process digitized signals **16** and **18** to yield estimated blood pressure values. In typical commercial embodiments of the invention processing device **26** is integrated with other parts of system **10** within a common housing and may comprise an embedded processor.

Data processing device **26** determines the time separating selected corresponding locations on the first and second signals **16** and **18**. Preferably, processing device **26** determines both the time difference T_S between the peaks of signals **16** and **18** for use in systolic blood pressure estimation and the time difference T_D between the valleys of the first and second signals **16** and **18** for use in diastolic blood pressure estimation.

There are numerous ways in which T_S and T_D can be measured. A preferred method 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:

$$C_{p1p2}(m) = \frac{1}{N}\sum_{n=0}^{N-m-1} p_1(n)p_2(n+m) \quad (1)$$

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

$$T=m|_{C\ max}\Delta t \quad (2)$$

The sampling time Δt may be, for example, 1 millisecond. The sampling time is determined by the sampling frequency.

In general, T_S and T_D are different. One way to separately measure T_S and T_D is to create from signals **16** and **18** a first set of signals $p_1(t)$ and $p_2(t)$ which include the peaks of signals **16** and **18** but do not include the 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_S. Similarly, a second set of signals $p_1(t)$ and $p_2(t)$ which include the valleys of signals **16** and **18** but do not include the peaks of signals **16** and **18** can be cross-correlated to obtain a value for T_D. The values for T_S and T_D can be used as described below to compute systolic and diastolic blood pressures, respectively.

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 a fixed value, such as 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 these average values as thresholds. Mean values of signals **16** and **18** could also be used as thresholds and may be considered, for the purpose of this disclosure, to be a type of average value.

The second set of signals can be created from signals **16** and **18**, for examples 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 a fixed value, such as zero, all data points having values greater than the threshold. A suitable threshold may be derived, for example, by computing the average or mean 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.

The values T_S and T_D may be obtained from signals **16** and **18** by methods other than computing correlations between signals **16** and **18**. For example, peaks or valleys of signals **16** and **18** may be determined by so-called "landmark detection" techniques. Some example landmark detection techniques which may be used in the invention are described in Schneider et al, "A noninvasive EMG technique

for investigating the excitation propagation in single motor units," *EMG Clinical Neurophysiology,* Vol. 29, pp.273–250, 1989 which is incorporated herein by reference.

Times T_S and T_D may be used to compute an estimate of a subject's blood pressure. The speed at which pulse waves propagate through a subject'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, N.J., 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:

$$v = \sqrt{tE_0/\rho d)e^{\lambda P}} = \frac{L}{T} \tag{3}$$

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; ρ is the density of blood; d is the diameter of the vessel; λ is a constant that depends on the elasticity 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 elasticity and geometry of a subject's blood vessels. Many of those who have attempted to measure blood pressure by measuring the propagation times of 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:

$$P=AT+B \tag{4}$$

where P and T are as defined above and A and B are parameters which are specific to each individual subject. 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) generally leads to inaccurate blood pressure estimates in case, where a subject 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 pulse signals at two locations **L1** and **L2** by way of a non-linear function. The non-linear function is preferably generally decreasing and is most preferably monotonically decreasing with increases in T. The non-linear function is preferably concave upward and is preferably specified by a pair of two parameters which can both be adjusted for purposes of calibration. In a preferred embodiment of the invention the non-linear function is generated by the following equation:

$$P=a+b\ln(T) \tag{5}$$

where P and T are as defined above and a and b are a pair of parameters to be determined for each individual subject by performing a calibration.

The inventors have discovered that the use of a function according to equation (5) for estimating blood pressure provides 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 P of a subject from a time difference T it is necessary to obtain values for the constants which are appropriate to the individual in question. Each of equations (4) and (5) includes two constants.

One way to calibrate system **10** for a specific individual is to make measurements of both time T and the subject's blood pressure P (using an alternative blood pressure measurement device such as sphygmomanometer or automatic blood pressure measurement device) at two times when the subject's blood pressure is different. At least two measurements are required. This yields two equations which can be solved to obtain the constants a and b for A and B).

Obtaining measurements of T at times when a subject has different blood pressures is inconvenient. In general a subject's blood pressure will not predictably fluctuate through a large enough range to obtain measurements of T at two different blood pressures within a convenient time.

Various techniques can be used to deliberately alter a subject'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 subject which have the effect of raising or lowering the subject's blood pressure (i.e. vasoactive drugs) by taking measurements both when a limb of the subject is in a raised position (so that the base hydrostatic pressure within the subject's blood circulatory system is increased) and in a lowered position (so that the base hydrostatic pressure within the subject's circulatory system is decreased); or causing the subject 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. Pat. No. 5,921,926. While all of these techniques may be used in some embodiments of the invention, none is ideal.

Clinical trials have been conducted to determine the values a and b of Equation (5). The parameters a and b were experimentally measured for a number of subjects. This can be done, for example, by measuring the subject's blood pressure and pulse transit time at a number of different times as the subject's blood pressure varies. Then one can fit the curve of Equation (5) to the data points for each subject to directly obtain values for a and b for that subject. The inventors have discovered that a and b are related generally linearly to one another by the equation:

$$a=c_1+c_2b \tag{6}$$

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 subjects is shown in FIG. **5**. A plot of the values of a and b for diastolic blood pressure measurements made on a number of subjects is shown in FIG. **6**.

By taking advantage of the unexpected 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:

$$P_S=c_{1S}+c_{2S}b_S+b_S\ln(T_S) \tag{7}$$

where P_S is estimated systolic blood pressure; and,

$$P_D=c_{1D}+c_{2D}b_D+b_D\ln(T_D) \tag{8}$$

where P_D is estimated diastolic blood pressure. The sets of constants b_S, C_{1S}, C_{2S}, and b_D, C_{1D}, C_{2D} in equations 7) and (8) are for systolic and diastolic blood pressures respec-

tively. In general, in this disclosure, the subscript S refers to systolic blood pressure and the subscript D refers to diastolic blood pressure.

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_{2D} and c_{2D} are respectively about 49.36 and −4.30 when blood pressure is expressed in mmHg, and PTT or DPTT is expressed in milliseconds. 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 −4.7±1. Preferably c_{1D} is in the range 50±10 and c_{2D} is in the range of −4.3±1. It will be appreciated that these constants will vary depending upon the units in which P and T are expressed.

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 calibration process can be done by taking a single reliable measurement of the subjects blood pressure (reference blood pressure, P_0) and a corresponding pulse transit time (reference pulse transit time, T_0) and calculating the values of a and b for the subject as follows:

$$a = c_1 + \frac{c_2(P_0 - c_1)}{\ln(T_0) + c_2} \tag{9}$$

$$b = \frac{P_0 - c_1}{\ln(T_0) + c_2} \tag{10}$$

where P_0 is obtained with a reference blood pressure device; T_0 is the measured elapsed time (either T_S or T_D) between the detection of a pulse at L**1** and the detection of the 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 either a data communication interface, or a manual interface (e.g. a keyboard). A reference blood pressure measuring device may also be integrated with system **10**.

After system **10** has been calibrated for a particular subject and for a particular pair L**1** and L**2** of sensor locations then the subject's systolic and diastolic blood pressures can be continuously estimated by frequently measuring T_S and T_D, as described above and computing estimated systolic and diastolic blood pressures through the use of the following equation:

$$P = c_1 + \frac{c_2(P_0 - c_1)}{\ln(T_0) + c_2} + \frac{P_0 - c_1}{\ln(T_0) + c_2}\ln(T). \tag{11}$$

System **10** can then display the subject's estimated blood pressure on a suitable display **54** (FIG. **11**), can compare the subject'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 subject and so on.

Those skilled in the art will understand that equation (5) may be closely approximated by various alternative equations. For example, the relationship between P and T may be represented over a suitable range of values of P by one of the following equations (where α, β, δ and λ are constant parameters):

$$P = \alpha T^{-\beta} \tag{12}$$

$$P = \delta e^{-\lambda T} \tag{13}$$

The values for the constant parameters in equations (12) and (13) or similar equations may be determined by performing a calibration using experimental data. This may be accomplished, for an individual subject by measuring several pairs of P and T values under conditions such that the subjects' blood pressure is not the same during all of the pairs of measurements. The equation in question can then be fit to the data using a suitable fitting technique such as least-squares fitting.

In general, the parameters of equation (12) (or (13)) are related to one another. This fact can be urged to permit single-point calibration of a device which uses one of these equations, or a similar equation, to model the relationship between P and T. The relationship may be derived, for example, by performing calibrations as described in the preceding paragraph, for a significant number of subjects, generating a scatter plot of points (α, β) (or (δ, λ)) and then fitting a curve to the resulting scatter of point. The cure can subsequently used to predict the value of one of the parameters given a value for the other one of the parameters.

When the values of the constants in Equation (5) (or one of equations (12) and (13)) have been determined (Parameters in equations (12) and (13) may be calibrated from a single or multiple reference blood pressure measurements), then an estimated value for P may be obtained by substituting the measured value for T into the appropriate equation.

In some cases performing calibration as described above can produce erroneous results. This is because no measurement of both a reference blood pressure and a corresponding reference pulse transit time can be precisely accurate. Errors in the values measured for the reference blood pressure and reference pulse transit time may result in significant errors in the values computed for the parameters a and b.

The inventors have discovered that there is a sufficiently good correlation between the parameter b of Equation (5) and the pulse transit time for use in calibration. This correlation is illustrated in FIGS. **7** and **8**. The curves of FIGS. **7** and **8** may be generated by: obtaining multiple P-T data points for each of a number of subjects; obtaining accurate values of a and b by fitting a "best" logarithmic trend line (Equation (5') to the P-T data points (which may be represented in a scatter chart) for each individual subject; plotting b as a function of T_a for selected subjects (for whom R-squared values for "best" logarithmic trend lines are greater than a suitable value such as 0.5), where T_a is the initial pulse transit time corresponding to the reference blood pressure or the average of all pulse transit time values for each individual subject, and then fitting a suitable curve to the resulting points b-T_a (which may be represented in a scatter chart). It has been found that good results can be obtained when the fitted curve is a "best" linear trend line,

$$b = c_3 T + c_4.$$

While the linear relationship between the value for b and the pulse transit time T_a is not perfect it is sufficient to permit calibration of system **10**. It can be seen from FIGS. **7** and **8** that the relationship between b and T_a is reasonably linear (pairs of b and T_a were selected with R-squared values for "best" P-T trend lines are typically greater than 0.5). The inventors have found that, for systolic blood pressure, the b-T relationship can be expressed as:

$$b=-0.4381T_a-9.1247 \quad (15)$$

(i.e. $c_{3S}=-0.4381$, $c_{4S}=-9.1247$).

For diastolic blood pressure, the inventors have found that the b-T relationship can be expressed as:

$$b=-0.2597T_a-4.3789 \quad (18)$$

(i.e. $c_{3D}=-0.2597$, $c_{4D}=-4.3789$).

Accordingly, some embodiments of the invention achieve calibration by determining the parameter b (of Equation (5)) from the measured reference differential pulse transit time T_0 according to the appropriate one of Equations (14) and (15). Then, the other parameter a is obtained based on both the reference blood pressure and reference differential pulse transit time (P_0, T_0) and the relationship of Equation (5).

In particular, a may be obtained as follows:

$$a=P_0-b\ln(T_0)=P_0-(c_3T_0+c_4)\ln(T_0) \quad (16)$$

After system **10** has been calibrated for a particular subject and for a particular pair L**1** and L**2** of sensor locations using one of the above methods, the subject's systolic and diastolic blood pressures can be continuously estimated by frequently measuring T_S and T_D, as described above, and computing estimated systolic and diastolic blood pressures through the use of the following equation:

$$P = P_0 - (c_3T_0 + c_4)\ln(T_0) + (c_3T_0 + c_4)\ln(T) \quad (17)$$

$$= P_0 + (c_3T_0 + c_4)\ln(T/T_0)$$

After the values of the parameters which define the relationship between T and P have been determined, it is not necessary to actually calculate the results of an equation every time that it is desired to make a new measurement of P. After appropriate values for the applicable constants have been determined then any of the above equations can be represented by storing values for P in a lookup table so that the value for P which corresponds to a measured value for T can be obtained by looking up the measured value for T in the lookup table.

Computer software or hardware that uses equation (5), a mathematical equivalent of equation (5), an alternative equation which relates P and T in substantially the same manner as equation (5) (such as one of equations (12) or (13)), or a lookup table to obtain a pre-computed value for P from a corresponding value for T may be called a "blood pressure estimation means".

FIG. **9** illustrates a method **100** that may be implemented in device **26** for deriving an estimated blood pressure from first and second pulse signals **16** and **18** device **26** executes software instructions which direct device **26** to request digitized signals **16** and **18** (block s**1**). Block s**1** may involve device **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 s**2** device **26** is directed to determine T_S and T_D by comparing digitized signals **16** and **18**. Block s**2** preferably involves computing cross-correlations from signals **16** and **18** as described above.

In block s**3**, device **26** is directed to determine whether it has calibration information for the current subject. If so then method **100** continues at block s**5** if not then method **100** proceeds to block s**4** in which device **26** runs computer instructions which cause device **26** to obtain calibration information for the current subject. Such calibration information may be obtained, for example, by requesting and obtaining information identifying a file accessible to device **26** in which calibration information for the subject in question gas been stored previously or by requesting input values for measured systolic and diastolic blood pressure from which the values for b can be calculated as described above.

System **10** may include a separate sub-system (not shown) for obtaining reference blood pressure values for calibration purposes. If so, calibration block s**4** may include reading a reference blood pressure value from such a sub-system. In the alternative, reference blood pressure valued may be entered on a keypad or other user interface.

In block s**5** device **26** runs computer instructions which cause it to obtain systolic and diastolic blood pressure estimates from the measured time delay (T_S or T_D) using equation (5) above (or an equivalent) and the values for a and b determined in block s**4**.

In block s**6** device **26** is directed to display computed blood pressure estimates on a suitable display connected to device **26**. Block **26** preferably includes saving the blood pressure estimate(s) in a file, and/or otherwise making the blood pressure estimates available for use.

In block s**7** data processing device **26** runs computer instructions which determine whether the blood pressure monitoring should continue. Block s**7** may include a user selectable delay so that a user can decide how frequently a new blood pressure estimate will be obtained. If device **26** determines in block s**7** that a further blood pressure estimate should be obtained then method **100** continues to block s**1**. If device **26** determines in block s**7** that a further blood pressure estimate should not be obtained then method **100** terminates and device **26** awaits further user instructions.

Method **100** may be implemented by running suitable computer software on a personal computer, micro-controller, or other suitable computer device. The computer device may comprise multiple processors. Different steps in method **100** may be performed on different processors.

Method **100** could also be completely implemented in hardware. For example, circuitry for implementing the methods of the invention could be provided on a field programmable gate array ("FPGA") or an application specific integrated circuit ("ASIC"). Apparatus according to the invention may be integrated within a device which performs additional functions. For example, signals **16** and/or **18** could be used to provide data for pulse oximetry determinations and/or pulse rate determinations.

FIG. **10** illustrates a possible software architecture for software **50** to be run on a device **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 FIG. **11**. 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** includes a portion **55**A for displaying estimated systolic blood pressure, a portion **55**B for displaying estimated diastolic blood pressure; a portion **55**C for displaying the subject's measured heart rate; and a portion **55**D for displaying the number of elapsed blood pressure measurement cycles. Portions **55**E and **55**F show digitized signals **16** and **18**. Portion **55**G displays status information. Portion **55**H displays the current system date and time.

Display **54** may include a number of user controls including a control **56**A for setting the cycle time; a control **56**B for starting a sequence of blood pressure estimations; a control **56**C for reviewing previously recorded blood pressure estimates for the same subject; a portion **57** for setting and displaying the name of the subject 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 parameter values for use in calculating a subject's blood pressure as described above. Calibration object **58** includes, or has access to, calibration information (such as the relationship of Equation (6)).

A file management object **59** moderates the storage of data in files and the retrieval of data from files accessible to device **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™ EXCEL™.

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 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 a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the multi-parameter equation is the calculation:

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

or a mathematical equivalent thereof, where a and b are constants.

2. The method of claim **1** wherein determining the plurality of constant parameters in the multi-parameter equation comprises performing calculations mathematically equivalent to:

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

and,

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

to obtain values for the constants a and b, where c_1 and c_2 are predetermined constants.

3. The method of claim **1** wherein the plurality of constant parameters comprise a first parameter a and a second parameter b and determining the plurality of constant parameters in the multi-parameter equation comprises performing calculations mathematically equivalent to:

$$a=P_0-(c_3T_0+c_4)\ln(T_0)$$

and,

$$b=c_3T_0+c_4$$

where c_3 and c_4 are predetermined constants.

4. A method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the multi-parameter equation comprises a non-linear function which is generally decreasing and concave upward in a manner specified by the constant parameters.

5. The method of claim **4** wherein the function is monotonically decreasing.

6. A method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the multi-parameter equation is the calculation:

ti $P=\alpha T^{-\beta}$

or a mathematical equivalent thereof where α and β are constants.

7. A method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the multi-parameter equation is the calculation:

$$P=\delta e^{-\lambda T}$$

or a mathematical equivalent thereof where δ and λ are constants.

8. A method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the timedifference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the blood pressure is a systolic blood pressure.

9. A method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters

wherein the method comprises measuring a systolic blood pressure of the subject wherein measuring the time difference T comprises measuring a first time difference T_s for portions of the first and second signals which do not include at least some diastolic portions of the signals.

10. A The method of claim **9** comprising additionally measuring a diastolic blood pressure of the subject by measuring a second time difference T_D for portions of the first and second pulse signals which do not include at least some systolic portions of the signals.

11. The method of claim **10** wherein measuring a reference blood pressure comprises measuring a calibration diastolic pressure and the method comprises, from the calibration diastolic blood pressure and corresponding second time difference T_D, determining a second plurality of constant parameters in the multi-parameter equation relating blood pressure and the second time-difference; and

the method comprises monitoring the subject's diastolic blood pressure by periodically measuring the second time difference T_D and, computing an estimated diastolic blood pressure, P_D, from the time difference, T_D, using the multi-parameter equation and the second plurality of constant parameters.

12. The method of claim **9** wherein measuring the first time difference comprises maximizing a cross-correlation between the first and second pulse signals.

13. The method of claim **12** wherein, in measuring the first time difference, portions of the first and second pulse signals below a first threshold are not considered.

14. The method of claim **13** wherein the threshold for the first pulse signal is an average value of the first pulse signal and the threshold for the second pulse signal is an average value of the second pulse signal.

15. A method for estimating a blood pressure of a subject, the method comprising:

a) detecting a first pulse signal at a first location;

b) detecting a second pulse signal at a second location;

c) determining an elapsed times, T, between the arrival of corresponding points of the first and second pulse signals; 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.

16. The method of claim **15** wherein the corresponding points are peaks of the pulse signals.

17. The method of claim **15** wherein the corresponding points are valleys of the pulse signals.

18. The method of claim **15** wherein determining the elapsed time comprises computing a cross-correlation of the first pulse signal and the second pulse signal.

19. The method of claim **18** comprising performing a calibration by taking a reference blood pressure reading to obtain a reference blood pressure P_0 and measuring the elapsed time T_0 corresponding to the reference blood pressure and performing the calculations:

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

and,

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

or calculations substantially equivalent thereto to obtain values for the parameters a and b.

20. The method of claim **18** comprising performing a calibration by taking a reference blood pressure reading to obtain a reference blood pressure P_0 and measuring the elapsed time T_0 corresponding to the reference blood pressure and performing the calculations:

$$a=P_0-(c_3T_0+c_4)\ln(T_0)$$

and,

$$b=c_3T_0+c_4$$

or calculations substantially equivalent thereto where c_3 and c_4 are predetermined constants.

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

a) detecting a first pulse signal at a first location on the subject;

b) detecting a second pulse signal at a second location on the subject;

c) performing a calibration by measuring the subject's blood pressure P_0 and measuring a corresponding elapsed time, T_0, between the arrival of corresponding points of the first and second pulse signals;

d) subsequently monitoring the subject's blood pressure by determining an elapsed time, T, between the arrival of corresponding points of the first and second pulse signals; and,

e) calculating an estimated blood pressure, P, based on the value:

$$\frac{(P_0 - c_1)}{(\ln(T_0) + C_2)}$$

where c_1 and a_2 are constants.

22. The method of claim **21** wherein calculating the estimated blood pressure comprises performing the computation:

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

or a substantially mathematically equivalent computation.

23. The method of claim **22** wherein c_1 is about 85.41, and c_2 is about −4.73 for systolic pressure measurements.

24. The method of claim **23** wherein c_1 is about 49.36 and c_2 is about −4.3 for diastolic pressure measurements.

25. The method of claim **23** wherein c_1 is in the range of 85±10 and c_2 is in the range of −4.7±1 for systolic pressure measurements.

26. The method of claim **23** wherein c_1 is in the range of 50±10 and c_2 is in the range of −4.3±1 for diastolic pressure measurements.

27. The method of claim **23** where c_1 and c2 are derived by:

for several subjects, at each of two or more times, measuring a reference blood pressure value P_0 and a corresponding elapsed time, T_0, between corresponding points of the first and second pulse signals;

for each of the subjects determining best fit values for a and b such that:

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

for the measured reference blood pressure values find elapsed times;

based upon the values for a and b determining best fit values for c_1 and c_2 such that:

$$a=c_1+c_2b.$$

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

a) detecting a first pulse signal at a first location on the subject;

b) detecting a second pulse signal at a second location on the subject;

c) performing a calibration by measuring the subject's blood pressure P_0 and measuring a corresponding elapsed time, T_0, between the arrival of corresponding points of the first and second pulse signals;

d) subsequently monitoring the subject's blood pressure by determining an elapsed time, T, between the arrival of corresponding points of the first and second pulse signals; and,

f) calculating and estimated blood pressure, P, substantially according to the equation:

$$P=P_0+(c_3T_0+c_4)\ln(T/T_0)$$

where c_3 and c_4 are constants.

29. The method of claim **28** wherein c_3 is about −0.4381 and c_4 is about −9.1247 for systolic pressure measurements.

30. The method of claim **28** wherein c_3 is about −0.2597 and c_4 is about −4.3789 for diastolic pressure measurements.

31. The method of claim **28** wherein c_3 is in the range of −0.4381±0.1 and c_4 is in the range of −9.1247±1.2 for systolic pressure measurements.

32. The method of claim **28** wherein c_3 is in the range of −0.2597±0.1 and c_4 is in the range of −4.3789±1.0 for diastolic pressure measurements.

33. The method of claim **28** where c_3 and c_4 are derived by:

for several subjects, at each of two or more times, measuring a reference blood pressure value P_0 and a corresponding elapsed time, T_0, between corresponding points of first and second pulse signals detected at first and second locations on the subject;

for each of the subjects 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 b and an initial pulse transit time or an average pulse transit time, T_a, determining best fit values for c_3 and c_4 such that:

$$b=c_3T_a+c_4.$$

34. 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 pulse signal detected at a first location;

c) an input for receiving a second signal corresponding to the pulse signal detected at a second location;

d) 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.

35. The apparatus of claim **34** wherein the corresponding points correspond to the valleys of the pulse signals for a diastolic blood pressure estimation.

36. The apparatus of claim **34** wherein the corresponding points correspond to the peaks of the pulse signals for a systolic blood pressure estimation.

37. The apparatus of claim **34** wherein the software comprises a set of instructions which cause the computer processor to compute a cross-correlation of the first and second signals.

38. The apparatus of claim **37** comprising an input for receiving a reference signal indicative of a reference blood pressure value.

39. Apparatus for estimating a blood pressure of a subject, the apparatus comprising:

a) signal detection means for detecting first and second pulse signals;

b) correlation means for determining an elapsed time, T, between the first and second pulse signals;

c) computation means for computing an estimated blood pressure, P, from the elapsed time according to a non-linear function which is generally decreasing and concave upward in a manner specified by two or more settable parameters; and,

d) calibration means for receiving a reference blood pressure and associating the reference blood pressure with an elapsed time determined by the correlation means; and,

e) means responsive to the calibration means for establishing values for the two or more settable parameters from the reference blood pressure and elapsed time.

40. The apparatus of claim **39** wherein the non-linear function is monotonical decreasing.

41. The apparatus of claim **39** wherein the calculation means performs the calculation:

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

where a and b are the settable parameters.

42. The apparatus of claim **39** wherein the correlation means determines separate first and second time differences T_S and T_D respectively from higher and lower portions of the first and second pulse signals respectively.

43. The apparatus of claim **42** wherein the computation means comprises diastolic blood pressure computation means for computing a diastolic blood pressure from the first time difference and systolic blood pressure computation means for computing a systolic blood pressure from the second time difference.

44. The apparatus of claim **39** wherein the correlation means comprises a buffer for holding a segment of the first pulse signal, a buffer for holding a segment of the second pulse signal and a processor executing instructions which cause the processor to determine a time difference for which a cross correlation between the segment of the first pulse signal and the segment of the second pulse signal is maximized.

45. The apparatus of claim **44** wherein the correlation means determines separate first and second time differences T_S and T_D respectively from higher and lower portions of the first and second pulse signals respectively.

46. The apparatus of claim **45** wherein the correlation means comprises means for computing an average value of each of the first and second pulse signals and the higher portions comprise portions having a value in excess of the average value.

47. The apparatus of claim **44** wherein the correlation means comprises means for creating from the first and second pulse signals a first set of modified signals $p_1(t)$ and $p_2(t)$ which include the peaks of the first and second pulse signals but do not include valleys of the first and second pulse signals and the correlation means determines a first time difference T_S by determining a time shift which yields a maximum correlation between signals of the first set of modified signals.

48. A program product comprising a medium bearing computer-readable signals, the signals containing instructions which, when executed on a computer processor, cause the computer processor to perform a method for monitoring blood pressure, the method comprising:

a) detecting a first pulse signal at a first location on a subject and detecting a second pulse signal at a second location on the subject;

b) measuring a reference blood pressure P_0 and a corresponding time difference T_0 between the first and second pulse signals;

c) from the reference blood pressure and corresponding time difference, determining a first plurality of constant parameters in a multi-parameter equation relating blood pressure and the time-difference;

d) monitoring the subject's blood pressure by periodically measuring a time difference T between the first and second pulse signals; and,

e) computing an estimated blood pressure, P, from the time difference, T, using the multi-parameter equation and the first plurality of constant parameters.

49. A method for obtaining a value representing a blood pressure of a subject, the method comprising:

measuring a reference blood pressure P_0 and determining a corresponding reference time difference, T_0 by at least:

receiving a first pulse signal detected at a first location on the subject;

receiving a second pulse signal detected at a second location on the subject; and,

determining the reference time difference, T_0, by measuring a time shift between corresponding points of the first and second pulse signals;

based upon the reference blood pressure and the reference time difference, obtaining a non-linear function relating blood pressure and time difference for the subject; and,

at one or more subsequent times, computing an estimated blood pressure, P, by at least:

at the one or more subsequent times, determining a time difference, T, between corresponding points of the first and second pulse signals and computing the non-linear function of the time difference

wherein obtaining the non-linear function comprises determining at least two parameters of the non-linear function.

50. The method of claim **49** wherein obtaining the non-linear function comprises determining a first one of the at least two parameters as a predetermined function of the reference time difference.

51. The method of claim **50** wherein obtaining the non-linear function comprises determining a second one of the at least two parameters based upon the first one of the at least two parameters the reference blood pressure and the reference time difference.

52. The method of claim **51** wherein the non-linear function comprises a logarithmic function of T and, in the non-linear function, the logarithmic function of T is multiplied by the first one of the parameters.

53. The method of claim **52** wherein, the non-linear function comprises adding the second one of the parameters to a result.

54. The method of claim **51** wherein obtaining the first parameter comprises performing the calculation

$$b=c_3T_0+c_4$$

where b is the first parameter and c_3 and c_4 are predetermined constants, or a calculation mathematically equivalent thereto.

55. The method of claim **54** wherein obtaining the second parameter comprises performing the calculation:

$$a=P_0-b\ln(T_0)$$

where a is the second parameter, or a calculation mathematically equivalent thereto.

56. The method of claim **50** wherein the predetermined function is a function obtained by:

collecting multiple pairs of reference time difference and reference blood pressure for each of a plurality of reference subjects;

for each of the plurality of reference subjects fitting the non-linear function to the multiple pairs of reference time difference and reference blood pressure to obtain values for the first and second parameters for each of the plurality of reference subjects; and,

fitting a suitable curve to obtain the predetermined function.

57. The method of claim **56** wherein the suitable curve comprises a linear trend line.

58. The method of claim **57** wherein the plurality of reference subjects is selected by picking reference subjects for whom a measure of fit between the non-linear function and the multiple pairs of reference time difference and reference blood pressure exceeds a threshold.

59. The method of claim **58** wherein the measure of fit comprises an R-squared value.

60. A method for obtaining a value representing a blood pressure of a subject, the method comprising:

measuring a reference blood pressure P_0 and determining a corresponding reference time difference, T_0 by at least:

receiving a first pulse signal detected at a first location on the subject;

receiving a second pulse signal detected at a second location on the subject; and,

determining the reference time difference, T_0, by measuring a time shift between corresponding points of the first and second pulse signals;

based upon the reference blood pressure and the reference time difference, obtaining a nonlinear function relating blood pressure and time difference for the subject; and,

at one or more subsequent times, computing an estimated blood pressure, P, by at least:

at the one or more subsequent times, determining a time difference, T, between corresponding points of the first and second pulse signals and computing the non-linear function of the time difference

wherein the non-linear function comprises a logarithmic function of T.

61. A method for obtaining a value representing a blood pressure of a subject, the method comprising:

measuring a reference blood pressure P_0 and determining a corresponding reference time difference, T_0 by at least:

receiving a first pulse signal detected at a first location on the subject;

receiving a second pulse signal detected at a second location on the subject; and,

determining the reference time difference, T_0, by measuring a time shift between corresponding points of the first and second pulse signals;

based upon the reference blood pressure and the reference time difference, obtaining a non-linear function relating blood pressure and time difference for the subject; and,

at one or more subsequent times, computing an estimated blood pressure, P, by at least:

at the one or more subsequent times, determining a time difference, T, between corresponding points of the first and second pulse signals and computing the non-linear function of the time difference

wherein the value representing a blood pressure of a subject represents a systolic blood pressure of the subject and the corresponding points on the first and second signals are in parts of the first and second signals corresponding to a systolic portion of the subject's pulse.

62. A method for obtaining a value representing a blood pressure of a subject, the method comprising:

measuring a reference blood pressure P_0 and determining a corresponding reference time difference, T_0 by at least:

receiving a first pulse signal detected at a first location on the subject;

receiving a second pulse signal detected at a second location on the subject; and,

determining the reference time difference, T_0, by measuring a time shift between corresponding points of the first and second pulse signals;

based upon the reference blood pressure and the reference time difference, obtaining a non-linear function relating blood pressure and time difference for the subject; and,

at one or more subsequent times, computing an estimated blood pressure, P, by at least:

at the one or more subsequent times, determining a time difference, T, between corresponding points of the first and second pulse signals and computing the non-linear function of the time difference

wherein the non-linear function comprises a logarithmic function of T.

63. A method for obtaining a value representing a blood pressure of a subject, the method comprising:

measuring a reference blood pressure P_0 and determining a corresponding reference time difference, T_0 by at least:

receiving a first pulse signal detected at a first location on the subject;

receiving a second pulse signal detected at a second location on the subject; and,

determining the reference time difference, T_0, by measuring a time shift between corresponding points of the first and second pulse signals;

based upon the reference blood pressure and the reference time difference, obtaining a non-linear function relating blood pressure and time difference for the subject; and,

at one or more subsequent times, computing an estimated blood pressure, P, by at least:

at the one or more subsequent times, determining a time difference, T, between corresponding points of the first and second pulse signals and computing the non-linear function of the time difference

wherein the value representing a blood pressure of a subject represents a systolic blood pressure of the subject and the corresponding points on the first and second signals are in parts of the first and second signals corresponding to a systolic portion of the subject's pulse.

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