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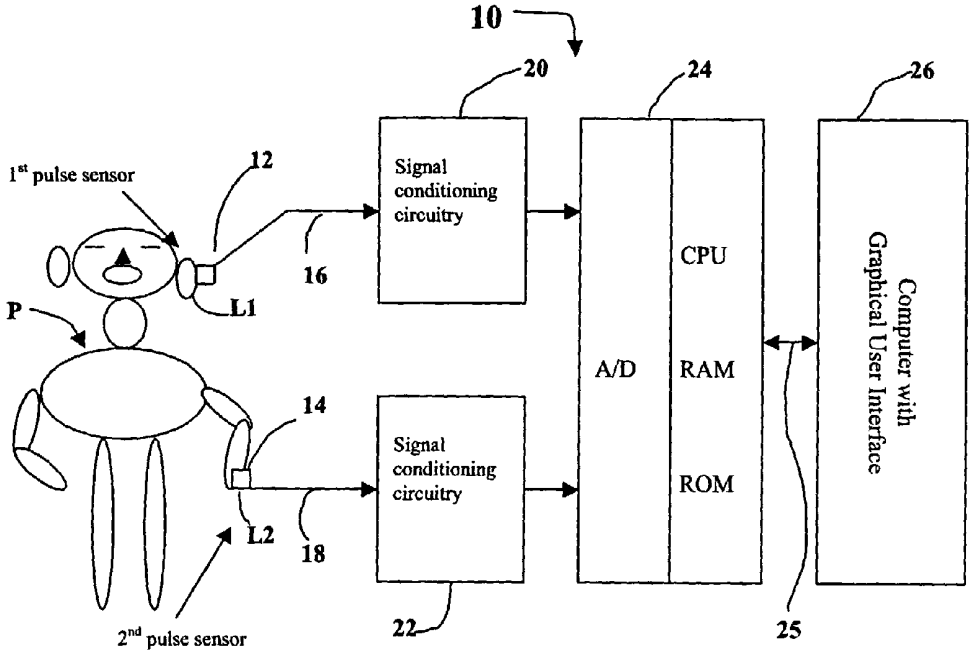

(57) Abstract: A non-invasive apparatus and method for monitoring the blood pressure of a subject detects a blood pressure pulse signal at both a first and second location on the subject's body. The elapsed time between the arrival of corresponding points of the blood pressure pulse signal at the first 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.

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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 **L2** should be chosen so that a pressure pulse wave from the patient's heart takes a different amount of time to propagate to **L1** than the pulse 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 patient'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 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:

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

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

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

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

One way to separately measure the time differences **T1** and **T2** 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 **T1**. 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 **T2**. The values for **T1** and **T2** 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:

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

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; ***d*** is the diameter of the vessel; λ 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:

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

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 ***L1*** and ***L2*** as follows:

$$P = a + b\ln(T) \quad (5)$$

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:

$$a = c_1 + c_2 b \qquad (6)$$

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 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 and 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±1. Preferably c_{1D} is in the range 50±10 and c_{2D} is in the range of -4±1.

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:

$$P_{systolic} = c_{1S} + c_{2S}b_S + b_S \ln(T1) \quad (7)$$

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

$$P_{Diastolic} = c_1 + c_2 b_D + b_D \ln(T2) \quad (8)$$

$P_{diastolic}$ 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:

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

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

where P_0 is the measured reference blood pressure; T_0 is the measured elapsed time (either ***T1*** or ***T2***) between the detection of a pressure pulse at **L1** and the detection of the pressure pulse at **L2** 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 **L1** and **L2** of sensor locations then the patient's blood pressure can be continuously estimated by frequently measuring ***T1*** and ***T2***, as described above, and computing an estimated blood pressure through the use of the following equation:

$$P = \{c_1 + c_2(P_0 - c_1)/[\ln(T_0) + c_2]\} + \{(P_0 - c_1)/[\ln(T_0) + c_2]\}\ln(T) \tag{11}$$

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 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, micro-controller, 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™ **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 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_0 and measuring the elapsed time T_0 corresponding to the reference blood pressure and performing the calculations:

$$a = c_1 + c_2(P_0 - c_1)/(\ln(T_0) + c_2)$$

and,

$$b = (P_0 - c_1)/(\ln(T_0) + c_2)$$

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 1

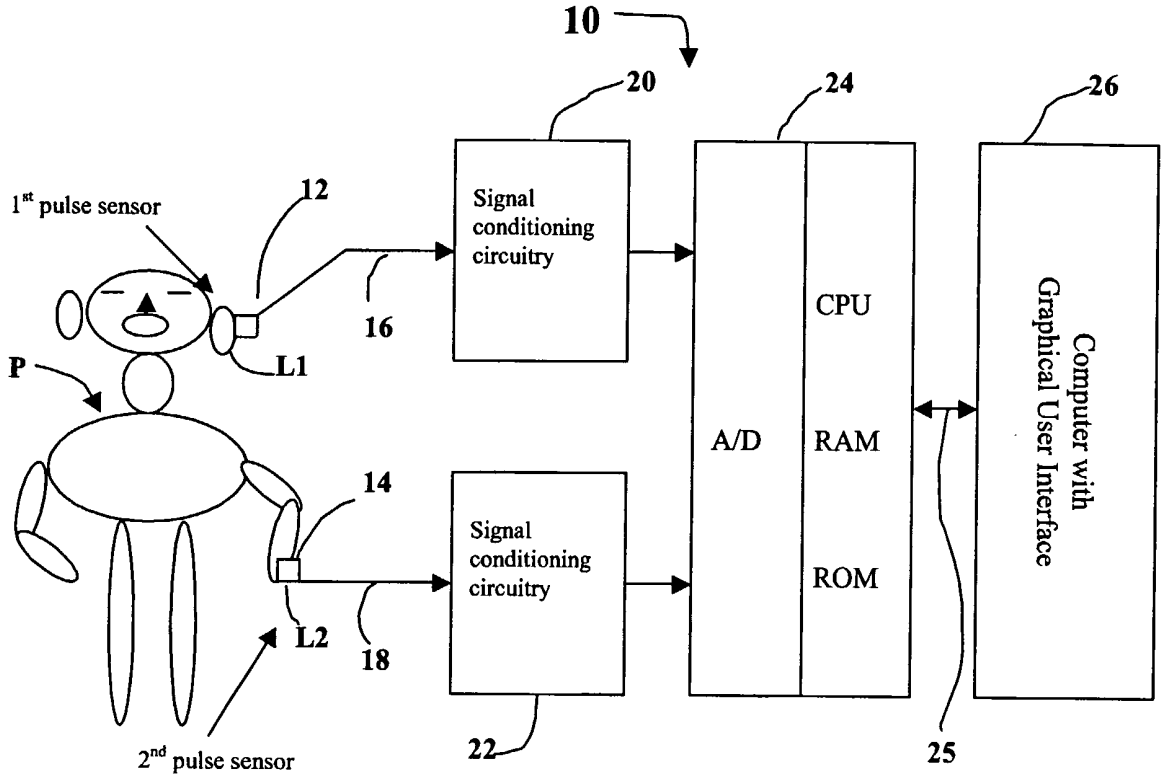
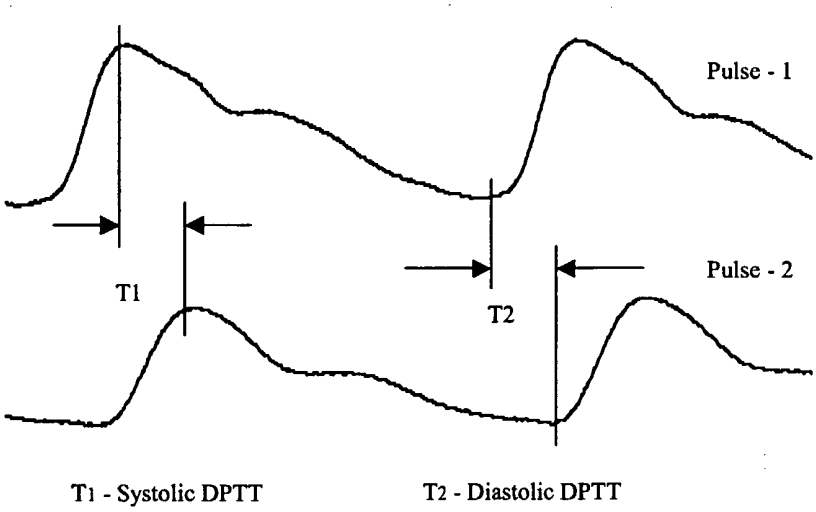

10
20
24
26
1st pulse sensor
12
Signal conditioning circuitry
CPU
Computer with Graphical User Interface
16
P
L1
A/D
RAM
14
Signal conditioning circuitry
ROM
L2
18
2nd pulse sensor
22
25

Figure 2



T_1 - Systolic DPTT T_2 - Diastolic DPTT

Figure 3

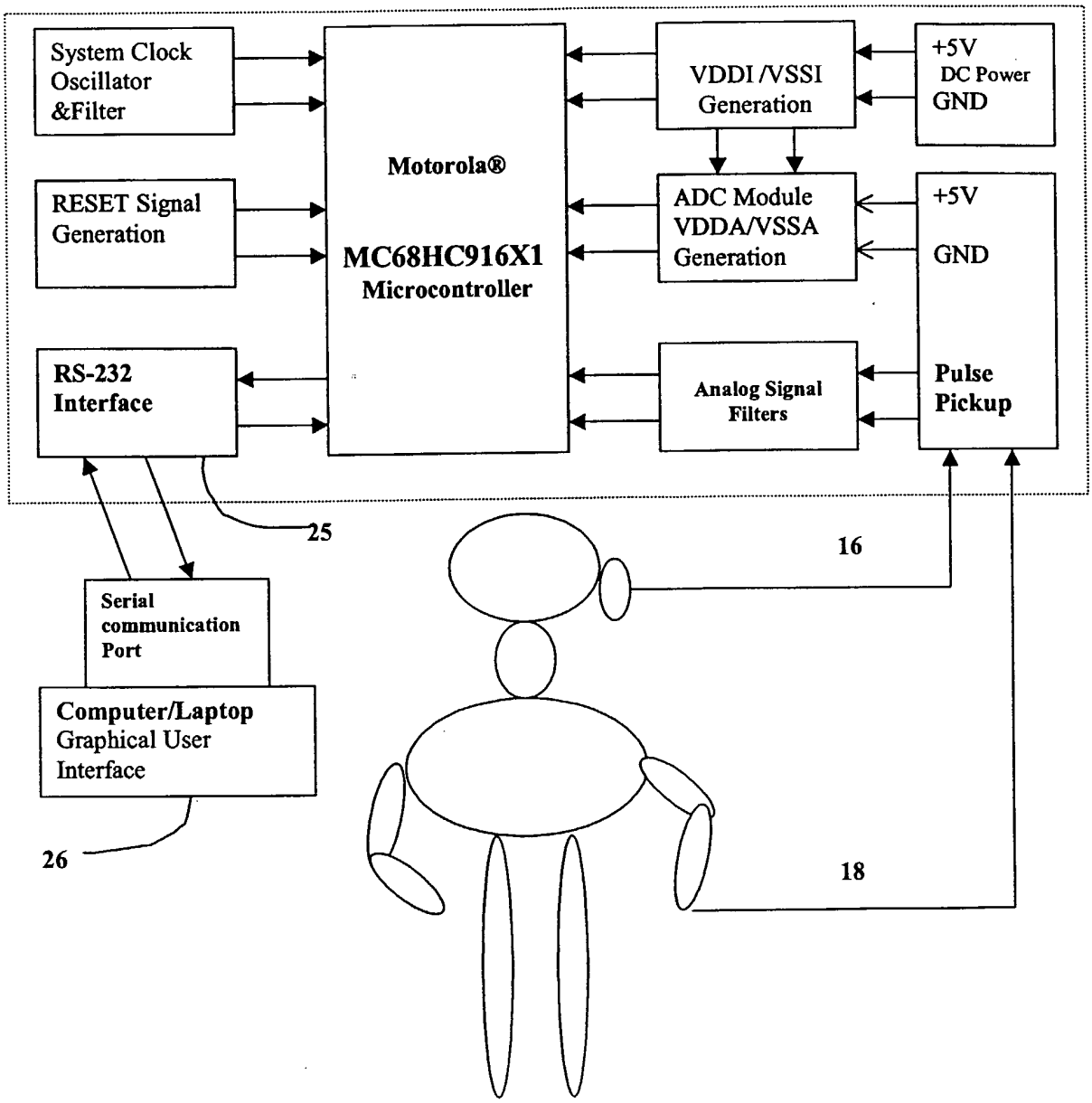

System Clock Oscillator &Filter
RESET Signal Generation
RS-232 Interface
Motorola®
MC68HC916X1
Microcontroller
VDDI /VSSI Generation
ADC Module VDDA/VSSA Generation
Analog Signal Filters
+5V DC Power GND
+5V
GND
Pulse Pickup
25
16
18
Serial communication Port
Computer/Laptop Graphical User Interface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

Figure 4

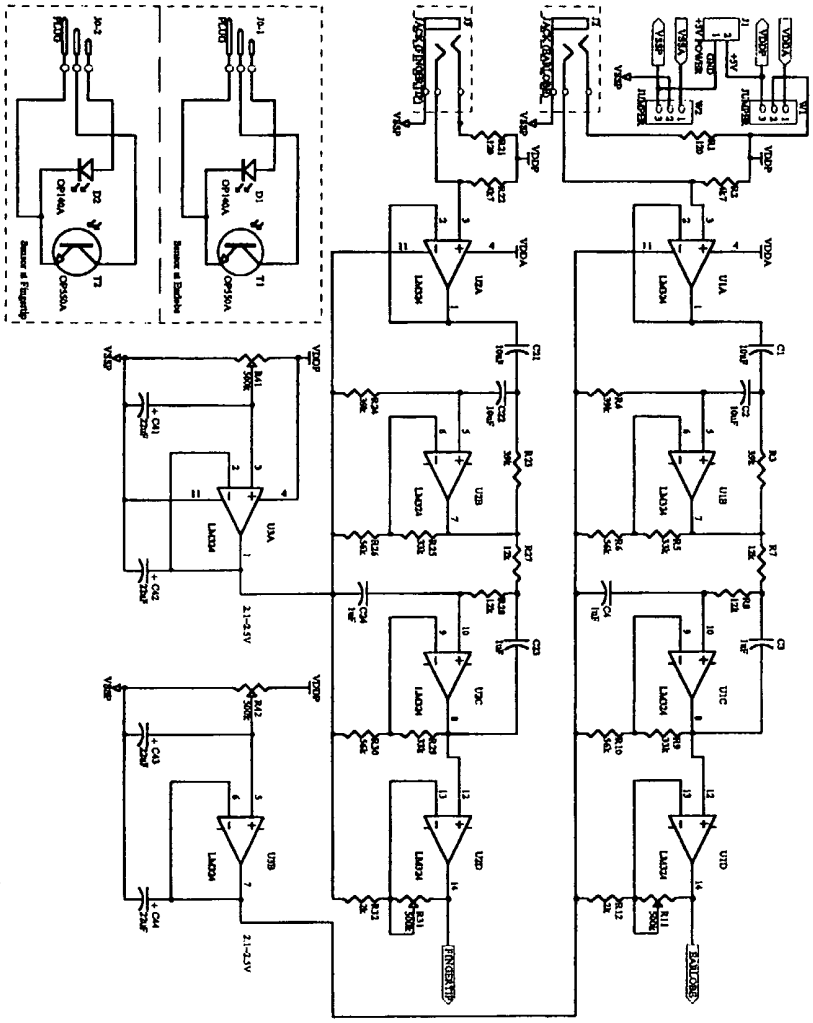


Figure 6

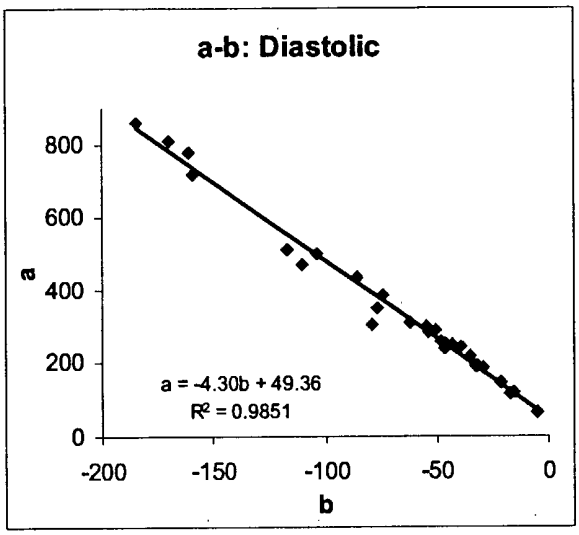


Figure 5

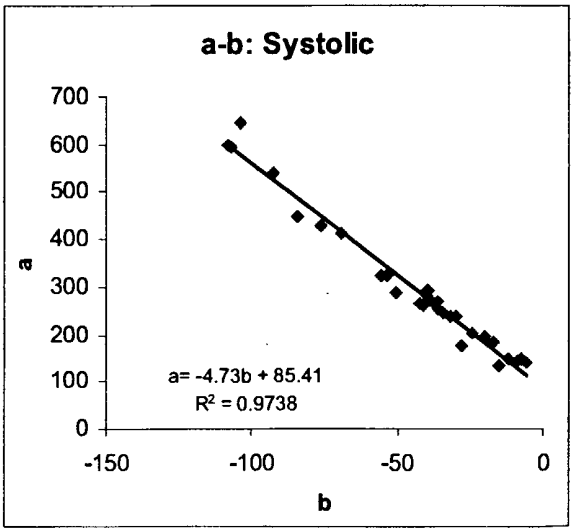
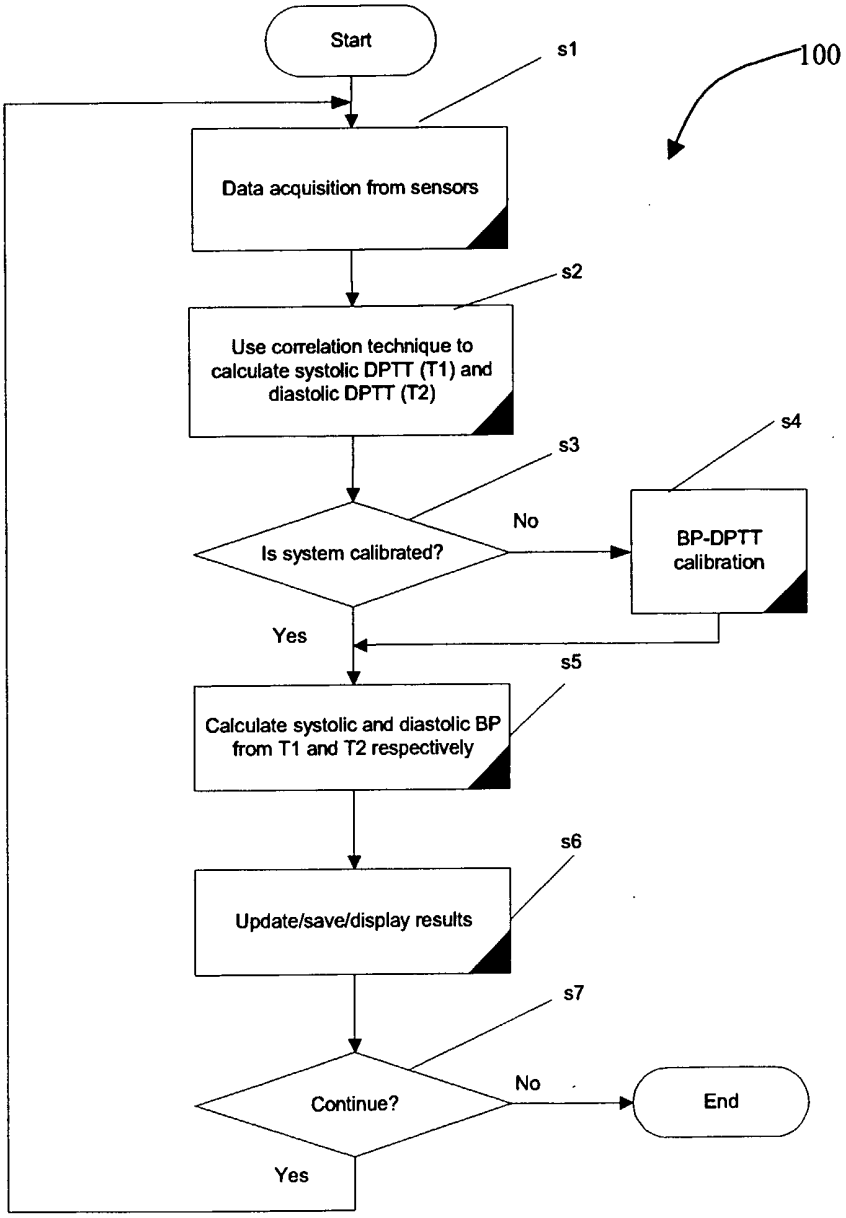


Figure 7


Start
s1
100
Data acquisition from sensors
s2
Use correlation technique to calculate systolic DPTT (T1) and diastolic DPTT (T2)
s3
s4
Is system calibrated?
No
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

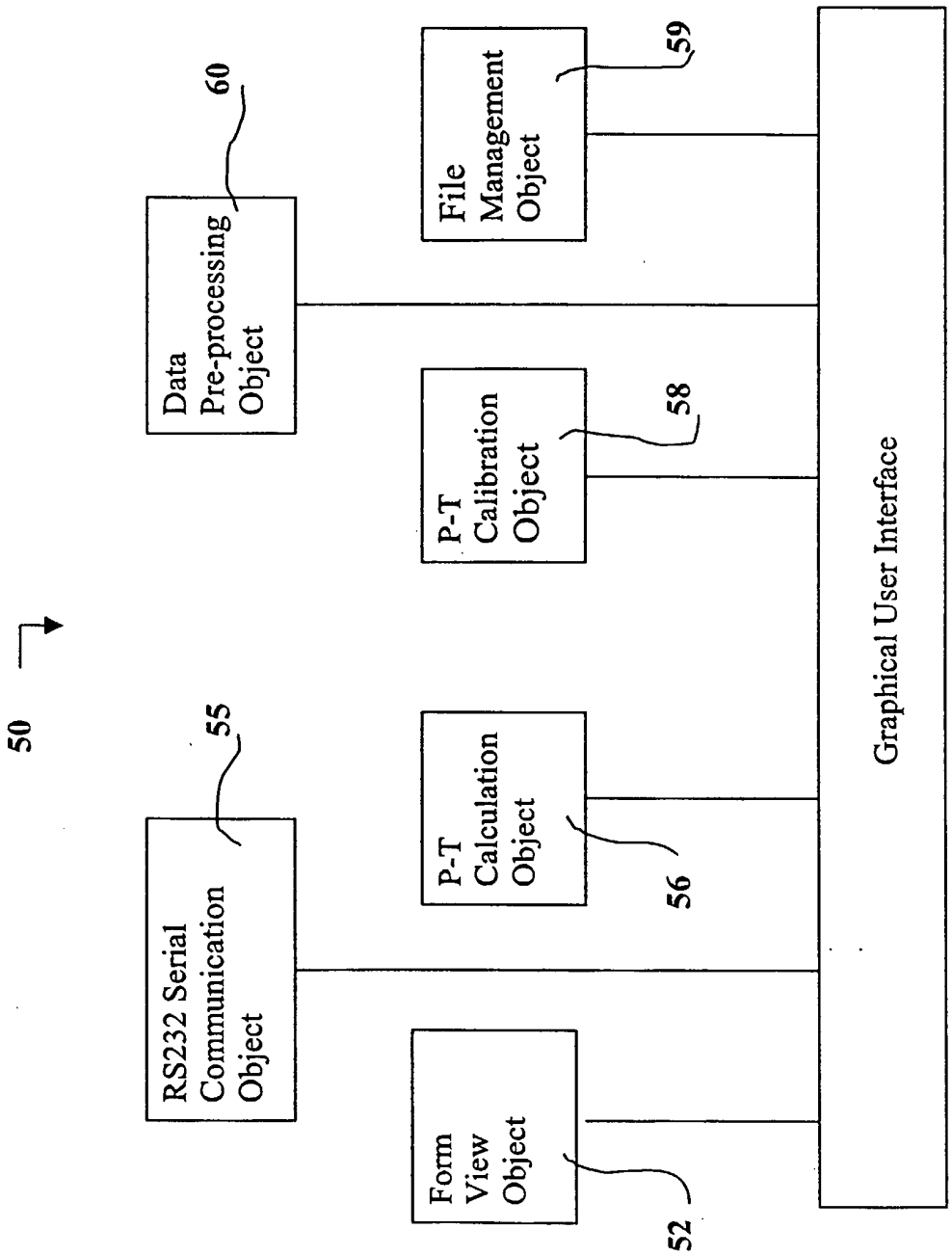

50
Graphical User Interface
Form View Object
52
RS232 Serial Communication Object
55
P-T Calculation Object
56
P-T Calibration Object
58
Data Pre-processing Object
60
File Management Object
59

Figure 8

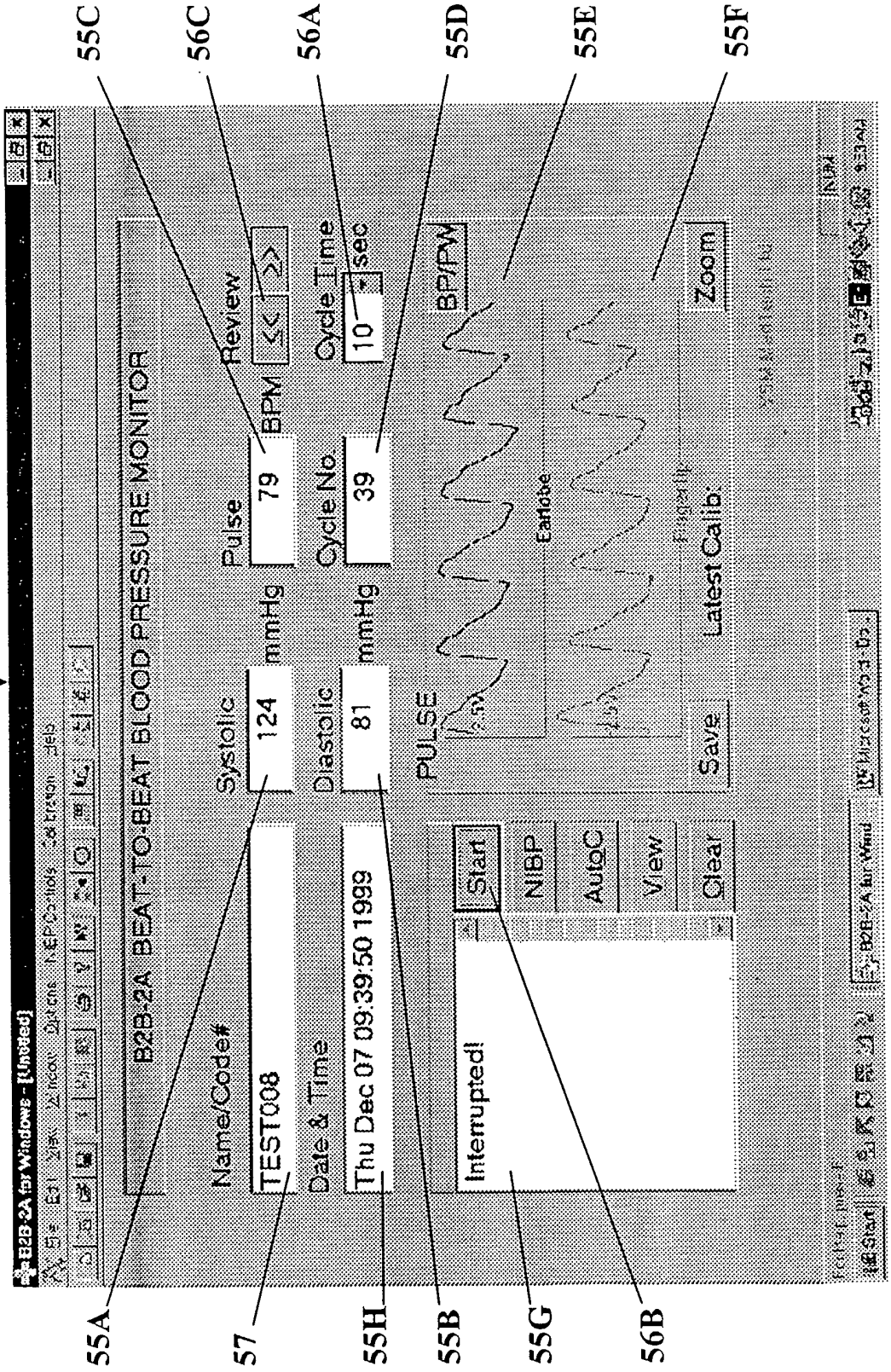

54
55C
56C
56A
55D
55E
55F
B2B-2A BEAT-TO-BEAT BLOOD PRESSURE MONITOR
Review
<<
>>
Pulse
79
BPM
Cycle Time
10
sec
Cycle No
39
Systolic
124
mmHg
Diastolic
81
mmHg
Name/Code#
TEST008
Date & Time
Thu Dec 07 09:39:50 1999
PULSE
BP/PW
Zoom
Latest Calib:
Save
Start
NIBP
AutoC
View
Clear
Interrupted!
55A
57
55H
55B
55G
56B

Figure 9

INTERNATIONAL SEARCH REPORT

Inti :ional Application No
PCT/CA 00/01552

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

Electronic data base 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

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	PATENT ABSTRACTS OF JAPAN vol. 2000, no. 07, 29 September 2000 (2000-09-29) & JP 2000 107141 A (DENSO CORP;NIPPON SOKEN INC), 18 April 2000 (2000-04-18)	1,3
A	abstract	4,5,7, 12,18

X	EP 0 443 267 A (SENTINEL MONITORING INC) 28 August 1991 (1991-08-28)	1,3,6
A	column 10, line 25 - line 51 column 9, line 23 -column 10, line 1; table 1	4,5,7-9, 12,18

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

'A' document defining the general state of the art which is not considered to be of particular relevance

'E' earlier document but published on or after the international filing date

'L' document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

'O' document referring to an oral disclosure, use, exhibition or other means

'P' document published prior to the international filing date but later than the priority date claimed

'T' later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

'X' document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

'Y' document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

'&' document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 May 2001	18/05/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Weihs, J

INTERNATIONAL SEARCH REPORT

Int ional Application No
PCT/CA 00/01552

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	WO 89 08424 A (VECTRON GES FUER TECHNOLOGIEEN) 21 September 1989 (1989-09-21) abstract page 3, line 9 - line 30 page 4, line 7 - line 32 page 5, line 17 -page 6, line 16; tables 1,2	1,3-9, 11,12, 18-20
A	US 5 755 669 A (ONO KOHEI ET AL) 26 May 1998 (1998-05-26) column 3, line 1 -column 5, line 29; table 1	1,3,6,7, 12,18
A	PATENT ABSTRACTS OF JAPAN vol. 1996, no. 09, 30 September 1996 (1996-09-30) & JP 08 131410 A (OMRON CORP), 28 May 1996 (1996-05-28) abstract	1,6,7,10
X	PATENT ABSTRACTS OF JAPAN vol. 1995, no. 08, 29 September 1995 (1995-09-29) & JP 07 136136 A (OMRON CORP), 30 May 1995 (1995-05-30) abstract	1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Int ional Application No
PCT/CA 00/01552

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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EP 0443267 A	28-08-1991	CA 2036900 A	24-08-1991
		JP 6014891 A	25-01-1994
WO 8908424 A	21-09-1989	DE 3807672 A	21-09-1989
		EP 0403522 A	27-12-1990
		JP 3505533 T	05-12-1991
		US 5237997 A	24-08-1993
US 5755669 A	26-05-1998	NONE	
JP 08131410 1 A		NONE	
JP 07136136 1 A		NONE	