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(54) **ASSESSING CARDIOVASCULAR FUNCTION USING AN OPTICAL SENSOR**

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A61B 5/00	(2006.01)
A61B 5/103	(2006.01)
A61B 5/11	(2006.01)
A61B 5/021	(2006.01)

(52) **U.S. Cl.**
CPC ***A61B 5/0205*** (2013.01); ***A61B 5/0077*** (2013.01); ***A61B 5/021*** (2013.01); ***A61B 5/02427*** (2013.01); ***A61B 5/02433*** (2013.01); ***A61B 5/1032*** (2013.01); ***A61B 5/1102*** (2013.01)

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USPC 600/301
See application file for complete search history.

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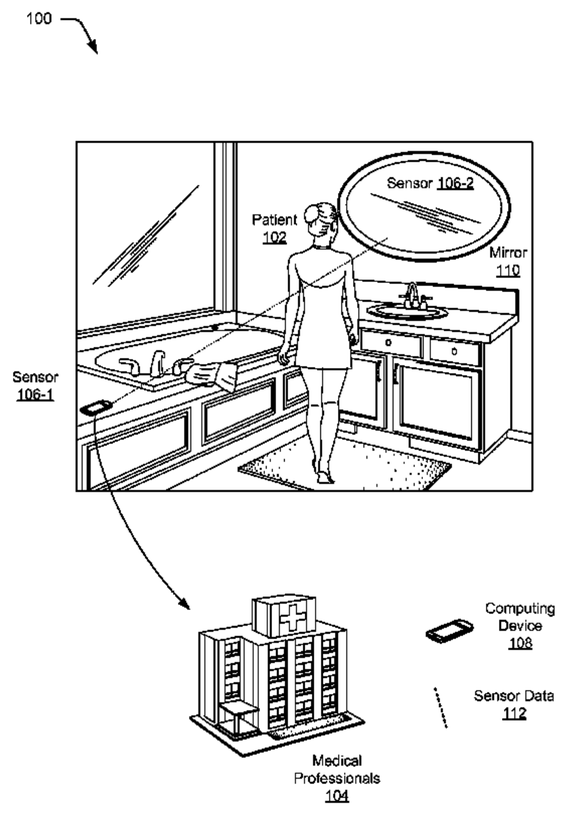
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(57) **ABSTRACT**

This document describes assessing cardiovascular function using an optical sensor, such as through sensing relevant hemodynamics understood by pulse transit times, blood pressures, pulse-wave velocities, and, in more breadth, ballistocardiograms and pressure-volume loops. The techniques disclosed in this document use various optical sensors to sense hemodynamics, such as skin color and skin and other organ displacement. These optical sensors require little if any risk to the patient and are simple and easy for the patient to use.

20 Claims, 9 Drawing Sheets



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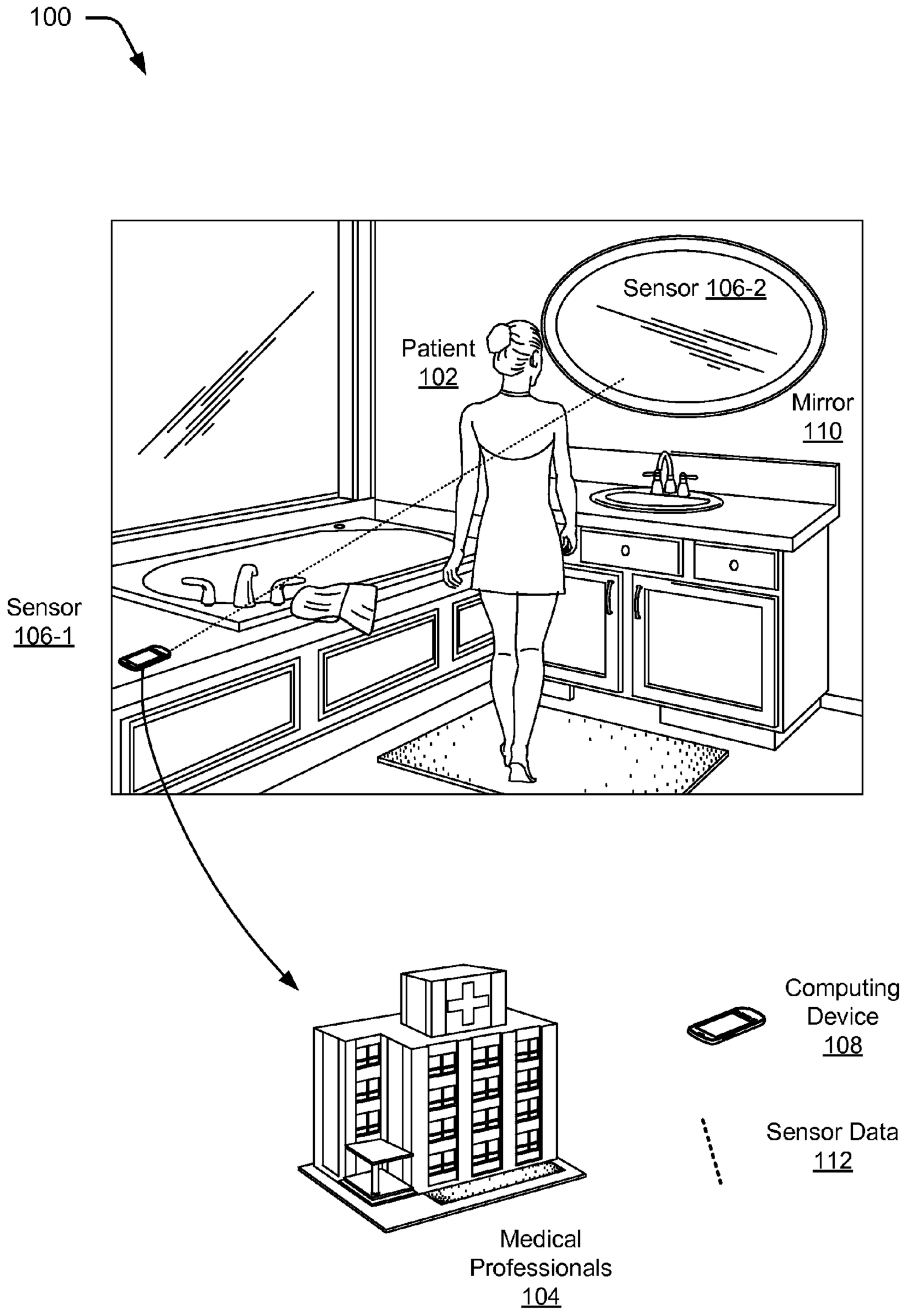

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Patient 102
Mirror 110
Sensor 106-1
Medical Professionals 104
Computing Device 108
Sensor Data 112

Fig. 1

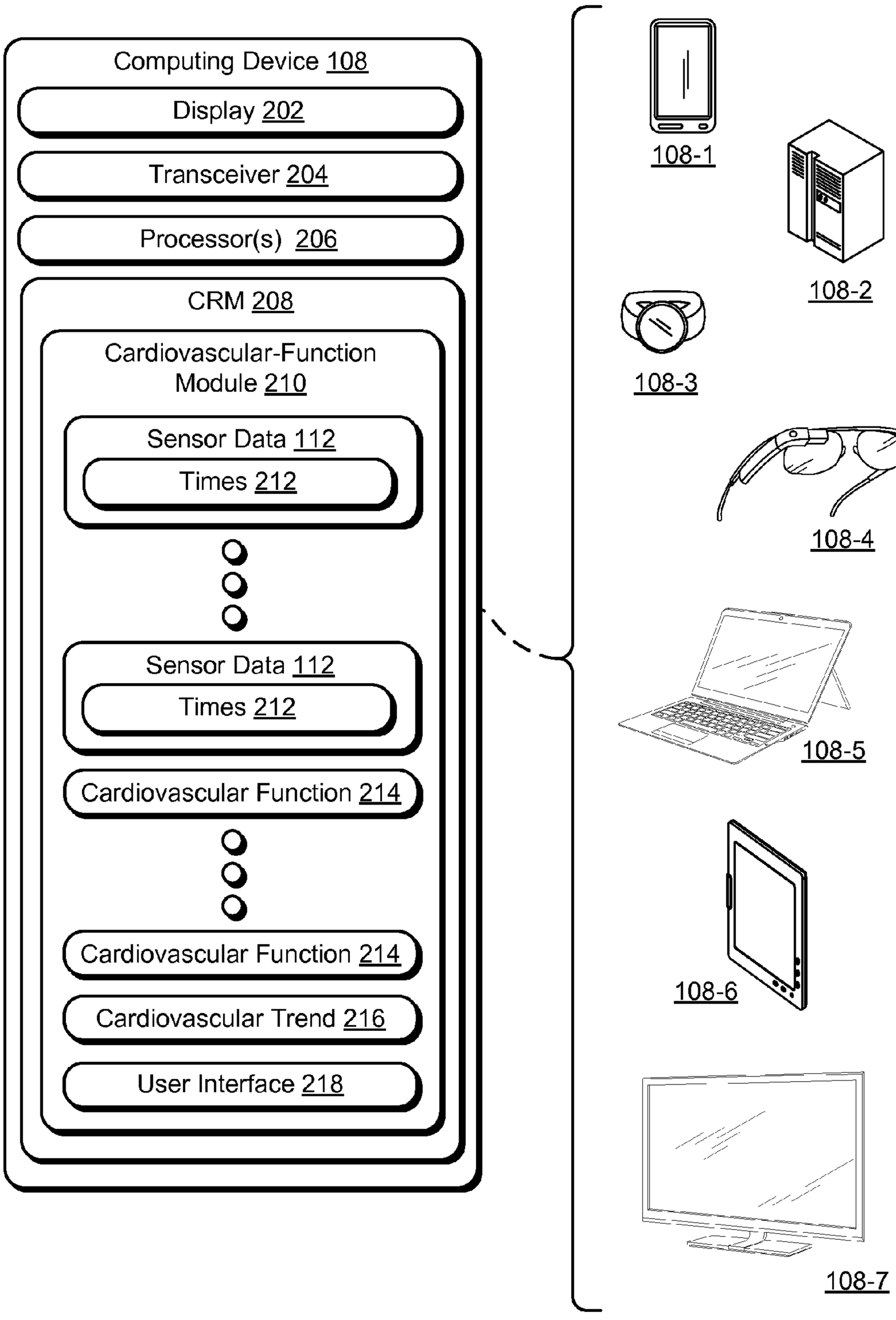
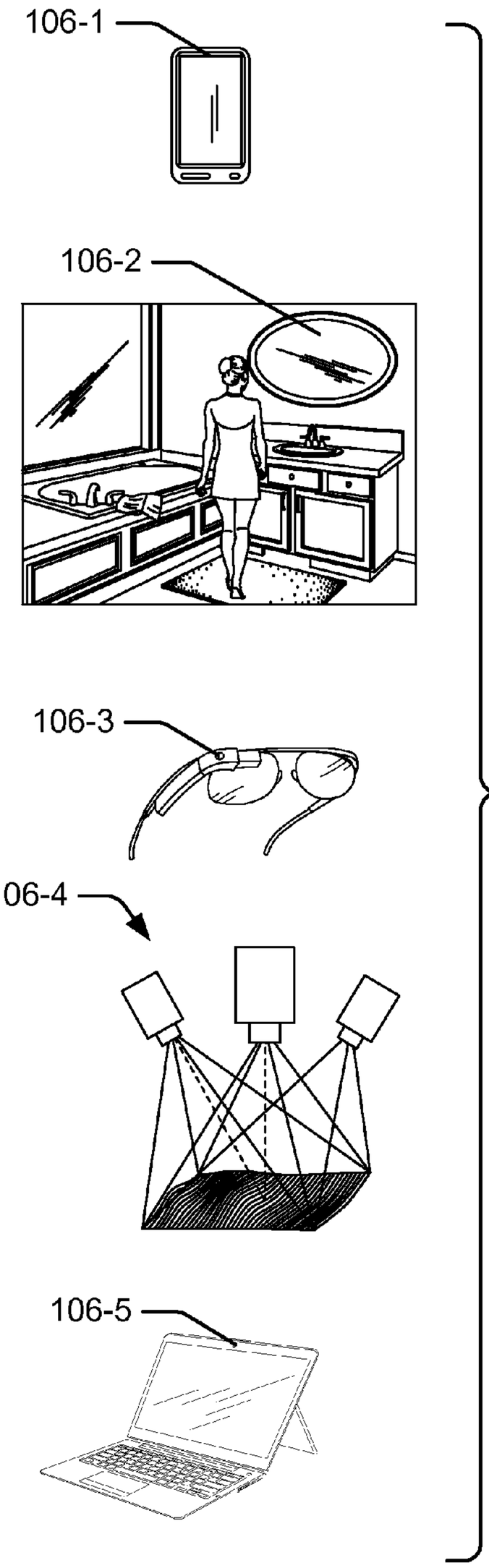

Computing Device 108
Display 202
Transceiver 204
Processor(s) 206
CRM 208
Cardiovascular-Function Module 210
Sensor Data 112
Times 212
Sensor Data 112
Times 212
Cardiovascular Function 214
Cardiovascular Function 214
Cardiovascular Trend 216
User Interface 218
108-1
108-2
108-3
108-4
108-5
108-6
108-7

Fig. 2


106-1
106-2
106-3
106-4
106-5

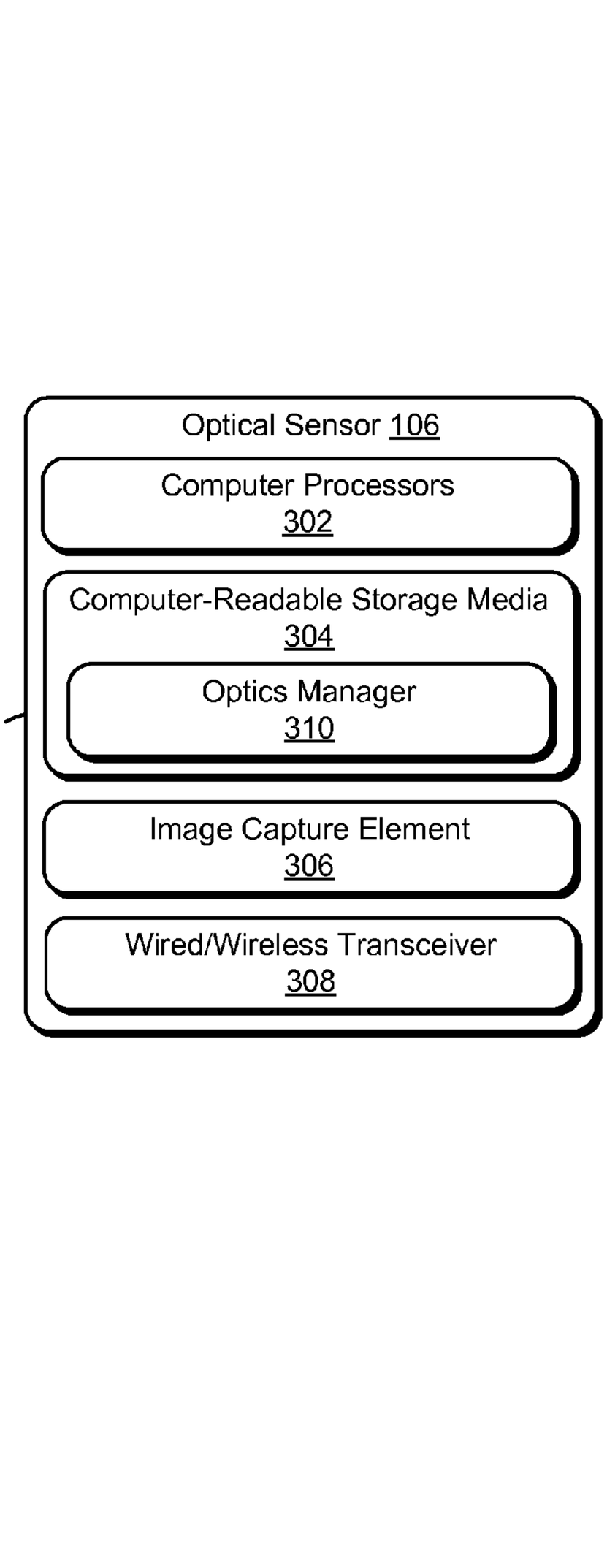

Optical Sensor 106
Computer Processors 302
Computer-Readable Storage Media 304
Optics Manager 310
Image Capture Element 306
Wired/Wireless Transceiver 308

Fig. 3

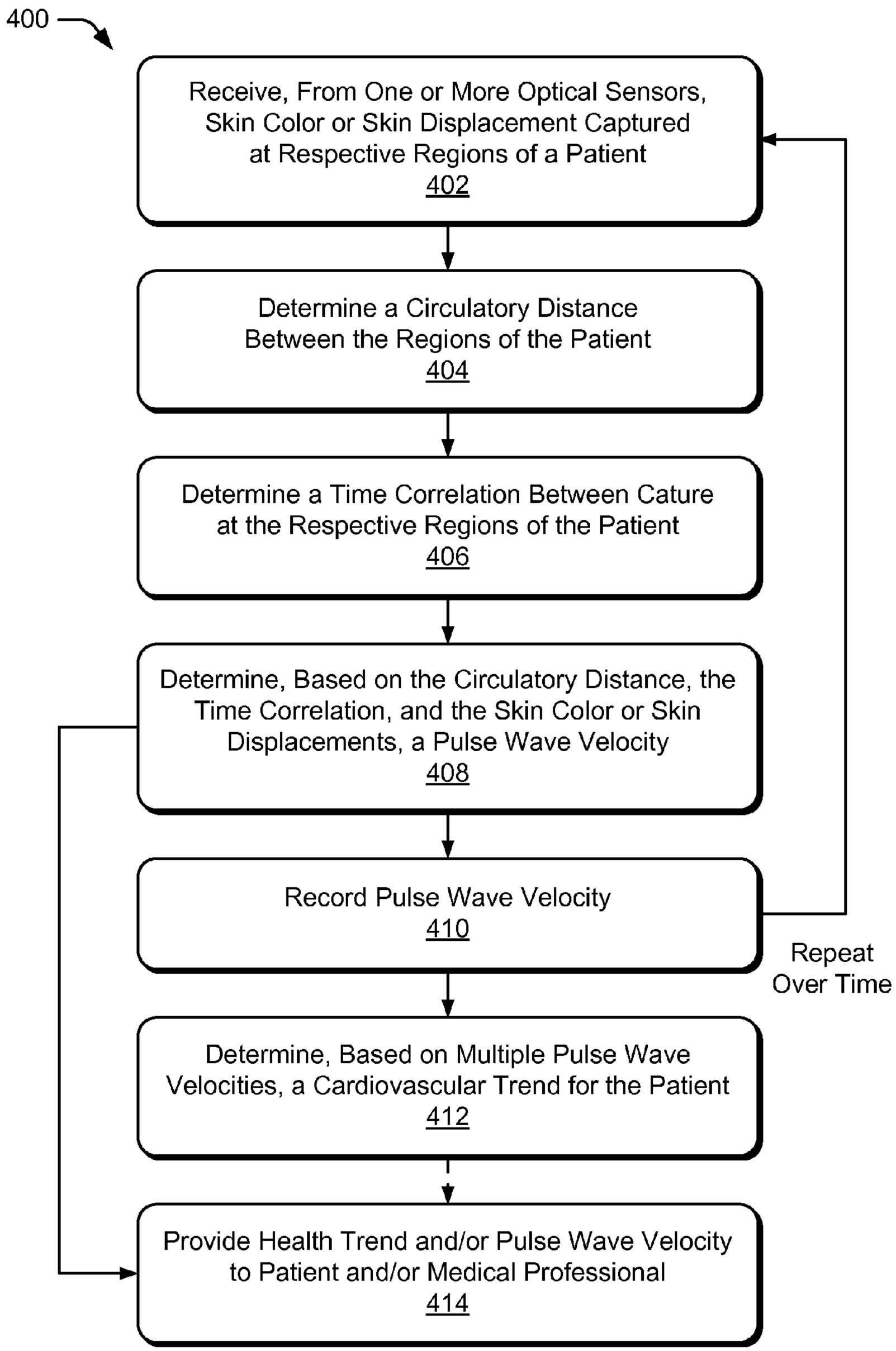

400
Receive, From One or More Optical Sensors, Skin Color or Skin Displacement Captured at Respective Regions of a Patient
402
Determine a Circulatory Distance Between the Regions of the Patient
404
Determine a Time Correlation Between Cature at the Respective Regions of the Patient
406
Determine, Based on the Circulatory Distance, the Time Correlation, and the Skin Color or Skin Displacements, a Pulse Wave Velocity
408
Record Pulse Wave Velocity
410
Repeat Over Time
Determine, Based on Multiple Pulse Wave Velocities, a Cardiovascular Trend for the Patient
412
Provide Health Trend and/or Pulse Wave Velocity to Patient and/or Medical Professional
414

Fig. 4

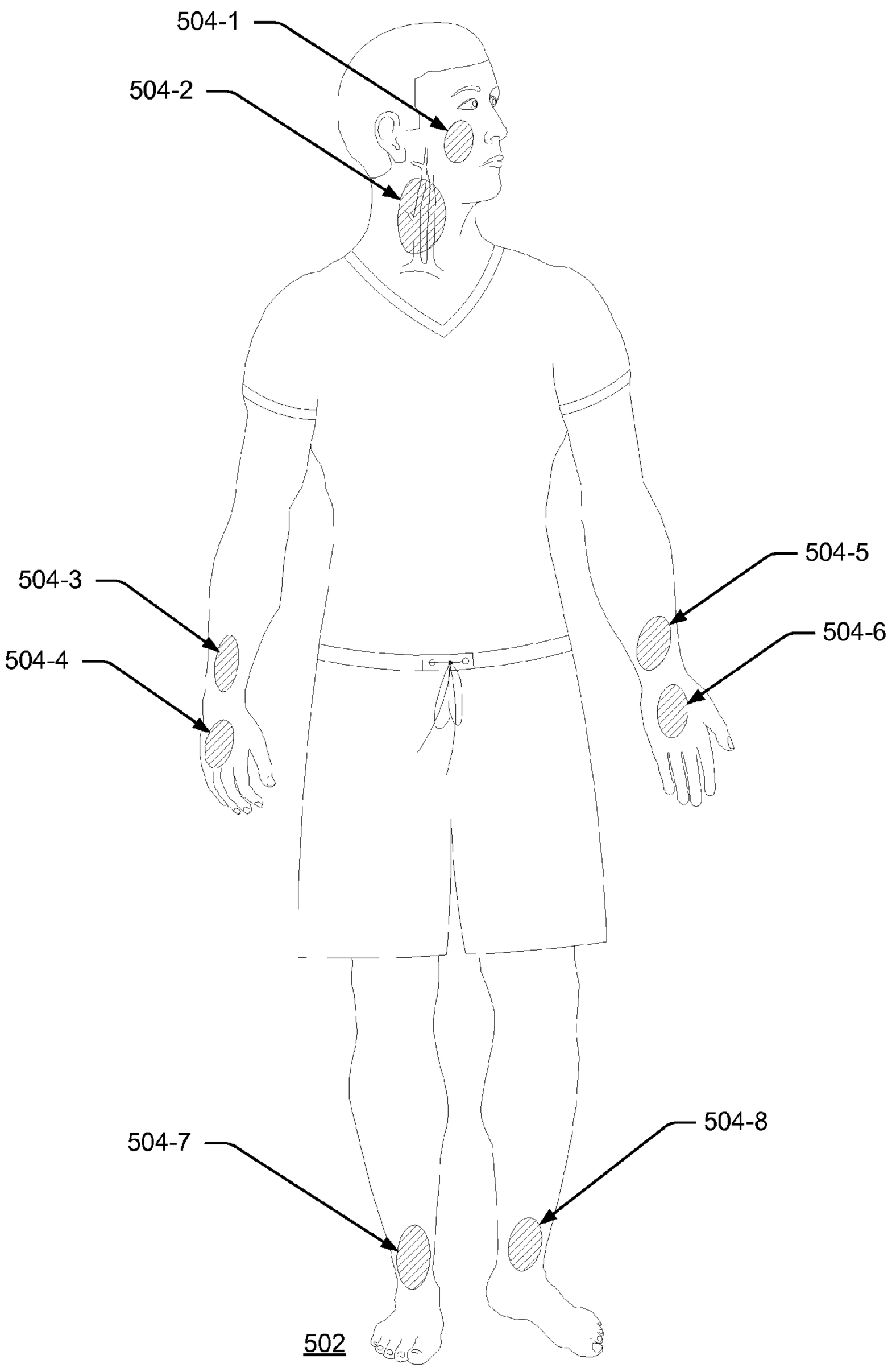


Fig. 5

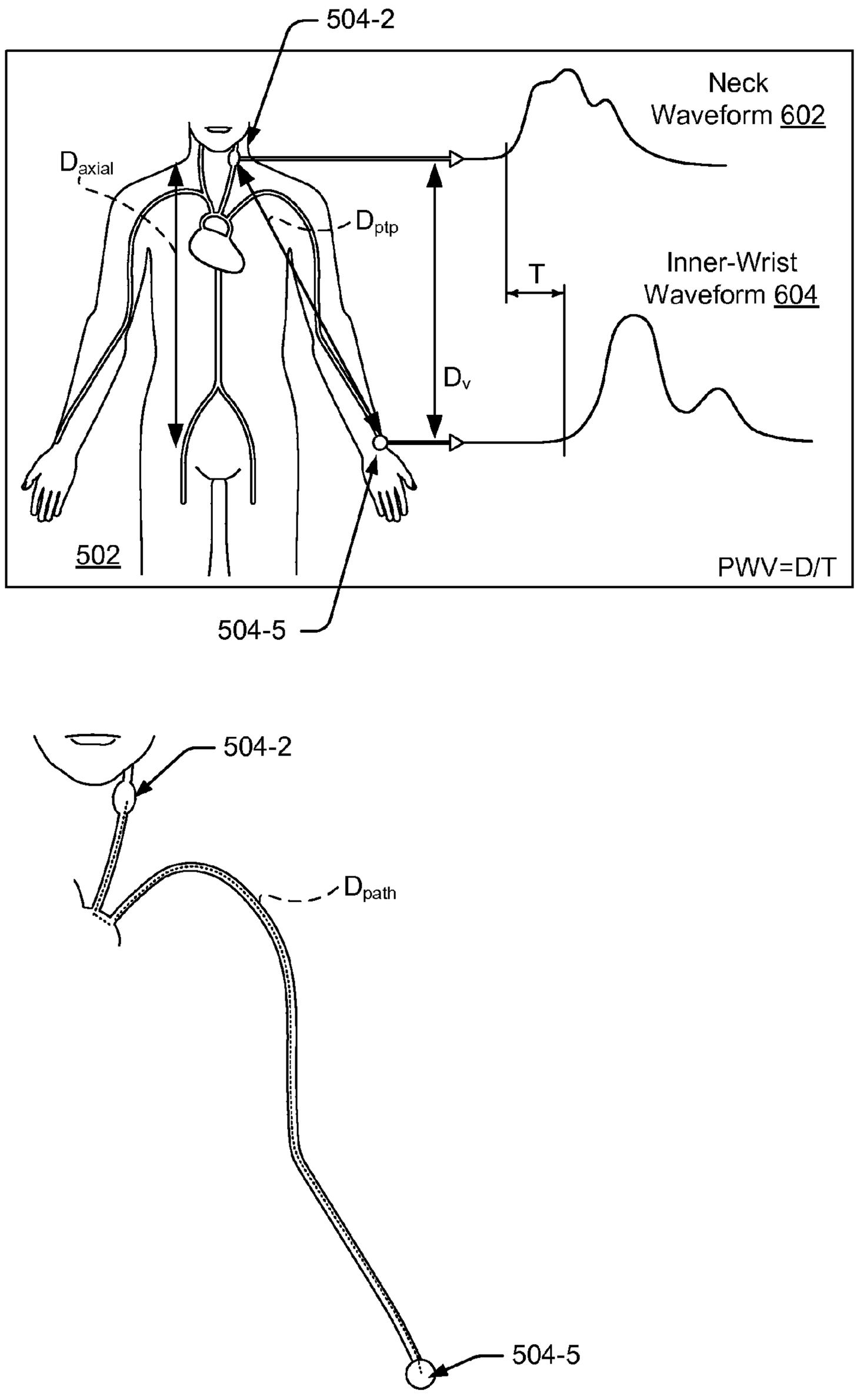

504-2
Neck
Waveform 602
D_{axial}
D_{ptp}
T
Inner-Wrist
Waveform 604
D_v
502
PWV=D/T
504-5
504-2
D_{path}
504-5

Fig. 6

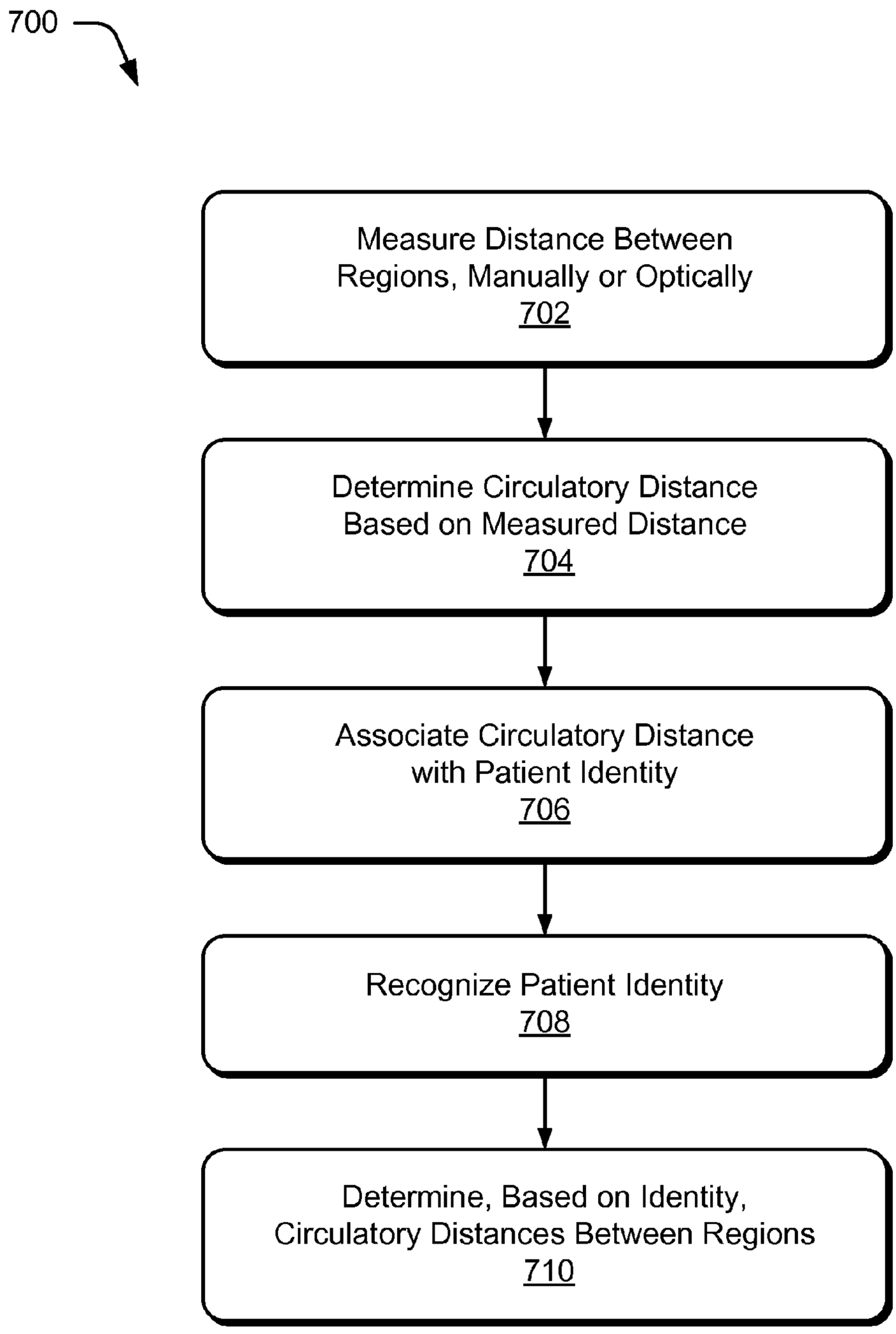

700
Measure Distance Between Regions, Manually or Optically
702
Determine Circulatory Distance Based on Measured Distance
704
Associate Circulatory Distance with Patient Identity
706
Recognize Patient Identity
708
Determine, Based on Identity, Circulatory Distances Between Regions
710

Fig. 7

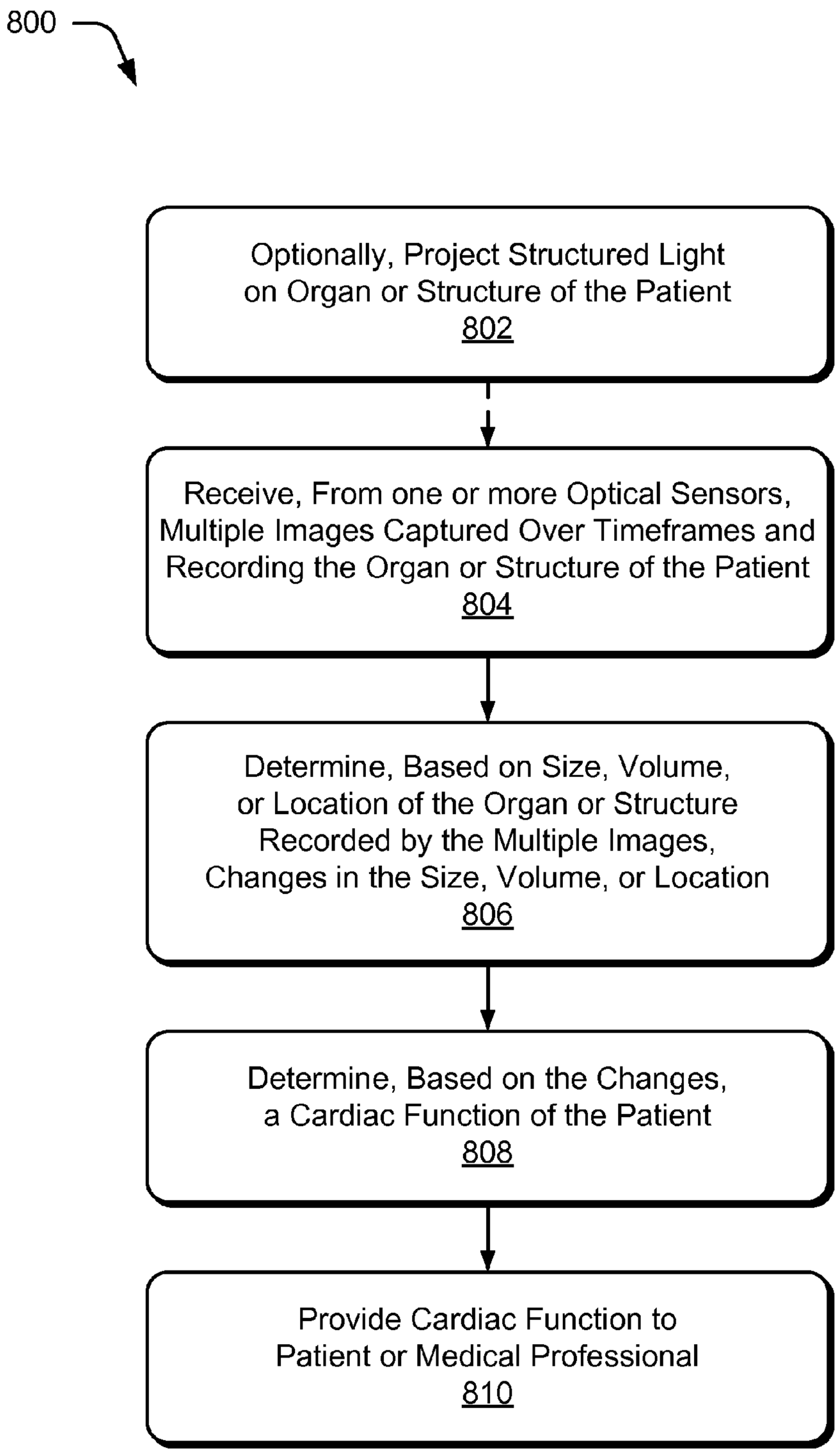

800
Optionally, Project Structured Light on Organ or Structure of the Patient
802
Receive, From one or more Optical Sensors, Multiple Images Captured Over Timeframes and Recording the Organ or Structure of the Patient
804
Determine, Based on Size, Volume, or Location of the Organ or Structure Recorded by the Multiple Images, Changes in the Size, Volume, or Location
806
Determine, Based on the Changes, a Cardiac Function of the Patient
808
Provide Cardiac Function to Patient or Medical Professional
810

Fig. 8

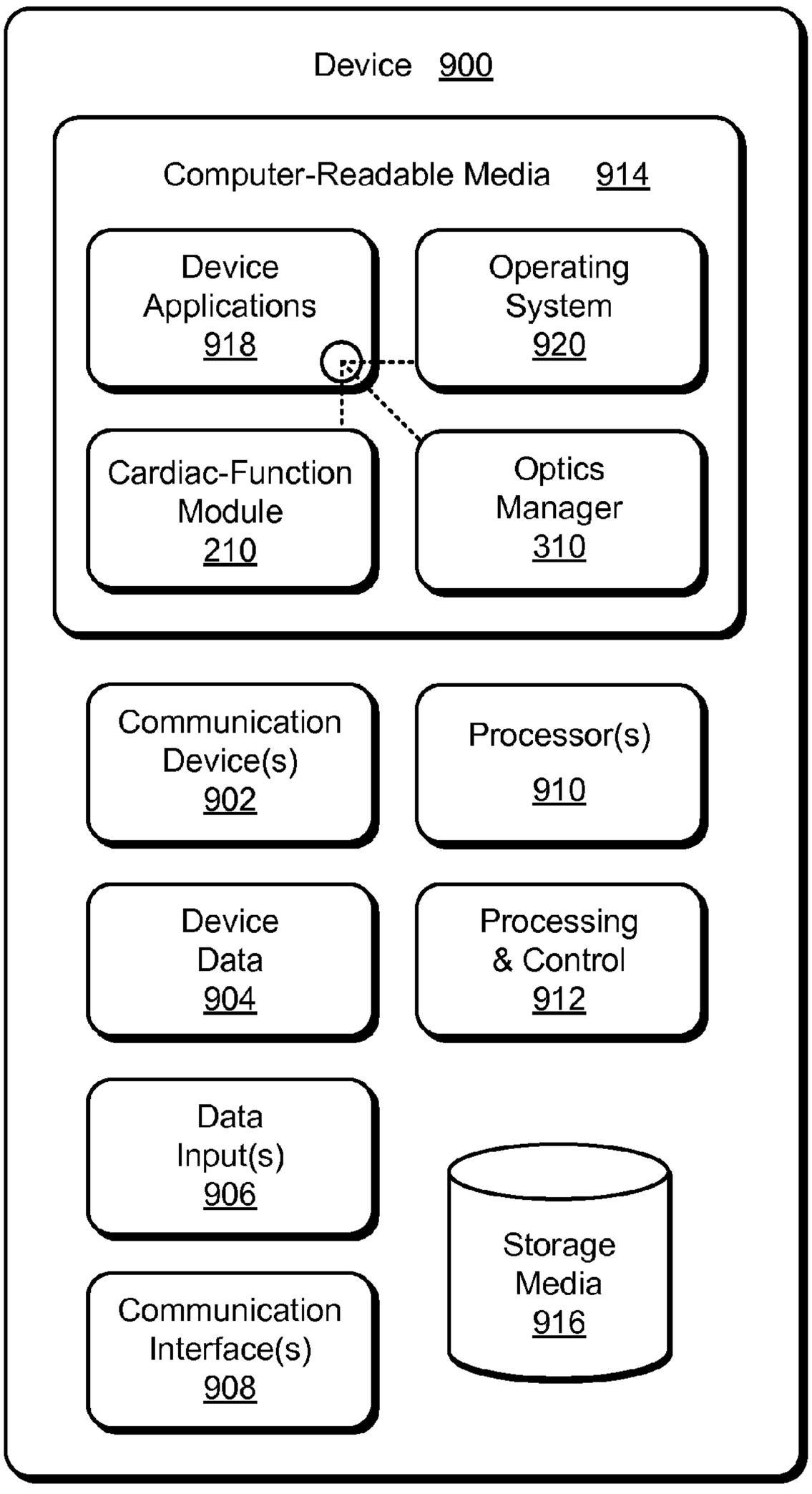

Device 900
Computer-Readable Media 914
Device Applications 918
Operating System 920
Cardiac-Function Module 210
Optics Manager 310
Communication Device(s) 902
Processor(s) 910
Device Data 904
Processing & Control 912
Data Input(s) 906
Storage Media 916
Communication Interface(s) 908

Fig. 9

ASSESSING CARDIOVASCULAR FUNCTION USING AN OPTICAL SENSOR

BACKGROUND

Cardiovascular disease is the leading cause of morbidity and mortality worldwide. At the same time this chronic disease is largely preventable. Medical science knows how to save most of these lives by removing the major risk factors of smoking, diabetes, and hypertension. And many people are told just what they need to do to reduce these risk factors—stop smoking, reduce sugar intake, eat healthier, reduce alcohol intake, increase cardiovascular exercise, lose weight, and, if needed, take blood-pressure medication. But many people do not follow this good advice. Because of this, millions of people needlessly die from cardiovascular disease.

People don't follow this good medical advice because they think they are different, they do not want to change their behaviors that are causing the disease, or they do not know what to change in their particular case. When a physician tells them that they are at risk from heart disease because they are overweight, for example, many people know that this judgment is not necessarily specific to them—it is based on averages and demographics. So being a particular weight may not negatively affect a particular patient's heart. Further, a lack of feedback that their behavior is harming their heart results in a lack of incentive for them to change their behavior.

This lack of incentive to follow good advice can be addressed by monitoring the state of the patient's cardiovascular system over time to show trends in heart health. Hard data often motivates patients to modify their behavior, such as data indicating that their heart shows measurable signs of heart disease. Unfortunately, current methods for measuring heart health can be inconvenient, stressful, and expensive. Simple home monitor products exist for measuring heart rate and blood pressure, but long-term user compliance is a problem due to inconvenience. More advanced cardiovascular monitoring, such as heart rate variability, arterial stiffness, cardiac output, and atrial fibrillation, involve expensive and time-consuming trips to a medical facility for a skilled assessment. Because of this, only patients that demonstrate late stage symptoms of heart disease are likely to receive these tests, which is generally too late to make simple lifestyle changes that would avoid a chronic disease.

Another reason that people don't follow this good advice, or don't follow it for long enough to prevent heart disease, is because they do not see the benefit. When people take the advice of changing their diet and habits—which most people do not want to do—they often don't see the improvement before they lose the motivation to continue monitoring their cardiovascular status. Because of this, many people go back to their old habits only to later die of heart disease.

SUMMARY

This document describes assessing cardiovascular function using an optical sensor, such as through sensing relevant hemodynamics understood by heart and respiration rates, heart rate variability, blood pressures, pulse-wave velocities, arterial stiffness, cardiac valve timing, ballistocardiogram force, photo-plethysmograms, blood oxygenation, and pressure-volume loops. The techniques disclosed in this document use various optical sensors to sense the effects of cardiovascular hemodynamics, such as skin color or displacement at multiple spatial locations on the body. These optical sensors require little if any risk to the patient and are simple and easy for the patient to use.

Further, the techniques described herein can determine blood flow asymmetries, which may indicate a stroke or other cardiovascular disease or pressure waveforms, which may indicate cardiac abnormalities, such as atrial fibrillation. These techniques may also determine trends in a patient's cardiovascular health. These trends can aid a patient by helping them know if the effort they are expending to improve their heart health is actually making a difference. Further, negative trends or conditions, such as cardiac irregularities or some asymmetries can be found that can spur people to improve their health or to get medical attention. By so doing, these techniques may save many people from dying of heart disease.

This summary is provided to introduce simplified concepts concerning the techniques, which are further described below in the Detailed Description. This summary is not intended to identify essential features of the claimed subject matter, nor is it intended for use in determining the scope of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of techniques and devices for assessing cardiovascular function using an optical sensor are described with reference to the following drawings. The same numbers are used throughout the drawings to reference like features and components:

FIG. **1** illustrates an example environment in which the techniques can be implemented.

FIG. **2** illustrates an example computing device of FIG. **1**.

FIG. **3** illustrates an example optical sensor of FIG. **1**.

FIG. **4** illustrates a method for assessing cardiovascular function using an optical sensor, including determination of a pulse-wave velocity for a patient.

FIG. **5** illustrates a male patient having various regions of which images are captured by optical sensors.

FIG. **6** illustrates various circulatory distances that can be used, along with time correlations, to determine a pulse-wave velocity.

FIG. **7** illustrates a method for determining circulatory distances, such as those described in FIG. **6**.

FIG. **8** illustrates a method for assessing cardiovascular function using an optical sensor based on size, volume, or location of an organ or structure of a patient.

FIG. **9** illustrates an example device embodying, or in which techniques may be implemented that assess cardiovascular function using an optical sensor.

DETAILED DESCRIPTION

Overview

This document describes techniques using, and devices enabling, assessment of cardiovascular function using an optical sensor. Through use of optical sensors a patient's skin color and displacement over time can be accurately measured, including by comparing colors and displacements at different regions of the patient. For example, an optical sensor can measure a color change at a patient's cheek and, based on that color change, the techniques can determine that the patient's heart beat has produced a peak blood-pressure flow at some particular instant at the cheek. Another optical sensor can measure a color change or displacement at the patient's wrist for the same heartbeat, which the techniques can determine indicates a peak blood-pressure

flow at the wrist at some other instant. By comparing the times and distance between these regions, a pulse-wave velocity can be assessed. This pulse-wave velocity can then be used to determine arterial stiffness, blood pressure, and other measurements of cardiovascular function. Simultaneously, those two measurement points can be used to independently measure other vitals like heart rate and respiration rate, with the combination of the two used to improve the measurement by compensating for movements, illumination changes, or occlusions.

In addition to assessing cardiovascular heath at some snapshot in time, the techniques may also measure trends in cardiovascular function. By way of one example, assume that a patient has an optical sensor in her bathroom that is capable of measuring color and displacement at multiple regions, such as her neck, palm, and forehead. This optical sensor measures skin color variations between or within a region, which can indicate differential blood volume to provide a photo-plethysmogram (PPG). If the patient has other optical sensors, such as one in her computing spectacles and another in her smartphone, these can further aid the accuracy and robustness of the measurements. Using these sensors, assume that over the course of a new diet and exercise routine that the techniques, using data from the optical sensors, determine that her heart's stroke volume (an important measure of heart health) has improved 6% in four weeks. With this positive feedback, this patient may continue her diet and exercise routine, thereby likely reducing the chances that she will die of heart disease.

For another case, assume that the techniques determine that there is an asymmetry in blood flow within a patient's face. This asymmetry can be indicated to the patient or a medical professional sufficient to perform further testing, as asymmetry can indicate a stroke (a deadly disease that, with a fast diagnosis and treatment can save the patient's life or quality of life) or other vascular disease.

These are but a few examples in which assessing cardiovascular function using an optical sensor can be performed, other examples and details are provided below. This document now turns to an example environment, after which example optical sensors and methods, cardiovascular functions and trends, and an example computing system are described.

Example Environment

FIG. **1** is an illustration of an example environment **100** in which assessing cardiovascular function using an optical sensor can be employed. Environment **100** illustrates a patient **102** that is a subject of the health monitoring, as well as a medical professional **104**, family member, or other caretaker that, in some cases, will receive results of the health monitoring. This example employs optical sensors **106**, a color and displacement optical sensor **106-1** (sensor **106-1**), which is part of computing device **108**, and a hyperspectral sensor **106-2** (sensor **106-2**), which is located within mirror **110**.

Sensor data **112** is provided by each of optical sensors **106** to some computing device. As shown, sensor data **112** is passed from sensor **106-2** to computing device **108** while sensor **106-1** is integral with computing device **108** and need not be passed if the techniques are performed at that device. Computing device **108** then performs some or all of the techniques, or passes that sensor data to some other computing device, such as a remote server through a communication network (not shown).

As shown with this example environment **100**, a sensing milieu (e.g., optical sensors **106** in patient **102**'s bathroom) in which a patient lives can be used that are capable of determining a cardiovascular function of a human cardiovascular system. This sensing milieu is capable of non-invasively and remotely determining this cardiovascular function and trends in this cardiovascular function. This sensing milieu senses various regions of the patient, which can then be compared, time correlated, aggregated, averaged, and so forth to determine a cardiovascular function. These cardiovascular functions can be represented by cardiovascular asymmetries (e.g., due to a stoke), cardiac irregularities (e.g. atrial fibrillation), blood pressure, pulse-wave velocity, waveforms of circulating blood, photo-plethysmograms (PPG), ballistocardiograms, and pressure-volume loops, to name a few.

With regard to the example computing device **108** of FIG. **1**, consider a detailed illustration in FIG. **2**. Computing device **108** can be one or a combination of various devices, here illustrated with seven examples: a smartphone **108-1**, a server **108-2**, a computing watch **108-3**, computing spectacles **108-4**, a laptop **108-5**, a tablet computer **108-6**, and a desktop **108-7**, though other computing devices and systems, such as a netbook or set-top box may also be used. As noted above, in some embodiments the techniques operate, in whole or in part, through a remote device such as server **108-2**. In such cases, some computing can be forgone locally, e.g., through a communication device having limited computing operations or even directly from optical sensors **106** to server **108-2**.

Computing device **108** includes or is able to communicate with a display **202** (six are shown in FIG. **2**), a transceiver **204**, one or more processors **206**, and computer-readable storage media **208** (CRM **208**). Transceiver **204** is capable of sending and receiving data directly or through a communication network, such as sensor data **112** from optical sensors **106** through a local area, wide area, functional area, cellular, or near-field network.

CRM **208** includes cardiovascular-function module **210**, which includes or has access to sensor data **112** from one or more of multiple optical sensors **106**. This sensor data **112** can be associated with particular times **212**, such that simultaneously received sensor data **112** can be correlated to determine cardiovascular functions **214** of human cardiovascular systems and trends **216** can be determined based on sensor data **112** changing over time. CRM **208** also includes or has access to a user interface **218**, that, while not required, can be used to present determined trends, health, and medical advice to patient **102**.

Generally, cardiovascular-function module **210** is capable of determining, based on sensor data **112**, a cardiovascular function of a cardiovascular system of a patient, such as patient **102** of FIG. **1**. With this cardiovascular function, cardiovascular-function module **210** may alert patient **102** or medical professionals **104** or family members/caretakers of a negative health condition needing immediate care, for example. Medical professional **104**, or a specialized machine intelligence, could schedule an in-person appointment or remotely adjust patient care through changes in medication or lifestyle. Cardiovascular-function module **210** is also configured to determine trends based on the current cardiovascular function and prior-determined cardiovascular functions, such as those determined at prior times.

More specifically, cardiovascular-function module **210** is capable of receiving and using optical sensor data indicating a skin, organ, or structure's color or displacement. This data may come from single or multiple optical sensors covering the same or different wavelengths observing multiple locations on the patient's body. With this data, cardiovascular-function module **210** can determine timing relationships,

pulse pressure waveforms, and asymmetries in a patient's cardiovascular system. With this data and a circulatory distance between data from different regions of the patient, as well as time correlations between the data, cardiovascular-function module **210** can determine a pulse-wave velocity and various simple or highly sophisticated measures of cardiovascular function, including charts of blood pressure, a ballistocardiogram, a photo-plethysmogram (PPG), and pressure-volume loops. Capabilities of cardiovascular-function module **210** are addressed further in methods described below.

With regard to optical sensors **106**, two examples of which are shown in FIG. **1**, consider a detailed illustration in FIG. **3**. Generally, optical sensors **106** are capable of detecting blood volume, color, and/or displacement at one or more regions of a patient. Optical sensors **106** may include a standard RGB (red, green, blue) sensor, a monochrome sensor, a hyperspectral sensor, a stereoscopic sensor, a structured light sensor, or combinations of multiple sensors, along with a combination of illumination sources such as uniform, infrared, tangential, modulated/coded, or coherent (laser). Optical sensors **106** may also have a fixed camera position or consist of one or more cameras and light sources on mechanical targeting platforms or those that simply move due to being part of a mobile device. Optical sensors **106** may also be separated into physically and spatially distinct devices capable of monitoring the body from multiple view angles or observing different regions of the body. Thus, one of optical sensors **106** may capture an image indicating blood volume at two different regions of patient **102**, which then can be compared, by cardiovascular-function module **210**, to determine a blood-volume asymmetry or other cardiac function. In the case of a blood-volume asymmetry, a difference in vascular function between the regions may indicate a cardiac-related health problem, such as a stroke. Optical sensors **106** provide various types of information, and are not limited to determining asymmetries.

In more detail, optical sensor **106** can be one or a combination of various devices, here illustrated with color and displacement optical sensor **106-1** (e.g., a camera of computing device **108**), sensor **106-2**, which is stationary and located within mirror **110**, a wearable color and displacement optical sensor **106-3**, which is part of computing spectacles **108-4**, structured-light or stereoscopic sensor system **106-4**, and optic sensor **106-5** of laptop **108-5**. The cameras can also be motorized to accurately point at specific points on the body.

As noted in part, sensor **106-2** is capable of capturing images in an ultraviolet, visible, or infrared optical wavelength. Images recording these wavelengths can be used to determine various changes in blood movement or as calibration signals to detect changes in illumination or patient movement. In some cases blood perfusion and oxygen content can be ascertained, thereby further enabling robust measurement of cardiac function. Due to differential wavelength absorption between human tissue and blood, a hyperspectral sensor can also be used to penetrate the skin to map out veins and arteries to target closer examination for displacement and other measurements.

Structured-light sensor system **106-4** is capable of projecting structured light at patient **102** and sensing, often with two or more optical sensors, the projected structured light on patient **102** effective to enable capture of images having surface information. This surface information can be used to calculate depth and surface changes for a region of patient **102**, such as skin, another organ, or other structure. These changes can be highly accurate, thereby indicating small vibrations and other changes in an organ or structure caused by the cardiovascular system, and thus how that system is operating. Structured-light sensor system **106-4** can, alternatively, be replaced with or supplemented with a targeted, coherent light source for more-accurate displacement measurements. This may include LIDAR (e.g., "light radar" or the process measuring distance by illuminating a target with a laser and analyzing light reflected from the target), laser interferometry, or a process of analyzing light speckle patterns produced by a coherent light on a skin's surface through optical tracking, which enables detection of very small skin displacements.

These optical sensors **106** can capture images with sufficient resolution and at sufficient shutter speeds to show detailed colors and displacement, and thus enable determination of mechanical movements or vibrations. These mechanical movements and mechanical vibrations are sufficient to determine a ballistocardiogram (BCG) showing patient **102**'s cardiac function. Other sensing manners, such as color change or skin displacement in a different region of a patient's body, can be used to establish motion frequency bands to amplify, as well as a timing reference for aggregating multiple heartbeat measurements to improve accuracy of a BCG motion. This BCG information can also be used to provide reference timing information about when a blood pressure pulse leaves the left ventricle and enters the aorta, which combined with the other measurements across the body allows for more-precise estimates of pulse transit times and pulse-wave velocities.

While the BCG signal indicates the timing of the aortic valve, the timing of the atrial valve can be monitored by tracking atrial pressure waveforms visible in the external or internal jugular. This also allows for the opportunity to detect atrial fibrillation by detecting missing atrial-pressure pulses. Additionally, aortic-wall stiffness has proven prognostic value in predicting cardiovascular morbidity and mortality. Measuring the pulse-transit time from the start of ejection from the left ventricle into the aorta and up the carotid allows an estimate of that aortic stiffness as well as trending of changes in that stiffness. Thus, determination of arterial-wall stiffness can made independent of blood pressure measurements.

In more detail, optical sensors **106** are configured to capture sufficient information for the techniques to determine blood asymmetries and other cardiac function, including a pulse-wave velocity of patient **102**'s blood. This pulse-wave velocity is a measure of a patient's arterial health. In healthy arteries the pulse-wave velocity is low due to the elasticity of the arteries but, as they harden and narrow, the pulse-wave velocity rises. Additionally, as blood pressure increases and dilates the arteries, the walls become stiffer, increasing the pulse-wave velocity. While a particular pulse-wave velocity as a snapshot in time may or may not accurately indicate cardiovascular health (e.g., a one-time test at a doctor's office), a change in this pulse-wave velocity (that is, a trend), can be an accurate measure of a change in patient **102**'s cardiovascular health. If a positive trend, this can reinforce patient **102**'s healthy habits and, if negative, encourage changes to be made.

In more detail, each of the color-sensing optical sensors **106** is configured to record colors in a patient's skin sufficient to determine a photo-plethysmogram. This PPG measures variations in a size or color of an organ, limb, or other human part from changes in an amount of blood present in or passing through it. These colors and color variations in a patient's skin can show heart rate and efficiency.

These examples show some ways in which the techniques can provide substantially more-valuable (or at least different) data by which to assess a patient's cardiac function than those provided in a medical office or hospital. As noted, conventional health monitoring is often performed at a hospital or medical practitioner's office. Health monitoring at a hospital or office, however, cannot monitor a patient during their normal course of life or as often as desired. This can be a serious limitation because a snapshot captured at a hospital or office may not accurately reflect the patient's health or may not performed at all due to the infrequency of a patient's visits. Even if testing at a hospital or medical office is performed often, it can be inaccurate due to it being of a short duration or due to the testing being in an artificial environment. Note that this does not preclude the use of the techniques disclosed herein at a hospital or medical office, where they may prove valuable in supplementing or replacing conventional measurements, and in the case of in-patient care, may provide a manner for continuous monitoring of patients that are critically (or otherwise) ill.

Returning to FIG. **3**, optical sensor **106** generally may have various computing capabilities, though it may instead be a low-capability device having little or no computing capability. Here optical sensor **106** includes one or more computer processors **302**, computer-readable storage media **304**, image capture element **306**, and a wired or wireless transceiver **308** capable of receiving and transmitting information (e.g., to computing device **108**). Image capture element **306** may include simple or complex cameras, such as those having low or high shutter speeds, low or high frame rates, low or high resolutions, and having or not having non-visible imaging capabilities. Computer-readable storage media **304** includes optics manager **310**, which is capable of processing sensor data and recording and transmitting sensor data, as well as receive or assign appropriate time markers by which to mark or compare the time of various captured images. Optics manager **310** and cardiovascular-function module **210** may also calibrate image capture element **306** through use of an external sensor. This can aid in calibrating skin colors or displacements to a calibration color or displacement, or even to a cardiac function, such as to a blood pressure or pulse-wave velocity. Thus, while one of optical sensors **106** captures images for two regions, a blood pressure between those regions is also measured through a different device, thereby enabling more-accurate determination of cardiac functions for the optical sensor and for that patient. Other potential calibration sensors include, but are not limited to, ECG, conventional BCG, digital stethoscopes, ultrasound, and the like. Another example is the use of an external blood pressure meter to calibrate the pulse wave velocity over time to determine long-term changes in arterial-wall stiffness by separating arterial stiffness due to blood pressure versus that due to the dilation by blood pressure.

These and other capabilities, as well as ways in which entities of FIGS. **1-3** act and interact, are set forth in greater detail below. These entities may be further divided, combined, and so on. The environment **100** of FIG. **1** and the detailed illustrations of FIGS. **2** and **3** illustrate some of many possible environments capable of employing the described techniques.

Example Methods

FIGS. **4** and **8** depict methods that assess cardiovascular function using an optical sensor. These methods are shown as sets of blocks that specify operations performed but are not necessarily limited to the order or combinations shown for performing the operations by the respective blocks. In portions of the following discussion reference may be made to environment **100** of FIG. **1** and entities detailed in FIGS. **2** and **3**, reference to which is made for example only. The techniques are not limited to performance by one entity or multiple entities operating on one device.

At **402**, skin colors or skin displacements are received from one or more optical sensors. These skin colors or displacements are captured at regions of a patient, such as a color captured at a patient's skin on her forehead and a displacement of skin on her neck or on her clavicle. Optionally, as part of operation **402**, cardiovascular-function module **210** or optics manager **310** may automatically determine which regions of a patient are fully visible or partially occluded, and thereby determine better regions of a patient to capture images.

By way of illustration, consider FIG. **5**, which shows a male patient **502** having various regions **504** of which images are captured. These regions **504** include, by way example, a cheek region **504-1**, a neck region **504-2**, an outer wrist region **504-3**, an outer hand region **504-4**, an inner wrist region **504-5**, a palm region **504-6**, a front ankle region **504-7**, and an inner ankle region **504-8**, to name but a few. By way of an ongoing example, assume that one optical sensor captures a color change or displacement of skin at neck region **504-2** and another color change or displacement of skin at inner wrist region **504-5**.

At **404**, a circulatory distance is determined between the regions of the patient at which the colors or displacements are captured. This circulatory distance can be an approximation based on a linear distance between the regions, such as a linear distance based on an axial distance oriented relative to an axis of the patient's spine, or simply a vertical distance with the patient standing. In some cases, however, the techniques determine or approximate a circulatory distance based on an arterial-path distance. This arterial-path distance can be determined or approximated using an arterial structure of the patient or determined based on a skeletal structure of the patient, including automatically by optical visualization of the patient.

By way of illustration of the various circulatory distances that can be used, consider FIG. **6**. Here assume that multiple images are captured of patient **502**'s neck region **504-2** (also shown in FIG. **5**) sufficient to determine a neck waveform **602**. Multiple images are also captured of inner wrist region **504-5** sufficient to determine an inner-wrist waveform **604**.

At operation **404**, cardiovascular-function module **210** determines the circulatory distance from neck region **504-2** and inner wrist region **504-5** in one of the following four manners. In the first, a vertical distance D_v is calculated with the patient standing. In the second, an axial distance D_{axial} is calculated based on the distance relative to an axis of the patient's spine—here it is similar to the vertical distance, D_v, but if the person is oriented at an angle, the distances are different. In the third, cardiovascular-function module **210** calculates the distance as a point-to-point between the regions, here shown as D_{ptp}. In the fourth, cardiovascular-function module **210** calculates or approximates the distance that blood travels through patient **502**'s arteries, D_{path}. This arterial-path distance can be determined based on the arteries themselves or an approximation based on a skeletal structure or an overall body shape of the person. Data for skeletal structure and overall body shape can be determined using images captured for the regions and structures in between the regions, optically or otherwise. In some cases radar can be used that penetrates clothing to track bony surfaces, thereby providing a skeletal structure from which arterial distance can be approximated.

While not required, operation **404** may be performed, in whole or in part, using method **700** illustrated in FIG. **7**, which is described following method **400** below. By way of overview, in this example method, the techniques determine one or more of the distances illustrated in FIG. **6**.

The more-accurate distance calculations provide a better pulse-wave velocity, and thus indicate a current cardiovascular function. While potentially valuable, more-accurate distances are not necessarily required to show trends in cardiovascular function. Trends are provided by consistently calculated distances more than accurate distances, and for a specific individual, should not change significantly over time for same measurement points. If the measurement points vary due to visibility issues (such as clothing), then distance measurement estimates increase in importance for accurate trending.

At **406**, a time correlation between capture of the colors and displacements is determined. This time correlation is between the instant of capture at the regions, as this time correlation is later used. Cardiovascular-function module **210** may determine the time correlation based on a time at which a maximum or minimum blood volume is determined for each of the regions, or some other consistent and comparable point in a waveform, such as a beginning of a pressure increase in the waveform (show in FIG. **6**). In more detail, this time correlation can be considered a temporal distance between multiple images capturing some measure of cardiac operation, such as blood volume at each of the regions. Thus, by comparing various images for a region cardiovascular-function module **210** can determine a maximum, minimum, or median color at the region as well as at another region, and by comparing these and times at which each were taken, can determine the time correlation for a same heartbeat.

Note that waveforms **602** and **604** can be determined through color, or in some locations of the body, related waveforms can be determined through displacement. Cardiovascular-function module **210** can determine, based on a change in color to regions over time, a waveform. These color changes indicate a peak or crest of a wave based on blood content at the organ and thus can be used to determine a shape of the wave. While a shape of a wave can differ at different regions, they can still be compared to find a time correlation. In the case of lower-than-desired optical frame rates due to sensitivity or processing limitations, interpolation or curve fitting can be used to improve the estimate of the waveform for improved time correlation. Repeated measurements, which are time shifted relative to the pressure wave either naturally by the optical sampling frequency or intentionally by adjusting the sampling frequency, can build up a super-sampled estimate of the waveform. The higher timing-resolution waveform can be used for more-accurate timing measurements. Additionally, displacements, either through direct distance measurements or tangential shading, can show signals related to the pressure waveforms as the arteries and veins expand and contract. These waveforms can further reveal cardiac activity, such as valve timing, valve leakage (regurgitation), fibrillation, stroke volume, and the like.

At **408**, a pulse-wave velocity for blood circulation through the patient is determined based on the circulatory distance and the time correlation, as well as the skin colors or displacements. As shown in FIG. **6**, the time correlation is based on similar points in a waveform and the circulatory distance is some calculation or approximation of the distance blood travels from regions at which images are captured. In more detail, a pulse-wave velocity is the circulatory distance divided by the time correlation.

Pulse-wave velocity is a good measure of cardiac function. It can indicate, for example, an arterial stiffness of a patient (the faster the pulse-wave velocity, the higher the arterial stiffness), a blood pressure, and a mean arterial pressure for the patient. In more detail, the techniques can determine blood pressure based on the pulse-wave velocity using the Bramwell-Hill equation, which links pulse-wave velocity to compliance, blood mass density, and diastolic volume. Each of these are measures of cardiac function that can indicate a patient's cardiac health. As noted above, the techniques can provide these cardiac functions to a patient, thereby encouraging the patient to make changes or, in some cases, seek immediate medical care.

Note that, in some cases, three or more different regions are measured at operation **402**. In these cases, cardiovascular-function module **210** may determine which of the regions are superior to others, such as due to data captured for those regions being noisy or incomplete or otherwise of inferior quality. Those that are superior can be used and the others discarded, or cardiovascular-function module **210** may weigh the determined pulse wave velocity between different regions based on the quality of the data used to determine those pulse wave velocities. This can be performed prior to or after recording those pulse wave velocities as described below.

Following determination of the pulse-wave velocity at operation **408**, the techniques may proceed to record the pulse-wave velocity at operation **410** and the repeat operations **402-410** sufficient to determine a trend at operation **412**. In some cases, however, the determined pulse-wave velocity is provided, at operation **414**, to the patient or medical professional. Optionally, calibration data from an external sensor can be used to improve performance. For example, an external blood pressure monitor could be used to train the system to correlate PWV with blood pressure. The device could be captured through an electronic network (Bluetooth™ or the like) or the optical system could scan the user interface and perform OCR to read the results. Machine learning could be applied to create a patient specific model for estimating blood pressure from PWV.

At **412**, a cardiovascular trend for the patient is determined based on multiple pulse-wave velocity measurements, such as comparing prior and later-time determined pulse-wave velocities. This can simply show a trend of pulse-wave velocities rising or falling, such as with velocity rising due to increased arterial stiffness. Multiple locations across the body can be measured to map changes over time. Cardiovascular-function module **210** may also determine other measures of cardiac function, such as changes in flow asymmetries or pulse pressure waveforms over time.

At **414**, as noted, this trend determined at operation **412**, or a pulse-wave velocity determined at operation **408**, is provided to the patient or a medical professionals, e.g., patient **102** or **600** and medical professional **104**, of FIG. **1** or **6**.

In some cases skin color, skin displacement, or both are used by the techniques in method **400**. Thus, color changes can indicate blood flow over time, as can displacement changes. Furthermore, use of color and displacement both can indicate an amount of blood in capillaries in the skin while displacement can indicate a change to a volume of the skin or an organ under the skin, such as vein or artery, and thus an amount of blood in the skin or near it can be determined.

Note also that the techniques may repeat operations of method **400** for various other regions. Doing so may aid in altering the pulse-wave velocity to improve its accuracy or robustness by determining another pulse-wave velocity between two other regions or between another region and one of the regions for which images are captured. Thus, the techniques may determine a pulse-wave velocity for the patient based on two pulse-wave velocities between regions, such as regions **504-3** and **504-1**, **504-7** and **504-1**, and/or **504-8** and **504-2**.

As noted above, method **400** can be supplemented, and operation **404** may be performed, in whole or in part, using method **700** illustrated in FIG. **7**. In this example method, the techniques determine one or more of the distances illustrated in FIG. **6**. For operations **702-706**, a patient's circulatory distances between regions are establish for later use as a manner in which to calibrate the patient's distances. While calibration for a single sensing milieu to determined trends may not be required, use of different sensing milieus or to determine a cardiovascular function with quantitative precision both aid from use of calibration. Operation **708** and **710** can be used as one way in which the techniques may perform operation **404** of method **400**.

At **702**, a distance between various regions is measured, optically, manually, or in other manners. Consider, for example, capturing an image of patient **502** of FIG. **5**. Assume that some physical data is available, such as a distance between the optical sensor capturing the image and patient **502**, or a height of patient **502**, and so forth. With this physical data, the distance can be determined from the image. Generally, this distance is from point-to-point, and is later analyzed for circulatory distance. Other manners can also or instead be used, such as a nurse measuring patient **502**, either from point-to-point or along structures, such as from a wrist to an elbow, elbow to shoulder, and from shoulder to heart. A patient may also interact with optical sensor **106** and cardiovascular-function module **210** to calibrate distances between regions, such as standing at a particular location relative to optical sensor **106** and so forth. Various other technologies can be used as well, such as structured light optical sensors, radar, LIDAR, and SODAR (measuring distance through use of sound through air).

At **704**, a circulatory distance is determined using the measured distance. In some cases the measured distance is simply used as the circulatory distance, such as measuring D_{ptp} and then using D_{ptp} (of FIG. **6**) as the circulatory distance. As noted in part herein, however, other circulatory distances may be determined, such as measuring a point-to-point where patient **502**'s arm is bent, and thus calculating a fully extended point-to-point to maintain consistency of circulatory distance. Other examples include measuring D_v and then, based on data about patient **502**, determining an arterial-path distance (D_{path}).

At **706**, these various determined circulatory distances are associated with the patient's identity. The identity of the patient can be entered, queried from the patient, or simply associated with some repeatable measure of identity, even if the person's name is not known. Examples include determining identity using fingerprints or facial recognition, and then associating distances with that fingerprint or facial structure.

At **708**, the patient's identity is determined. This can be performed as part of operation **404**. With this identity, at **710** circulatory distances between regions are determined. For example, cardiovascular-function module **210** may use facial recognition to identify patient **502** and, after determining patient **502**'s identity, find previously determined cardiovascular distances between each of regions **504** by simply mapping the relevant regions to previously stored distances. When cardiovascular time correlations are determined at operation **406**, a pulse wave velocity can be determined using the mapped-to cardiovascular distance for the regions measured.

FIG. **8** depicts a method for assessing cardiovascular function using an optical sensor based on size, volume, or location of an organ or structure of a patient. In method **800**, images are captured over 2 to 10 millisecond-range or faster timeframes, thereby providing multiple images relating to an organ or structure of the patient. Note that sub-millisecond timeframes can also be useful for measure acoustic vibrations and are optional. Method **800** may operate, in whole or in part, in conjunction with method **400**, though this is not required.

At **802**, structured light is projected onto an organ or structure of a patient. Note that this is optional, though in some cases use of structured light aids in accurate measurement of movement and displacement of a region of the patient. Alternatively, tangential light may be used to generate shadowing to detect skin displacement, or a coded light source could be used to reject external interference. For example, an alternating on and off light source at the frame rate would allow sampling and canceling of the background illumination. Further, light reflected from background objects or patient clothing can be used to track changes in lighting over time or in different conditions, e.g., daylight vs night, light bulb luminosity degradation over time, and so forth. With this data, ambient light and its effect on images captured can be calibrated and for which cardiovascular-function module **210** can adjust for the various methods described herein.

At **804**, multiple images are received that capture an organ or structure of a patient. As noted, the images captured may include capture of structured light to aid in determining displacement using surface information captured. This surface information can be from one or multiple devices. These multiple images can be received from one or multiple optical sensors and over various timeframes, such as those captured at millisecond-range or faster timeframes.

At **806**, changes in the size, volume, or location of the organ or structure of the patient are determined. These changes are determined by comparing sizes, volumes, or locations of the organ or structure of the patient recorded by the various multiple images captured over time. Note that these changes can be used in coordination with, or to compensate for, data from methods **400**, and vice-versa. Thus, data from one portion of the body captured in any of the various manners described herein, can be used to compensate for other data, such as using a color or waveform determined at method **400** to compensate for motion artifacts in the data of method **800**.

At **808**, a cardiac function of the patient is determined based on the changes. This cardiac function can be one of the many described above, including heart rate, blood pressure, pulse-wave velocity, pressure volume loops, blood-volume and other asymmetries, and so forth, as well as respiration rate.

By way of a first example, consider a case where an asymmetry is determined between to different regions of the patient. In some cases this asymmetry is determined by blood-volume differences, which can be indicated by size or color. To determine an asymmetry, cardiovascular-function module **210** may compare the different cardiovascular pulse times of the regions, where one of the pulse times for a same heart beat is different, as it is further from the patient's heart.

Alternatively, the waveform's peak, median, or trough of blood volume can be accurately compared. Thus, assume that a right wrist and a left wrist of a patient have different blood volumes at each of their peaks, with one being a lower peak blood volume that the other, thereby indicating some difference in vascular function.

Cardiac function trends, as noted in part above, can greatly aid in helping patients maintain or change their habits to improve their cardiac health. Consider, for example, a trend showing a change to a cardiovascular function over weeks, months, or years using the techniques. This trend can show cardiac function in many ways superior to the best invasive cardiac testing because a trend need not require perfect accuracy—instead consistency is used. Furthermore, this can be performed by the techniques without interrupting the patient's day, making the patient perform a test, or requiring the patient to go see a medical professional. By so doing, many lives can be saved.

In more detail, consider the techniques in the context of FIGS. **1-3**. Here various kinds of optical sensors **106** sense regions (e.g., regions **504** of FIG. **5**) of a patient (e.g., patient **102** of FIG. **1** or patient **502** of FIGS. **5** and **6**) through image capture elements **306**. This sensor data (e.g., images) are then processed and/or stored by optics manager **310** (e.g., to mark the images with times), after which they are passed, through wired/wireless transceiver **308** as sensor data **112** to cardiovascular-function module **210** operating on computing device **108** of FIG. **2**. Also passed are indications of the region and the times **212** at which the sensor data **112** was captured.

Cardiovascular-function module **210** then performs operations of method **400** and/or method **800** to determine cardiac function, as noted above. Consider, for example, a case where cardiovascular-function module **210** determines that a cardiac function meets or exceeds a safety threshold. Example safety thresholds include a blood pressure being too high, a heart rate being too rapid or irregular, or a low blood-oxygen level. This safety threshold can also be complicated or more difficult to determine, such as a patient's heart showing an end-diastolic volume ejected out of a ventricle during a contraction being less than 0.55 (this is a measure of ejection fraction (EF) and low fractions can indicate a heart attack is imminent). These are but a few of the many safety thresholds for cardiac function enabled by the techniques. If a safety threshold is exceeded, medical professional **104** (or family/caretaker) and patient **102** can be informed, such by operation **810** of method **800**.

The preceding discussion describes methods relating to assessing cardiovascular function using an optical sensor for a human cardiovascular system. Aspects of these methods may be implemented in hardware (e.g., fixed logic circuitry), firmware, software, manual processing, or any combination thereof. These techniques may be embodied on one or more of the entities shown in FIGS. **1-3** and **9** (computing system **900** is described in FIG. **9** below), which may be further divided, combined, and so on. Thus, these figures illustrate some of the many possible systems or apparatuses capable of employing the described techniques. The entities of these figures generally represent software, firmware, hardware, whole devices or networks, or a combination thereof.

Example Computing System

FIG. **9** illustrates various components of example computing system **900** that can be implemented as any type of client, server, and/or computing device as described with reference to the previous FIGS. **1-8** to implement techniques for assessing cardiovascular function using an optical sensor. In embodiments, computing system **900** can be implemented as one or a combination of a wired and/or wireless wearable device, System-on-Chip (SoC), and/or as another type of device or portion thereof. Computing system **900** may also be associated with a user (e.g., a patient) and/or an entity that operates the device such that a device describes logical devices that include users, software, firmware, and/or a combination of devices.

Computing system **900** includes communication devices **902** that enable wired and/or wireless communication of device data **904** (e.g., received data, data that is being received, data scheduled for broadcast, data packets of the data, etc.). Device data **904** or other device content can include configuration settings of the device, media content stored on the device, and/or information associated with a user of the device. Media content stored on computing system **900** can include any type of audio, video, and/or image data, including complex or detailed results of cardiac function determination. Computing system **900** includes one or more data inputs **906** via which any type of data, media content, and/or inputs can be received, such as human utterances, user-selectable inputs (explicit or implicit), messages, music, television media content, recorded video content, and any other type of audio, video, and/or image data received from any content and/or data source.

Computing system **900** also includes communication interfaces **908**, which can be implemented as any one or more of a serial and/or parallel interface, a wireless interface, any type of network interface, a modem, and as any other type of communication interface. Communication interfaces **908** provide a connection and/or communication links between computing system **900** and a communication network by which other electronic, computing, and communication devices communicate data with computing system **900**.

Computing system **900** includes one or more processors **910** (e.g., any of microprocessors, controllers, and the like), which process various computer-executable instructions to control the operation of computing system **900** and to enable techniques for, or in which can be embodied, assessing cardiovascular function using an optical sensor. Alternatively or in addition, computing system **900** can be implemented with any one or combination of hardware, firmware, or fixed logic circuitry that is implemented in connection with processing and control circuits which are generally identified at **912**. Although not shown, computing system **900** can include a system bus or data transfer system that couples the various components within the device. A system bus can include any one or combination of different bus structures, such as a memory bus or memory controller, a peripheral bus, a universal serial bus, and/or a processor or local bus that utilizes any of a variety of bus architectures.

Computing system **900** also includes computer-readable media **914**, such as one or more memory devices that enable persistent and/or non-transitory data storage (i.e., in contrast to mere signal transmission), examples of which include random access memory (RAM), non-volatile memory (e.g., any one or more of a read-only memory (ROM), flash memory, EPROM, EEPROM, etc.), and a disk storage device. A disk storage device may be implemented as any type of magnetic or optical storage device, such as a hard disk drive, a recordable and/or rewriteable compact disc (CD), any type of a digital versatile disc (DVD), and the like. Computing system **900** can also include a mass storage media device **916**.

Computer-readable media **914** provides data storage mechanisms to store device data **904**, as well as various device applications **918** and any other types of information

and/or data related to operational aspects of computing system **900**. For example, an operating system **920** can be maintained as a computer application with computer-readable media **914** and executed on processors **910**. Device applications **918** may include a device manager, such as any form of a control application, software application, signal-processing and control module, code that is native to a particular device, a hardware abstraction layer for a particular device, and so on.

Device applications **918** also include any system components, modules, or managers to implement the techniques. In this example, device applications **918** include cardiovascular-function module **210** or optics manager **310**.

CONCLUSION

Although embodiments of techniques for, and apparatuses enabling, assessing cardiovascular function using an optical sensor have been described in language specific to features and/or methods, it is to be understood that the subject of the appended claims is not necessarily limited to the specific features or methods described. Rather, the specific features and methods are disclosed as example implementations of these techniques.

What is claimed is:

1. A method comprising:

receiving, by a computing device and from one or more optical sensors operatively coupled to the computing device, multiple images captured external to a patient by the one or more optical sensors over millisecond-range or faster timeframes, the multiple images recording a color or displacement corresponding to an organ or structure of the patient;

calculating at least one of a change in size, a change in volume, or a change in location of the organ or structure of the patient by:

analyzing the multiple images to determine the color or displacement corresponding to the organ or structure in different said images;

correlating the determined color or displacement with associated times of the different said images; and

comparing the determined color or displacement associated with different said times to determine at least one of a maximum, minimum, or median of the determined color or displacement across the multiple images;

determining, based on the calculated at least one change in size, volume, or location, at least one measurement indicative of cardiac function of the patient; and

displaying a user interface to present the at least one measurement.

2. The method of claim **1**, wherein the one or more optical sensors are hyperspectral cameras recording images in an ultraviolet, visible, or infrared optical wavelength and calculating the at least one change in size, volume, or location is based on the images recorded in the ultraviolet, visible, or infrared optical wavelength.

3. The method of claim **1**, wherein the calculated at least one change in size, volume, or location indicates a blood force or mechanical vibration enabling a ballistocardiogram to be determined, and the method further comprises determining and providing the ballistocardiogram for the patient.

4. The method of claim **1**, further comprising projecting structured light on regions of the patient corresponding to the organ or structure effective to enable capture of images having surface information enabling depth and surface changes for the organ or structure of the patient to be calculated.

5. The method of claim **4**, wherein the images having the surface information are the multiple images and calculating the at least one change in size, volume, or location is based on the surface information.

6. The method of claim **4**, wherein the images having the surface information are not the multiple images, and the method further comprises calculating the at least one change in size, volume, or location using both the multiple images and the images having the surface information.

7. The method of claim **1**, further comprising:

determining the at least one measurement indicative of the cardiac function of the patient at a plurality of different times; and

determining a trend in cardiovascular health of the patient based on the determined measurements at the plurality of different times.

8. A system comprising:

a processor; and

a memory having stored thereon computer-readable instructions that are executable by the processor to perform operations comprising:

receiving, from one or more optical sensors external to a patient, multiple images captured over millisecond-range or faster timeframes by the one or more optical sensors, the multiple images recording a color or displacement corresponding to an organ or structure of the patient;

calculating at least one of a change in size, a change in volume, or a change in location of the organ or structure of the patient by:

analyzing the multiple images to determine the color or displacement corresponding to the organ or structure in different said images;

correlating the determined color or displacement with associated times of the different images;

comparing the determined color or displacement associated with different said times; and

determining at least one of a maximum, minimum, or median of the determined color or displacement across the multiple images based on the comparing;

determining, based on the calculated at least one change in size volume, or location, at least one measurement indicative of cardiac function of the patient; and

generating a user interface for display that is configured to present the at least one measurement.

9. The system of claim **8**, wherein the operations further comprise displaying the generated user interface to present the at least one measurement.

10. The system of claim **8**, wherein the one or more optical sensors are hyperspectral cameras recording images in an ultraviolet, visible, or infrared optical wavelength and calculating the at least one change in size, volume, or location is based on the images recorded in the ultraviolet, visible, or infrared optical wavelength.

11. The system of claim **8**, wherein the calculated at least one change in size, volume, or location indicates a blood force or mechanical vibration enabling a ballistocardiogram to be determined, and the operations further comprise determining and providing the ballistocardiogram for the patient.

12. The system of claim **8**, wherein the operations further comprise projecting structured light on regions of the patient corresponding to the organ or structure effective to enable

capture of images having surface information enabling depth and surface changes for the organ or structure of the patient to be calculated.

13. The system of claim **12**, wherein the images having the surface information are the multiple images and calculating the at least one change in size, volume, or location is based on the surface information.

14. The system of claim **12**, wherein the images having the surface information are not the multiple images, and the operations further comprise calculating the at least one change in size, volume, or location using both the multiple images and the images having the surface information.

15. The system of claim **8**, wherein the operations further comprise:

determining the at least one measurement indicative of the cardiac function of the patient at a plurality of different times; and

determining a trend in cardiovascular health of the patient based on the determined measurements at the plurality of different times.

16. A method implemented by a computing device, the method comprising:

capturing multiple images external to a patient with one or more optical sensors operatively coupled to the computing device, the multiple images recording a color or displacement of at least one region of the patient that corresponds to an organ or structure of the patient;

receiving, by the computing device and from one or more optical sensors, the multiple images;

determining the color or displacement of the at least one region that corresponds to the organ or structure in different said images;

correlating the determined color or displacement to associated times of the different said images;

calculating at least one of a change in size, a change in volume, or a change in location of the organ or structure of the patient by comparing the determined color or displacement of the at least one region over the correlated times to determine at least one of a maximum, minimum, or median of the determined color or displacement of the at least one region across the multiple images;

determining at least one measurement indicative of cardiac function of the patient based on the calculated at least one change in size, volume, or location; and

displaying a user interface to present the at least one measurement.

17. The method of claim **16**, wherein the one or more optical sensors are hyperspectral cameras recording images in an ultraviolet, visible, or infrared optical wavelength and calculating the at least one change in size, volume, or location is based on the images recorded in the ultraviolet, visible, or infrared optical wavelength.

18. The method of claim **16**, wherein the calculated at least one change in size, volume, or location indicates a blood force or mechanical vibration enabling a ballistocardiogram to be determined, and the method further comprises determining and providing the ballistocardiogram for the patient.

19. The method of claim **16**, further comprising projecting structured light on regions of the patient corresponding to the organ or structure effective to enable capture of images having surface information enabling depth and surface changes for the organ or structure of the patient to be calculated.

20. The method of claim **16**, further comprising:

determining the at least one measurement indicative of the cardiac function of the patient at a plurality of different times; and

determining a trend in cardiovascular health of the patient based on the determined measurements at the plurality of different times.

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