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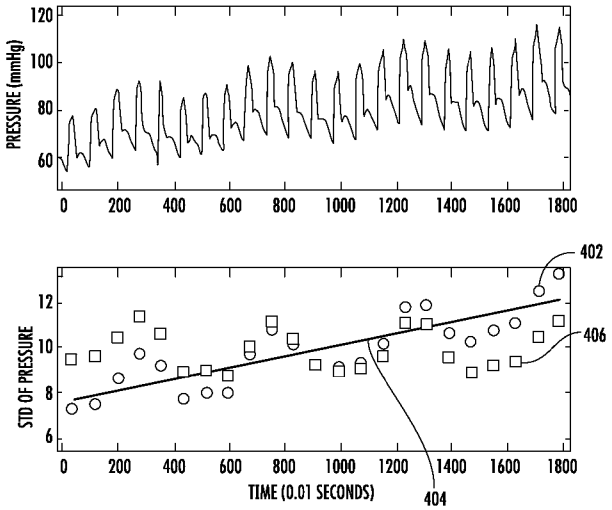

FIG. 4

(57) Abstract: Embodiments of the disclosure are directed to methods, apparatuses, and computer program products for determining a hemodynamic parameter. An exemplary method comprises: receiving data associated with at least one heart beat; calculating a first standard deviation for at least a portion of the data; interpolating a second standard deviation for at least a second portion of the data; and determining the hemodynamic parameter based on the first standard deviation and the second standard deviation.

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DETERMINATION OF A HEMODYNAMIC PARAMETER

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 61/843,722, filed July 08, 2013, entitled "A Method For The Calculation Of Stroke Volume Variation," the entirety which is incorporated herein by reference.

FIELD OF TECHNOLOGY

[0002] This disclosure is related to the field of patient hemodynamic monitoring and digital signal processing. This disclosure specifically relates to a method of calculating real-time hemodynamic parameters.

BACKGROUND

[0003] Indicators such as stroke volume (SV), cardiac output (CO), end-diastolic volume, ejection fraction, stroke volume variation (SVV), pulse pressure variation (PPV), systolic pressure variations (SPV), and plethysmographic variability index (PVI), among others, are important not only for diagnosis of disease, but also for "real-time" monitoring of preload dependence, fluid responsiveness, or volume responsiveness condition of both human and animal subjects. Few hospitals are therefore without some form of equipment to monitor one or more of these cardiac parameters. Many techniques, including invasive techniques, non-invasive techniques, and combinations thereof, are in use and even more have been proposed in the literature. References that disclose determination of hemodynamic parameters include WO2011094487 (Jian et al., filed 28 Jan., 2011) and WO 2009023713 (Derderian et al., filed 13 Aug., 2008).

[0004] One way to obtain a hemodynamic parameter is to mount a flow-measuring device on a catheter, and position the device in or near the subject's heart. Some such devices inject either a bolus of material or energy (usually heat) at an upstream position, such as in the right atrium, and determine flow based on the characteristics of the injected material or energy at a downstream position, such as in the pulmonary artery. Patents that disclose implementations of such invasive techniques (in

particular, thermodilution) include: U.S. Pat. No. 4,236,527 (Newbower et al., 2 Dec. 1980); U.S. Pat. No. 4,507,974 (Yelderman, 2 Apr. 1985); U.S. Pat. No. 5,146,414 (McKown, et al., 8 Sep. 1992); and U.S. Pat. No. 5,687,733 (McKown, et al., 18 Nov. 1997). Other invasive devices are based on the known Fick technique, according to which a hemodynamic parameter is calculated as a function of oxygenation of arterial and mixed venous blood. Doppler techniques, using invasive as well as non-invasive transducers, have also been used to obtain flow rate data that can then be used to calculate a hemodynamic parameter.

[0005] One blood characteristic that can be obtained with minimal or no invasion is blood pressure. In addition to causing minimal patient trauma, blood pressure measurement technology has the added benefit of being accurate and continuous. Many systems rely on the pulse contour method (PCM), which calculates an estimate of one or more hemodynamic parameters of interest from characteristics of a blood pressure waveform. In the PCM, "Windkessel" parameters, such as characteristic impedance of the aorta, compliance, and total peripheral resistance, are often used to construct a linear or non- linear hemodynamic model of the aorta. In essence, blood flow is analogized to a flow of electrical current in a circuit in which an impedance is in series with a parallel-connected resistance and capacitance (compliance). The three required parameters of the model are usually determined either empirically, through a complex calibration process, or from compiled "anthropometric" data, i.e., data about the age, sex, height, weight, and/or other parameters of other patients or test subjects. U.S. Pat. No. 5,400,793 (Wesseling, 28 Mar. 1995) and U.S. Pat. No. 5,535,753 (Petrucelli et al., 16 Jul. 1996) disclose systems that rely on a Windkessel circuit model to determine a hemodynamic parameter. PCM-based systems can monitor hemodynamic parameters using blood pressure measurements taken using a variety of measurement apparatus, such as a finger cuff, and can do so more or less continuously. Many improvements, with varying degrees of complexity, have been proposed for improving the accuracy of the basic PCM model. The present disclosure offers an improvement over the PCM model or any other models discussed in this section.

[0006] Yet more advanced methods for calculating hemodynamic parameters are described, for example, in United States Patent Nos. 7,967,757, and 8,721,556, in PCT patent application publication numbers WO2009/023713 and WO2011/094487, and in PCT International Patent Application Serial No. US2014/045538, the full contents of each of which are hereby incorporated by reference in their entireties.

BRIEF SUMMARY

[0007] In some embodiments, a method for determining a hemodynamic parameter is provided. The method comprises: receiving data associated with at least one heart beat; calculating a first standard deviation for at least a portion of the data; interpolating a second standard deviation for at least a second portion of the data; and determining, using a computing device processor, the hemodynamic parameter based on the first standard deviation and the second standard deviation.

[0008] In some embodiments, the hemodynamic parameter comprises a stroke volume variation (SVV), and the data comprises blood pressure data.

[0009] In some embodiments, the hemodynamic parameter comprises a pulse pressure variation (PPV), and the data comprises pulse pressure data.

[0010] In some embodiments, the hemodynamic parameter comprises a systolic pressure variation (SPV), and the data comprises systolic pressure data.

[0011] In some embodiments, the hemodynamic parameter comprises a plethysmographic variability index (PVI), and the data comprises pulse oximeter waveform data.

[0012] In some embodiments, the method further comprises determining, using a computing device processor, a polynomial function that fits the first standard deviation, the polynomial function being associated with at least one polynomial coefficient.

[0013] In some embodiments, the polynomial function is based on a least-squares function.

[0014] In some embodiments, receiving data comprises measuring at least one arterial blood pressure waveform and identifying the at least one heart beat.

[0015] In some embodiments, the method further comprises subtracting the second standard deviation from the first standard deviation.

[0016] In some embodiments, determining the hemodynamic parameter further comprises determining the hemodynamic parameter based on a constant, a standard deviation of the second standard deviation, and a mean of the first standard deviation.

[0017] In some embodiments, determining the hemodynamic parameter further comprises determining the hemodynamic parameter based on multiplying the constant and the standard deviation of the second standard deviation to produce a first computation, and dividing the first computation by the mean of the first standard deviation.

[0018] In some embodiments, the polynomial function is a first order polynomial function.

[0019] In some embodiments, the polynomial function is an n^{th} order polynomial function.

[0020] In some embodiments, an apparatus is provided for determining a hemodynamic parameter. The apparatus comprises a communication interface; a memory; a processor; and a module stored in the memory, executable by the processor, and configured to: receive data associated with at least one heart beat; calculate a first standard deviation for at least a portion of the data; interpolate a second standard deviation for at least a second portion of the data; and determine the hemodynamic parameter based on the first standard deviation and the second standard deviation.

[0021] In some embodiments, the apparatus further comprises a kit comprising at least one of a catheter and a pressure sensor associated with the catheter.

[0022] In some embodiments, the apparatus further comprises at least one of a signal filter or an analog-to-digital converter.

[0023] In some embodiments, a computer program product is provided for determining a hemodynamic parameter. The computer program product comprises a non-transitory computer-readable medium comprising a set of codes for causing a computer to: receive data associated with at least one heart beat; calculate a first standard

deviation for at least a portion of the data; interpolate a second standard deviation for at least a second portion of the data; and determine the hemodynamic parameter based on the first standard deviation and the second standard deviation.

[0024] In some embodiments, an apparatus is provided for determining a hemodynamic parameter. The apparatus comprises means for receiving data associated with at least one heart beat; means for calculating a first standard deviation for at least a portion of the data; means for interpolating a second standard deviation for at least a second portion of the data; and means for determining the hemodynamic parameter based on the first standard deviation and the second standard deviation.

[0025] In some embodiments, a method is provided for determining a hemodynamic parameter. The method comprises: receiving data associated with at least one heart beat; calculating a first standard deviation for at least a portion of the data; using a Fourier transform and filtering scheme to remove at least a second portion of the data; using an inverse Fourier transform to obtain a second standard deviation for at least a second portion of the data; and determining, using a computing device processor, the hemodynamic parameter based on the first standard deviation and the second standard deviation. Apparatus and computer program product may also be provided based on this method.

[0026] In some embodiments, another method is provided for determining a hemodynamic parameter. The method comprises: receiving a first portion of data associated with at least one heart beat; interpolating a second portion of the data based on the first portion of the data; calculating at least one standard deviation for at least one of the first portion of the data or the second portion of the data; and determining, using a computing device processor, the hemodynamic parameter based on the at least one standard deviation. In some embodiments, the hemodynamic parameter comprises at least one of SVV, PPV, SPV, or PVI. Apparatus and computer program product may also be provided based on this method.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] Having thus described embodiments of the disclosure in general terms, reference will now be made to the accompanying drawings, where:

Figure 1 shows an example of radial artery pressure before a bolus vasopressor of phenylephrine is given to patients;

Figure 2 shows an example of radial artery pressure after a bolus vasopressor of phenylephrine is given to patients;

Figure 3 shows an example of a hemodynamic parameter determination method using the pressure obtained before the bolus of phenylephrine is given to a patient;

Figure 4 shows an example of a hemodynamic parameter determination method using the pressure obtained after the bolus of phenylephrine is given to a patient;

Figure 5 shows an exemplary method for determining a hemodynamic parameter;

Figure 6 shows another exemplary method for determining a hemodynamic parameter; and

Figure 7 shows an exemplary apparatus for determining a hemodynamic parameter.

DETAILED DESCRIPTION

[0028] Embodiments of the present disclosure now may be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all, embodiments of the disclosure are shown. Indeed, the disclosure may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure may satisfy applicable legal requirements. Like numbers refer to like elements throughout.

[0029] Embodiments of the disclosure are directed to apparatuses, methods and computer program products for determining or calculating a hemodynamic parameter. This disclosure provides a new method to calculate hemodynamic parameters such as stroke volume variation (SVV), pulse pressure variation (PPV), systolic pressure variation (SPV), and plethysmographic variability index (PVI) based on blood pressure

waveforms. In today's patient hemodynamic monitoring, blood pressure is routinely monitored and many parameters that are of great clinical use, such as cardiac output, stroke volume, and stroke volume variation can be derived from blood pressure waveforms and displayed by monitors. Accurately calculating those parameters is of great importance because accurate calculations can help clinicians know more about patients and make more informed decisions in treating patients.

[0030] Exemplary methods of the present disclosure are directed to determining SVV. However, these methods or variations of these methods may be used to determine other hemodynamic parameters, including, but not limited to, SPV, PPV, or PVI. A method for calculating SVV, which is induced by mechanical ventilation, predicts fluid responsiveness with high sensitivity and specificity. As a result, it is often used by clinicians as a guide for fluid optimization. The SVV may be calculated using the formula: SVV = constant x std(std_bp) / mean(std_bp), where constant is a constant parameter, std is the standard deviation, std_bp is an array of the standard deviation of each beat in a 20 second window, and mean is the average value (e.g., average value of std_bp). Constant is an empirically determined scaling constant, which can be chosen largely for convenience and as appropriate for display to a user of a system embodying and performing the method. A suitable scaling constant might be 2.7, for example. Regardless of the number of respiratory cycles included in the computation interval; normal experimental methods may be used to determine a suitable scaling constant in any given implementation of the invention. This method of calculation or determination of the SVV may be referred to as the first method. The first method does reasonably well in predicting fluid responsiveness. The issue of this method, however, is that it does not completely distinguish the variation of stroke volume due to the mechanical ventilation from variation due to other causes. As a result, the first method may not predict fluid responsiveness with high accuracy (e.g., accuracy equal to or greater than a threshold accuracy).

[0031] Figure 1 shows an example of radial artery pressure before a bolus vasopressor of phenylephrine is given to patients. The top plot shows the pressure and

the bottom plot shows the standard deviation of blood pressure in each beat. The respiration-induced variation of stroke volume can be clearly observed in both plots of Figure 1.

[0032] Figure 2 shows an example of radial artery pressure after a bolus vasopressor of phenylephrine is given to patients. The top plot shows the pressure and the bottom plot shows the standard deviation of blood pressure in each beat. The respiration-induced variation of stroke volume can be observed, but in addition to that, it comes with a significant change of stroke volume induced by the bolus phenylephrine.

[0033] The present disclosure is directed to a second method to determine a hemodynamic parameter such as SVV. This method removes many of the variations of stroke volume due to other sources from the determination, thus improving the sensitivity and specificity of the SVV's or any other hemodynamic parameter's ability in predicting fluid responsiveness.

[0034] Figure 5 presents an exemplary process flow or method for determining a hemodynamic parameter. This is the second method described previously. The second method is different from the first method primarily due to an interpolation step (see block **530**). At block **510**, the process flow comprises receiving data associated with at least one heart beat. Receiving data associated with at least one heart beat may comprise measuring a waveform and identifying at least one heart beat using a digital signal processing algorithm. In some embodiments, receiving data comprises measuring at least one arterial blood pressure waveform and identifying at least one heart beat. As indicated previously, the data may comprise a blood pressure waveform. The blood pressure waveform corresponds to a signal, for example, from an arterial blood pressure, or any signal proportional to, or derived from the arterial pressure signal such as a pulse-oximetry signal, a Doppler ultrasound signal or a bioimpedance signal. At block **520**, the process flow comprises calculating a first standard deviation for at least a portion (or first portion) of the data.

[0035] The process flow further comprises determining a polynomial function that fits the first standard deviation, wherein the polynomial function (e.g., 1st order, 2nd

order, n^{th} order, or any combination thereof) is associated with at least one polynomial coefficient. The polynomial function may be based on a least-squares function. At block **530**, the process flow comprises interpolating a second standard deviation for at least a second portion of the data (different from the first portion of the data). The interpolation may be performed based on the polynomial function. In some embodiments, the process flow further comprises subtracting the second standard deviation from the first standard deviation.

[0036] At block **540**, the process flow comprises determining a hemodynamic parameter (e.g., associated with a non-respiration effect) based on the first standard deviation and the second standard deviation. In some embodiments, the determining of the hemodynamic parameter is further configured to determine the hemodynamic parameter based on multiplying the constant and the standard deviation of the second standard deviation to produce a first computation, and dividing the first computation by the mean of the first standard deviation. Constant is again an empirically determined or selected scaling constant. In some embodiments, the operation of determining a polynomial function and the operation depicted at **540** can be replaced with using a Fourier transform and filtering scheme (e.g., high-pass filtering scheme) to remove at least a second portion of the data, and then using an inverse Fourier transform to obtain the second standard deviation for at least a second portion of the data. As used herein, "first" standard deviation and "second" standard deviation are not used to indicate orders of standard deviation; instead, they are used to indicate a first standard deviation calculation and a second standard deviation calculation. Both the first standard deviation calculation and the second standard deviation calculation may be associated with any order of standard deviation.

[0037] The received data (as indicated in block **510**) of the second method changes depending on the hemodynamic parameter that is to be determined. When determining SVV, for example, blood pressure data (comprising a blood pressure waveform) is received at block **510**. At block **520**, the process flow comprises calculating a first standard deviation for at least a portion (or first portion) of the blood

pressure data. At block **530**, the process flow comprises interpolating a second standard deviation for at least a second portion of the blood pressure data (different from the first portion of the blood pressure data). At block **540**, the process flow comprises determining the SVV based on the first standard deviation and the second standard deviation.

[0038] When determining SPV, systolic pressure data (comprising a systolic pressure waveform) is received at block **510**. At block **520**, the process flow comprises calculating a first standard deviation for at least a portion (or first portion) of the systolic pressure data. At block **530**, the process flow comprises interpolating a second standard deviation for at least a second portion of the systolic pressure data (different from the first portion of the systolic pressure data). At block **540**, the process flow comprises determining the SPV based on the first standard deviation and the second standard deviation.

[0039] When determining PPV, pulse pressure data (comprising a pulse pressure waveform) is received at block **510**. At block **520**, the process flow comprises calculating a first standard deviation for at least a portion (or first portion) of the pulse pressure data. At block **530**, the process flow comprises interpolating a second standard deviation for at least a second portion of the pulse pressure data (different from the first portion of the pulse pressure data). At block **540**, the process flow comprises determining the PPV based on the first standard deviation and the second standard deviation.

[0040] When determining PVI, pulse oximeter waveform data (comprising a pulse oximeter waveform) is received at block **510**. At block **520**, the process flow comprises calculating a first standard deviation for at least a portion (or first portion) of the pulse oximeter waveform data. At block **530**, the process flow comprises interpolating a second standard deviation for at least a second portion of the pulse oximeter waveform data (different from the first portion of the pulse oximeter waveform data). At block **540**, the process flow comprises determining the PVI based on the first standard deviation and the second standard deviation.

[0041] Figure 3 shows an example of the second method using the pressure obtained before a bolus of phenylephrine is given to a patient. The SVV obtained with the first method and the second method are quite close, as expected, since in the second method, the variation of the stroke volume is mainly induced by the respiration effect.

[0042] The top plot in Figure 3 illustrates blood pressure before a bolus phenylephrine is given to a patient. In the bottom plot of Figure 3, each circle (e.g., circle **302**) shows the original standard deviation of blood pressure of each beat. The line **304** shows the fitted first order polynomial. Each square (e.g., square **306**) shows the new standard deviation of blood pressure of each beat, obtained by subtracting the line **304** from the original standard deviation. Some circles are only partially visible or not visible because they at least partially overlap with some squares. The SVV calculated via the first and second methods are very close to each other. They are 17.03% and 17.04%, respectively.

[0043] Figure 4 shows an example of the second method using the pressure obtained after the bolus of phenylephrine is given to a patient. The SVV obtained with the first method and the second method are quite different, as expected, since in the second method, the variation of the stroke volume is induced not only by the respiration effect, but also by other non-respiration induced effect. The SVV calculated using the second method removes much of the non-respiration effect and its value is much closer to the true value.

[0044] The top plot in Figure 4 shows the blood pressure after a bolus phenylephrine is given to a patient. In the bottom plot of Figure 4, each circle (e.g., circle **402**) shows the original standard deviation of blood pressure of each beat. The line **404** shows the fitted first order polynomial. The square (e.g., square **406**) shows the new standard deviation of blood pressure of each beat, obtained by subtracting the line **404** from the original standard deviation. Some circles are only partially visible or not visible because they at least partially overlap with some squares. The SVV calculated via the first and second methods are quite different. They are 44% and 24%, respectively.

[0045] The first order polynomial fit in the second method can be replaced with other orders of polynomial fit, such as the 2nd order, the 3rd order, etc., or can also be replaced with combinations of orders of polynomial fit. The fit does not have to use all data points; instead, it can be among selected data points, such as the first several data points and/or the last several data points.

[0046] Referring now to Figure 6, Figure 6 presents another exemplary process flow for determining a hemodynamic parameter. At block **610**, the process flow comprises receiving a first portion of data associated with at least one heart beat. At block **620**, the process flow comprises interpolating a second portion of the data based on the first portion of the data. At block **630**, the process flow comprises calculating at least one standard deviation for at least one of the first portion of the data or the second portion of the data. At block **640**, the process flow comprises determining the hemodynamic parameter based on the at least one standard deviation. Each step of any process flow described herein may be performed by a single computing device processor or different computing device processors. In some embodiments, some of the steps may be performed by a single computing device processor, while other steps may be performed by individual computing device processors. Similar to Figure 5, the process flow in Figure 6 may be applicable to any hemodynamic parameter, including, but not limited to SVV, SPV, PPV, and PVI.

[0047] Referring now to Figure 7, Figure 7 shows a system that may be used to determine any hemodynamic parameter, including, but not limited to SVV, SPV, PPV, and PVI. Figure 7 shows two types of pressure sensing for the sake of conciseness; in most practical applications of the disclosure, either one or several variations will typically be implemented. In invasive applications of the disclosure, a conventional pressure sensor **7100** (e.g., a disposable pressure transducer) is mounted on a catheter **7110**, which is inserted in an artery **7120** of a portion **7130** of the body of a human or animal patient. Such an artery could be an ascending aorta, or pulmonary artery, or, in order to reduce the level of invasiveness, the artery **7120** could be peripheral, such as the femoral, radial or brachial artery. In the non-invasive applications

of the disclosure, a conventional pressure sensor **7200**, such as a photo-plethysmographic blood pressure probe, is mounted externally in any conventional manner, for example using a cuff around a finger **7230** or a transducer mounted on the wrist of the patient. In some embodiments, the sensor **7100** or **7200** may comprise a pressure transducer (e.g., a disposable pressure transducer DPT). Figure 7 schematically shows both types.

[0048] The signals from the sensors **7100**, **7200** are passed via any known connectors as inputs to a processing system **7300**, which includes one or more processors and other supporting hardware and system software (not shown) usually included to process signals and execute code. The disclosure may be implemented using a modified, standard, personal computer, or it may be incorporated into a larger, specialized monitoring system. In this disclosure, the processing system **7300** also may include, or is connected to, conditioning circuitry **7302** which performs such normal signal processing tasks as amplification, filtering, ranging, etc., as needed, as well as optional high pass filtering. The conditioned, sensed input pressure signal P(t) is then converted to digital form by a conventional analog-to-digital converter ADC **7304**, which has or takes its time reference from a clock circuit **7305**. As is well understood, the sampling frequency of the ADC **7304** should be chosen with regard to the Nyquist criterion so as to avoid aliasing of the pressure signal. The output from the ADC **7304** will be the discrete pressure signal P(k), whose values may be stored in conventional memory circuitry (not shown).

[0049] The values P(k) are passed to (usually, accessed from memory by) to a software module **7310** comprising computer-executable code for computing whichever of the parameters are to be used in the chosen algorithm for calculating the K.

[0050] The patient-specific data such as age, height, weight, body surface area, etc., is stored in a memory **7315**, which may also store other predetermined parameters. These values may be entered using any known input device **7400** in the conventional manner.

[0051] A compliance calculation module **7320**, also comprising computer-executable code, then takes as inputs the various moment and patient-specific values and

performs the chosen calculations for computing the arterial compliance function K (or compliance factor C). For example, the module **7320** could enter the parameters into the expression given below for K (or C), or into some other expression derived by creating an approximating function that best fits a set of test data. The calculation module **7320** preferably also selects the time window over which each K, C, SV, CO, SVV, SPV, PPV, and/or PVI estimate is generated. This may be done as simply as choosing which and how many of the stored, consecutive, discretized P(t) values P(k) are used in each calculation, which is the same as selecting n in the range k=0, . . . , (n−1).

[0052] Taking K (and other parameters such as C) as inputs, a stroke volume computation module **7330**, again comprising computer-executable code, then computes an SV estimate. Taking as inputs both SV and a heart rate value HR generated by any known hardware device **7340** or software routine (for example, using Fourier or derivative analysis) for measuring heart rate along with any other parameters described herein, a CO computation module **7330** may then generate an estimate of CO using the method described herein.

[0053] Additional software modules **7360** and **7370** may be included to perform the calculations described above to estimate the exponential pressure decay constant tau and vascular resistance R. As used herein, the vascular resistance R may also be referred to as the systemic vascular resistance. Still additional software modules (not shown) may be included to determine or calculate any hemodynamic parameter described herein, including, but not limited to, SVV, PPV, SPV, or PVI.

[0054] As shown in Figure **7**, the software modules **7320**, **7330**, **7350**, **7360**, and **7370**, that is, whichever of these are included, may be implemented within an estimation software component **317**, which may of course be combined with the moment-calculating component **7310**, or with other software components of the processing system **7300** as desired.

[0055] It is not necessary for the system to compute SV or CO if these values are not of interest. The same is true for tau and R. In such case, the corresponding software modules will of course not be needed and may be omitted. For example, the disclosure

could be used in a study of arterial compliance itself. Nonetheless, as Figure 7 illustrates, any or all of the results K, SV, CO, tau and R may be passed to any conventional display or recording device **7500** for presentation to and interpretation by a user or another system. As with the input device **7400**, the display **7500** will typically be the same as is used by the processing system for other purposes.

[0056] The disclosure further relates to a computer program loadable in a computer unit or the processing system **7300** in order to execute the methods of the disclosure. Moreover, the various software modules **7310**, **7315**, **7320**, **7330**, **7340**, **7350**, **7360**, and **7370** used to perform the various calculations and perform related method steps according to the disclosure may also be stored as computer-executable instructions on a computer-readable medium in order to allow the instructions to be loaded into and executed by different processing systems.

[0057] In accordance with embodiments of the disclosure, the term "module" with respect to an apparatus may refer to a hardware component of the apparatus, a software component of the apparatus, or a component of the apparatus that includes both hardware and software. As used herein, a module may include one or more modules, where each module may reside in separate pieces of hardware or software. As used herein, an apparatus may alternatively be referred to as a "system" or a "device."

[0058] Although many embodiments of the present disclosure have just been described above, the present disclosure may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Also, it will be understood that, where possible, any of the advantages, features, functions, devices, and/or operational aspects of any of the embodiments of the present disclosure described and/or contemplated herein may be included in any of the other embodiments of the present disclosure described and/or contemplated herein, and/or vice versa. In addition, where possible, any terms expressed in the singular form herein are meant to also include the plural form and/or vice versa, unless explicitly stated

otherwise. Accordingly, the terms "a" and/or "an" shall mean "one or more," even though the phrase "one or more" is also used herein. Like numbers refer to like elements throughout.

[0059] As will be appreciated by one of ordinary skill in the art in view of this disclosure, the present disclosure may include and/or be embodied as an apparatus (including, for example, a system, apparatus, machine, device, computer program product, and/or the like), as a method (including, for example, a business method, computer-implemented process, and/or the like), or as any combination of the foregoing. Accordingly, embodiments of the present disclosure may take the form of an entirely business method embodiment, an entirely software embodiment (including firmware, resident software, micro-code, stored procedures in a database, or the like), an entirely hardware embodiment, or an embodiment combining business method, software, and hardware aspects that may generally be referred to herein as a "system" or "apparatus." Furthermore, embodiments of the present disclosure may take the form of a computer program product that includes a computer-readable storage medium having one or more computer-executable program code portions stored therein. As used herein, a processor, which may include one or more processors, may be "configured to" perform a certain function in a variety of ways, including, for example, by having one or more general-purpose circuits perform the function by executing one or more computer-executable program code portions embodied in a computer-readable medium, and/or by having one or more application-specific circuits perform the function.

[0060] It will be understood that any suitable computer-readable medium may be utilized. The computer-readable medium may include, but is not limited to, a non-transitory computer-readable medium, such as a tangible electronic, magnetic, optical, electromagnetic, infrared, and/or semiconductor system, device, and/or other apparatus. For example, in some embodiments, the non-transitory computer-readable medium includes a tangible medium such as a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a compact disc read-only memory (CD-

ROM), and/or some other tangible optical and/or magnetic storage device. In other embodiments of the present disclosure, however, the computer-readable medium may be transitory, such as, for example, a propagation signal including computer-executable program code portions embodied therein.

[0061] One or more computer-executable program code portions for carrying out operations of the present disclosure may include object-oriented, scripted, and/or unscripted programming languages, such as, for example, Java, Perl, Smalltalk, C++, SAS, SQL, Python, Objective C, JavaScript, and/or the like. In some embodiments, the one or more computer-executable program code portions for carrying out operations of embodiments of the present disclosure are written in conventional procedural programming languages, such as the "C" programming languages and/or similar programming languages. The computer program code may alternatively or additionally be written in one or more multi-paradigm programming languages, such as, for example, F#.

[0062] Some embodiments of the present disclosure are described herein with reference to flowchart illustrations and/or block diagrams of apparatus and/or methods. It will be understood that each block included in the flowchart illustrations and/or block diagrams, and/or combinations of blocks included in the flowchart illustrations and/or block diagrams, may be implemented by one or more computer-executable program code portions. These one or more computer-executable program code portions may be provided to a processor of a general purpose computer, special purpose computer, and/or some other programmable data processing apparatus in order to produce a particular machine, such that the one or more computer-executable program code portions, which execute via the processor of the computer and/or other programmable data processing apparatus, create mechanisms for implementing the steps and/or functions represented by the flowchart(s) and/or block diagram block(s).

[0063] The one or more computer-executable program code portions may be stored in a transitory and/or non-transitory computer-readable medium (e.g., a memory or the like) that can direct, instruct, and/or cause a computer and/or other programmable

data processing apparatus to function in a particular manner, such that the computer-executable program code portions stored in the computer-readable medium produce an article of manufacture including instruction mechanisms which implement the steps and/or functions specified in the flowchart(s) and/or block diagram block(s).

[0064] The one or more computer-executable program code portions may also be loaded onto a computer and/or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer and/or other programmable apparatus. In some embodiments, this produces a computer-implemented process such that the one or more computer-executable program code portions which execute on the computer and/or other programmable apparatus provide operational steps to implement the steps specified in the flowchart(s) and/or the functions specified in the block diagram block(s). Alternatively, computer-implemented steps may be combined with, and/or replaced with, operator- and/or human-implemented steps in order to carry out an embodiment of the present disclosure.

[0065] While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and not restrictive on the broad disclosure, and that this disclosure not be limited to the specific constructions and arrangements shown and described, since various other changes, combinations, omissions, modifications and substitutions, in addition to those set forth in the above paragraphs, are possible. Those skilled in the art will appreciate that various adaptations, modifications, and combinations of the just described embodiments can be configured without departing from the scope and spirit of the disclosure. Therefore, it is to be understood that, within the scope of the appended claims, the disclosure may be practiced other than as specifically described herein.

WHAT IS CLAIMED IS:

1. A method for determining a hemodynamic parameter, the method comprising:

receiving data associated with at least one heart beat;

calculating a first standard deviation for at least a portion of the data;

interpolating a second standard deviation for at least a second portion of the data; and

determining, using a computing device processor, the hemodynamic parameter based on the first standard deviation and the second standard deviation.

2. The method of claim 1, wherein the hemodynamic parameter comprises a stroke volume variation, and wherein the data comprises blood pressure data.

3. The method of claim 1, wherein the hemodynamic parameter comprises a pulse pressure variation, and wherein the data comprises pulse pressure data.

4. The method of claim 1, wherein the hemodynamic parameter comprises a systolic pressure variation, and wherein the data comprises systolic pressure data.

5. The method of claim 1, wherein the hemodynamic parameter comprises a plethysmographic variability index, and wherein the data comprises pulse oximeter waveform data.

6. The method of claim 1, further comprising determining, using a computing device processor, a polynomial function that fits the first standard deviation, the polynomial function being associated with at least one polynomial coefficient, and wherein the second standard deviation is interpolated based on the polynomial function.

7. The method of claim 6, wherein the polynomial function is based on a least-squares function.

8. The method of claim 1, wherein receiving data comprises measuring at least one arterial blood pressure waveform and identifying the at least one heart beat.

9. The method of claim 1, further comprising subtracting the second standard deviation from the first standard deviation.

10. The method of claim 1, wherein the determining of the hemodynamic parameter further comprises determining the hemodynamic parameter based on a constant, a standard deviation of the second standard deviation, and a mean of the first standard deviation.

11. The method of claim 10, wherein the determining of the hemodynamic parameter further comprises determining the hemodynamic parameter based on multiplying the constant and the standard deviation of the second standard deviation to produce a first computation, and dividing the first computation by the mean of the first standard deviation.

12. The method of claim 6, wherein the polynomial function is a first order polynomial function.

13. The method of claim 6, wherein the polynomial function is an n^{th} order polynomial function.

14. An apparatus for determining a hemodynamic parameter, the apparatus comprising:

a communication interface;

a memory;

a processor; and

a module stored in the memory, executable by the processor, and configured to:

receive data associated with at least one heart beat;

calculate a first standard deviation for at least a portion of the data;

interpolate a second standard deviation for at least a second portion of the data; and

determine the hemodynamic parameter based on the first standard deviation and the second standard deviation.

15. The apparatus of claim 14, further comprising at least one of a catheter and a pressure sensor associated with the catheter.

16. The apparatus of claim 14, further comprising at least one of a signal filter or an analog-to-digital converter.

17. An apparatus for determining a hemodynamic parameter, the apparatus comprising:

means for receiving data associated with at least one heart beat;

means for calculating a first standard deviation for at least a portion of the data;

means for interpolating a second standard deviation for at least a second portion of the data; and

means for determining the hemodynamic parameter based on the first standard deviation and the second standard deviation.

18. A method for determining a hemodynamic parameter, the method comprising:

receiving a first portion of data associated with at least one heart beat;

interpolating a second portion of the data based on the first portion of the data;

calculating at least one standard deviation for at least one of the first portion of the data or the second portion of the data; and

determining, using a computing device processor, the hemodynamic parameter based on the at least one standard deviation.

19. The method of claim 18, wherein the hemodynamic parameter comprises a stroke volume variation.

20. The method of claim 18, wherein the hemodynamic parameter comprises a pulse pressure variation.

21. The method of claim 18, wherein the hemodynamic parameter comprises a systolic pressure variation.

22. The method of claim 18, wherein the hemodynamic parameter comprises a plethysmographic variability index.

23. An apparatus for determining a hemodynamic parameter, the apparatus comprising:

means for receiving a first portion of data associated with at least one heart beat;

means for interpolating a second portion of the data based on the first portion of the data;

means for calculating at least one standard deviation for at least one of the first portion of the data or the second portion of the data; and

means for determining the hemodynamic parameter based on the at least one standard deviation.

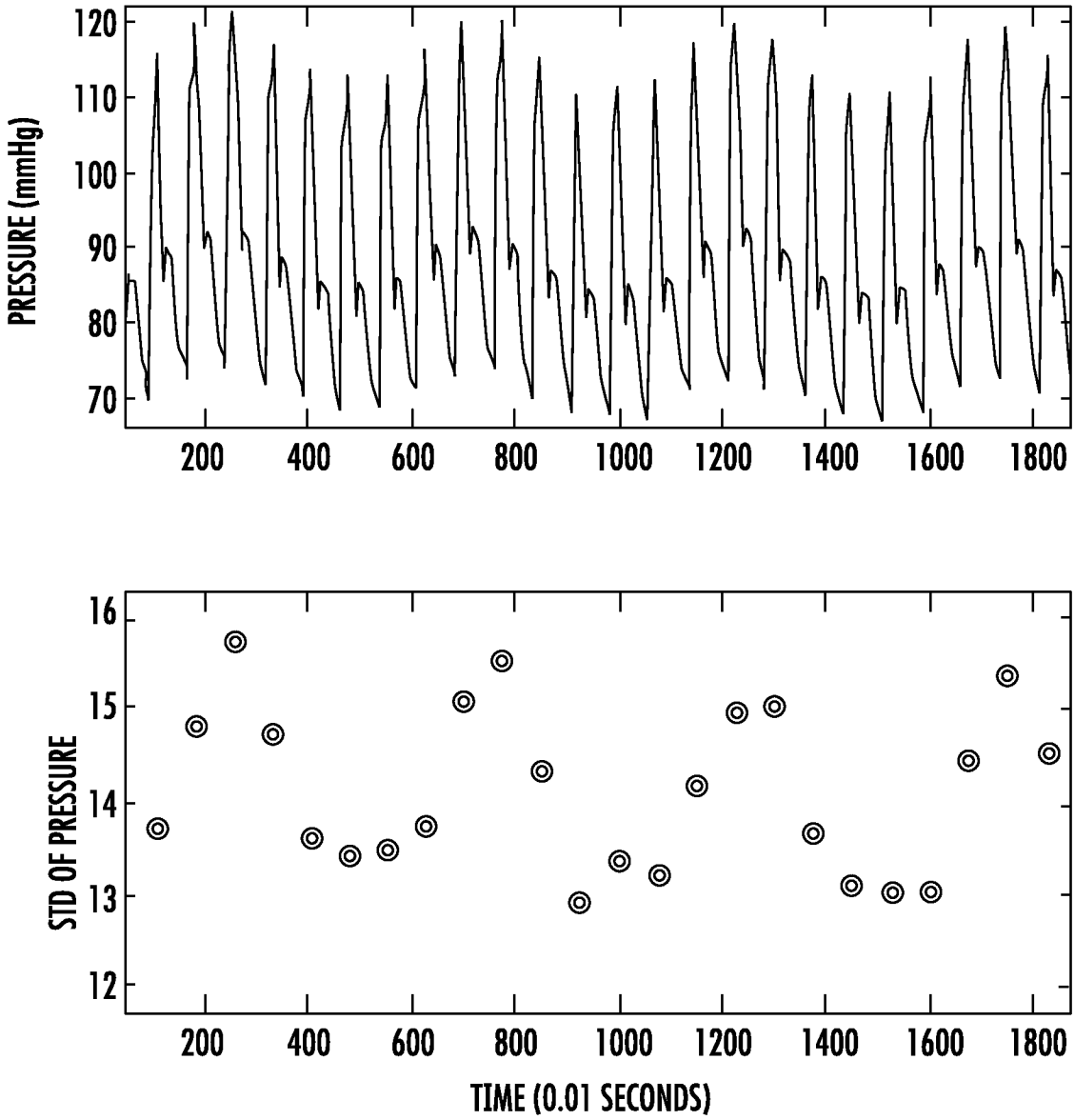
24. A method for determining a mechanical-respiration-induced variation in a cardiovascular parameter, the method comprising:

receiving, at a processing system, a waveform dataset derived from an arterial blood pressure waveform;

using the processing system to identify a trend in the waveform dataset, wherein the trend is not induced by the mechanical respiration;

using the processing system to remove the trend mathematically from the waveform dataset to produce a modified waveform dataset; and

using the processing system to determine the mechanical-respiration-induced variation in the cardiovascular parameter, based at least in part on the modified waveform dataset.


PRESSURE (mmHg)
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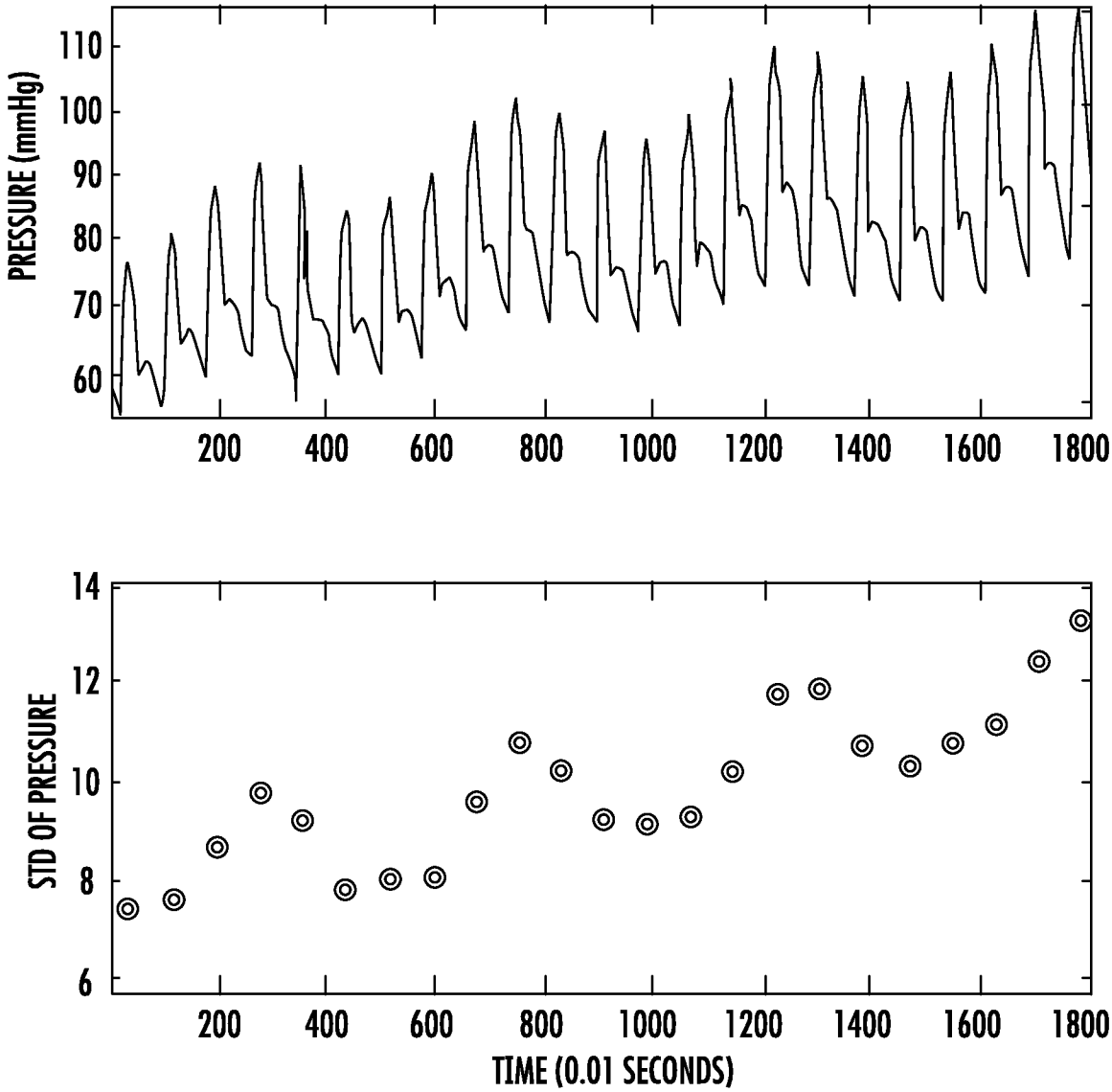
110
100
90
80
70
200
400
600
800
1000
1200
1400
1600
1800
STD OF PRESSURE
16
15
14
13
12
200
400
600
800
1000
1200
1400
1600
1800
TIME (0.01 SECONDS)

FIG. 1


PRESSURE (mmHg)
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100
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80
70
60
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400
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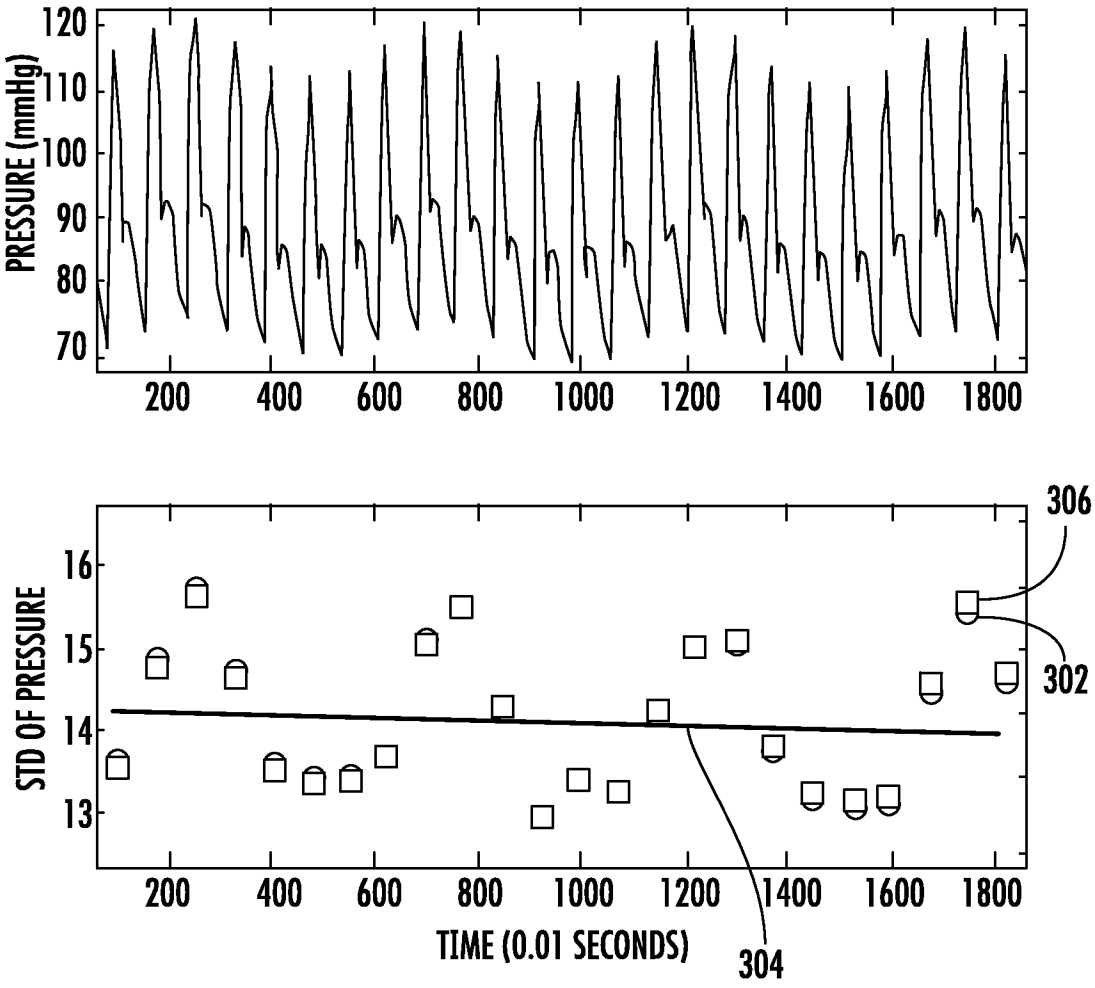
800
1000
1200
1400
1600
1800
STD OF PRESSURE
14
12
10
8
6
200
400
600
800
1000
1200
1400
1600
1800
TIME (0.01 SECONDS)

FIG. 2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100
90
80
70
200
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600
800
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1200
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1800
STD OF PRESSURE
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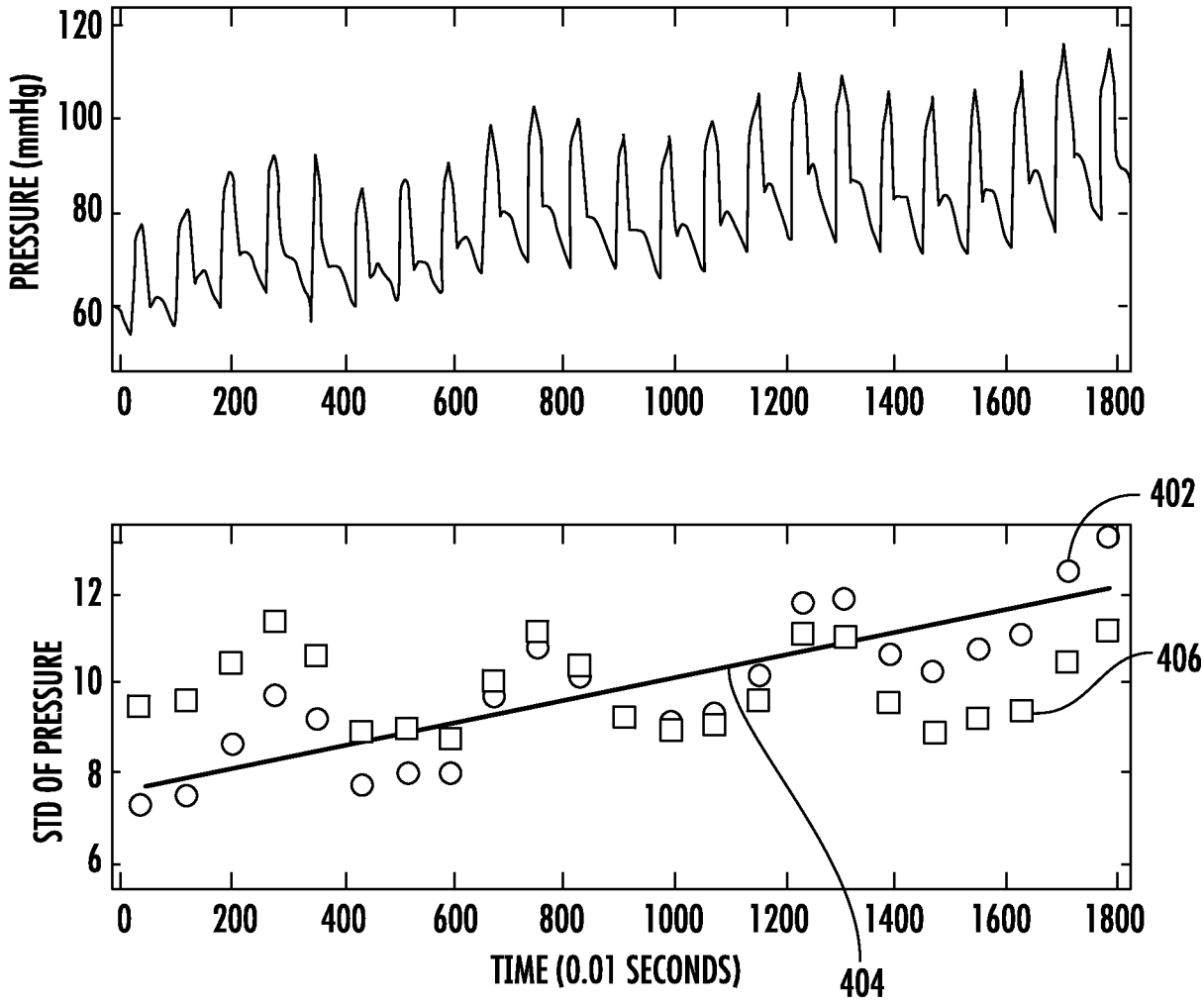
13
TIME (0.01 SECONDS)
306
302
304

FIG. 3


PRESSURE (mmHg)
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100
80
60
0
200
400
600
800
1000
1200
1400
1600
1800
STD OF PRESSURE
12
10
8
6
TIME (0.01 SECONDS)
402
406
404

FIG. 4

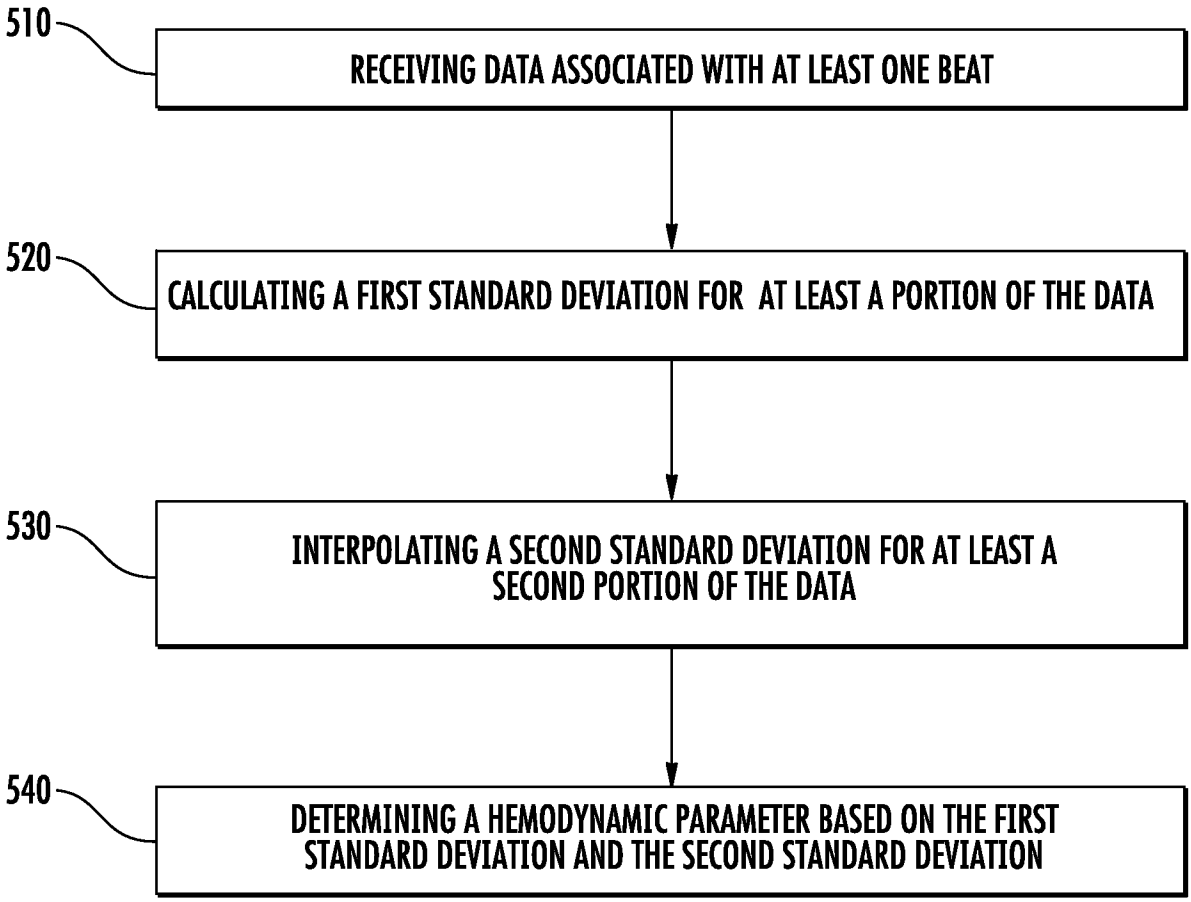

510
RECEIVING DATA ASSOCIATED WITH AT LEAST ONE BEAT
520
CALCULATING A FIRST STANDARD DEVIATION FOR AT LEAST A PORTION OF THE DATA
530
INTERPOLATING A SECOND STANDARD DEVIATION FOR AT LEAST A SECOND PORTION OF THE DATA
540
DETERMINING A HEMODYNAMIC PARAMETER BASED ON THE FIRST STANDARD DEVIATION AND THE SECOND STANDARD DEVIATION

FIG. 5

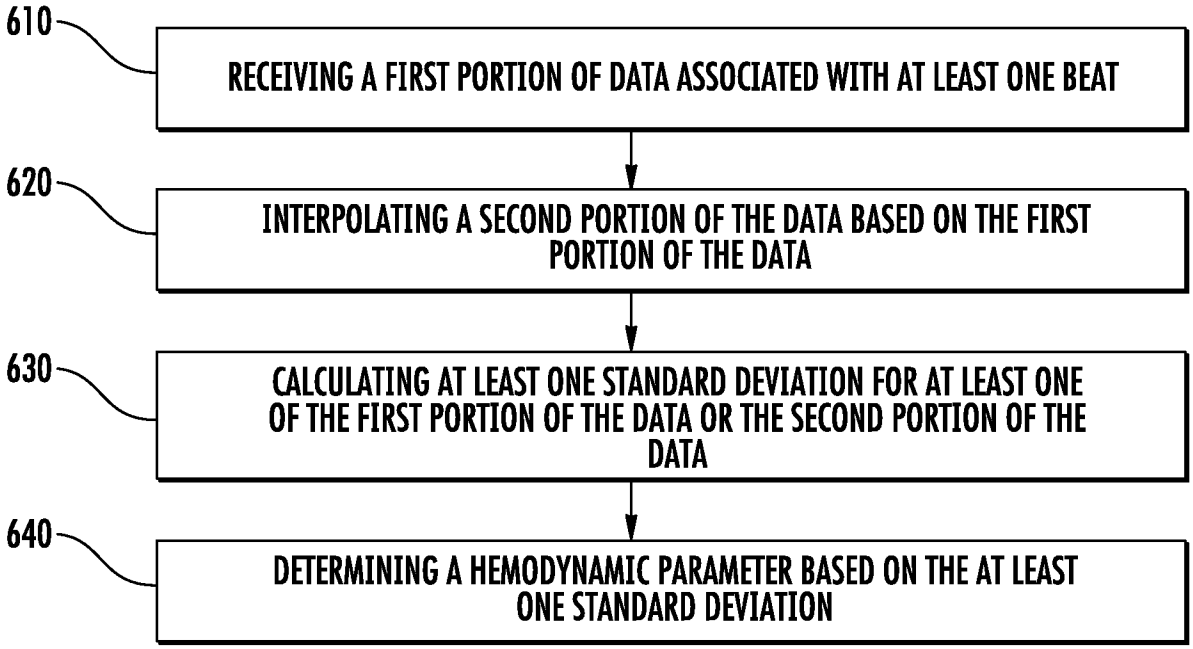
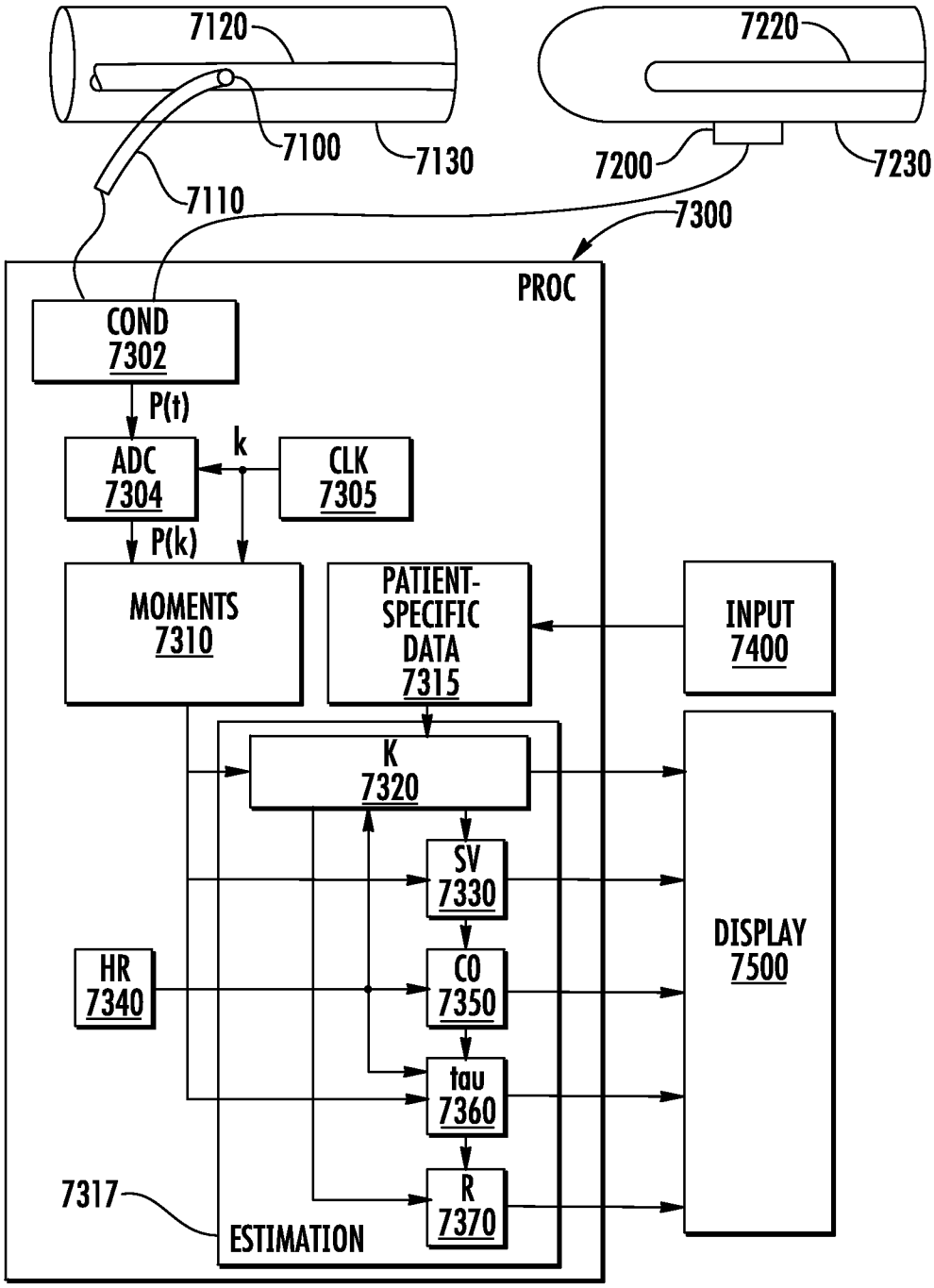

610
RECEIVING A FIRST PORTION OF DATA ASSOCIATED WITH AT LEAST ONE BEAT
620
INTERPOLATING A SECOND PORTION OF THE DATA BASED ON THE FIRST PORTION OF THE DATA
630
CALCULATING AT LEAST ONE STANDARD DEVIATION FOR AT LEAST ONE OF THE FIRST PORTION OF THE DATA OR THE SECOND PORTION OF THE DATA
640
DETERMINING A HEMODYNAMIC PARAMETER BASED ON THE AT LEAST ONE STANDARD DEVIATION

FIG. 6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7100
7130
7200
7230
7110
7300
PROC
COND
7302
P(t)
ADC
7304
k
CLK
7305
P(k)
MOMENTS
7310
PATIENT-
SPECIFIC
DATA
7315
INPUT
7400
K
7320
SV
7330
HR
7340
CO
7350
tau
7360
R
7370
DISPLAY
7500
7317
ESTIMATION

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/045701

A. CLASSIFICATION OF SUBJECT MATTER

A61B 5/02(2006.01)i, A61B 5/024(2006.01)i, A61B 5/029(2006.01)i, A61B 5/021(2006.01)i

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)
A61B 5/02; A61B 5/08; A61B 5/024; A61B 5/0295; A61B 5/0205; A61B 8/04; A61B 5/00; A61B 5/021

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: hemodynamic, heart beat, standard deviation, mechanical-respiration-induced variation

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013-0053664 A1 (ZHONGPING JIAN et al.) 28 February 2013 See abstract, paragraphs [0019]-[0061] and figures 1-16.	24
A		1-23
A	JP 2013-519410 A (LIDCO GROUP PLC) 30 May 2013 See abstract, paragraphs [0005],[0058]-[0062] and figures 1A-5.	1-24
A	KR 10-0954817 B1 (BIOSENSECREATIVE CO., LTD.) 28 April 2010 See abstract, paragraphs [0003]-[0015], claims 1,2 and figures 1-7.	1-24
A	US 2004-0077953 A1 (ROBERT G. TURCOTT) 22 April 2004 See abstract, paragraphs [0025]-[0039] and figures 1a-8.	1-24
A	US 2011-0319724 A1 (PAUL G. COX) 29 December 2011 See abstract, paragraphs [0052]-[0121] and figures 1-9.	1-24

☐ Further documents are listed in the continuation of Box C.

☒ See patent family 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 application or patent 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
24 October 2014 (24.10.2014)	**27 October 2014 (27.10.2014)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
KIM, Tae Hoon
Telephone No. +82-42-481-8407

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/045701

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Group I, claims 1-23 are directed to a method and an apparatus for determining a hemodynamic parameter.
Group II, claim 24 is directed to a method for determining a mechanical-respiration-induced variation in a cardiovascular parameter.

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/045701

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013-0053664 A1	28/02/2013	CN 102834047 A	19/12/2012
		EP 2528499 A2	05/12/2012
		JP 2013-517908 A	20/05/2013
		WO 2011-094487 A2	04/08/2011
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		US 2013-0006126 A1	03/01/2013
		WO 2011-098763 A1	18/08/2011
KR 10-0954817 B1	28/04/2010	None	
US 2004-0077953 A1	22/04/2004	DE 60314482 D1	02/08/2007
		DE 60314482 T2	21/02/2008
		EP 1410756 A1	21/04/2004
		EP 1410756 B1	20/06/2007
		US 6945939 B2	20/09/2005
US 2011-0319724 A1	29/12/2011	WO 2008-055173 A2	08/05/2008
		WO 2008-055173 A3	12/09/2008