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(54) **WRIST BOUND ULTRASOUND-ON-A-CHIP DEVICE**

(71) Applicant: **Butterfly Network, Inc.**, Guilford, CT (US)

(72) Inventors: **Jonathan M. Rothberg**, Guilford, CT (US); **Gregg Fergus**, Stoughton, WI (US); **Keith G. Fife**, Palo Alto, CA (US); **Tyler S. Ralston**, Clinton, CT (US); **Nevada J. Sanchez**, Guilford, CT (US); **Jaime Scott Zahorian**, Guilford, CT (US); **Kailiang Chen**, Branford, CT (US); **Christopher Thomas McNulty**, Guilford, CT (US)

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A61B 5/021	(2006.01)

(52) **U.S. Cl.**

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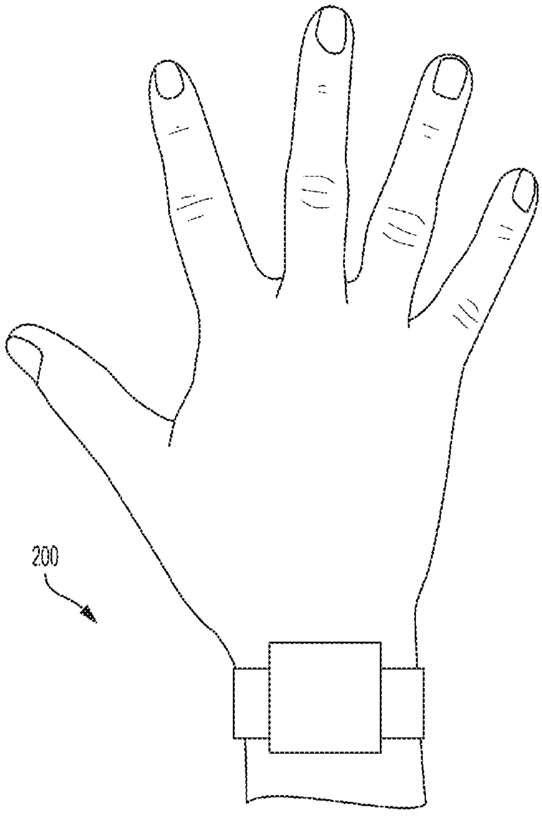
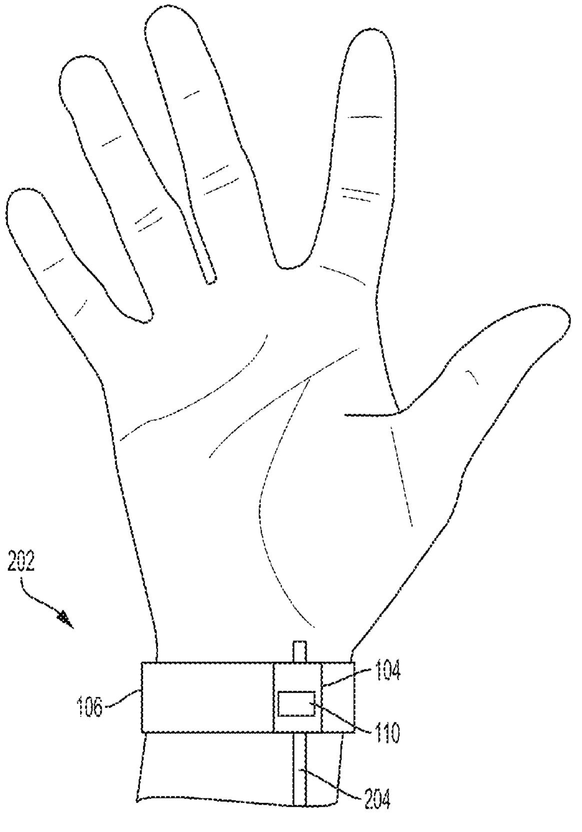
(57) **ABSTRACT**

Aspects of the technology described herein relate to an apparatus including an ultrasound-on-a-chip device configured to be bound to a user's wrist. The ultrasound-on-a-chip device may include a two-dimensional array of ultrasonic transducers. The transducers may be capacitive micromachined ultrasonic transducers (CMUTs) and may be configured to emit ultrasound waves having a frequency between approximately 5-20 MHz. A coupling strip may be coupled to the ultrasound-on-a-chip device to reduce the air gap between the ultrasound-on-a-chip device and the user's wrist. The ultrasound-on-a-chip device may be waterproof and may be able to perform both transverse and longitudinal ultrasound scanning without being rotated. The ultrasound-on-a-chip device may be configured to calculate pulse wave velocity through a blood vessel in a user's wrist.





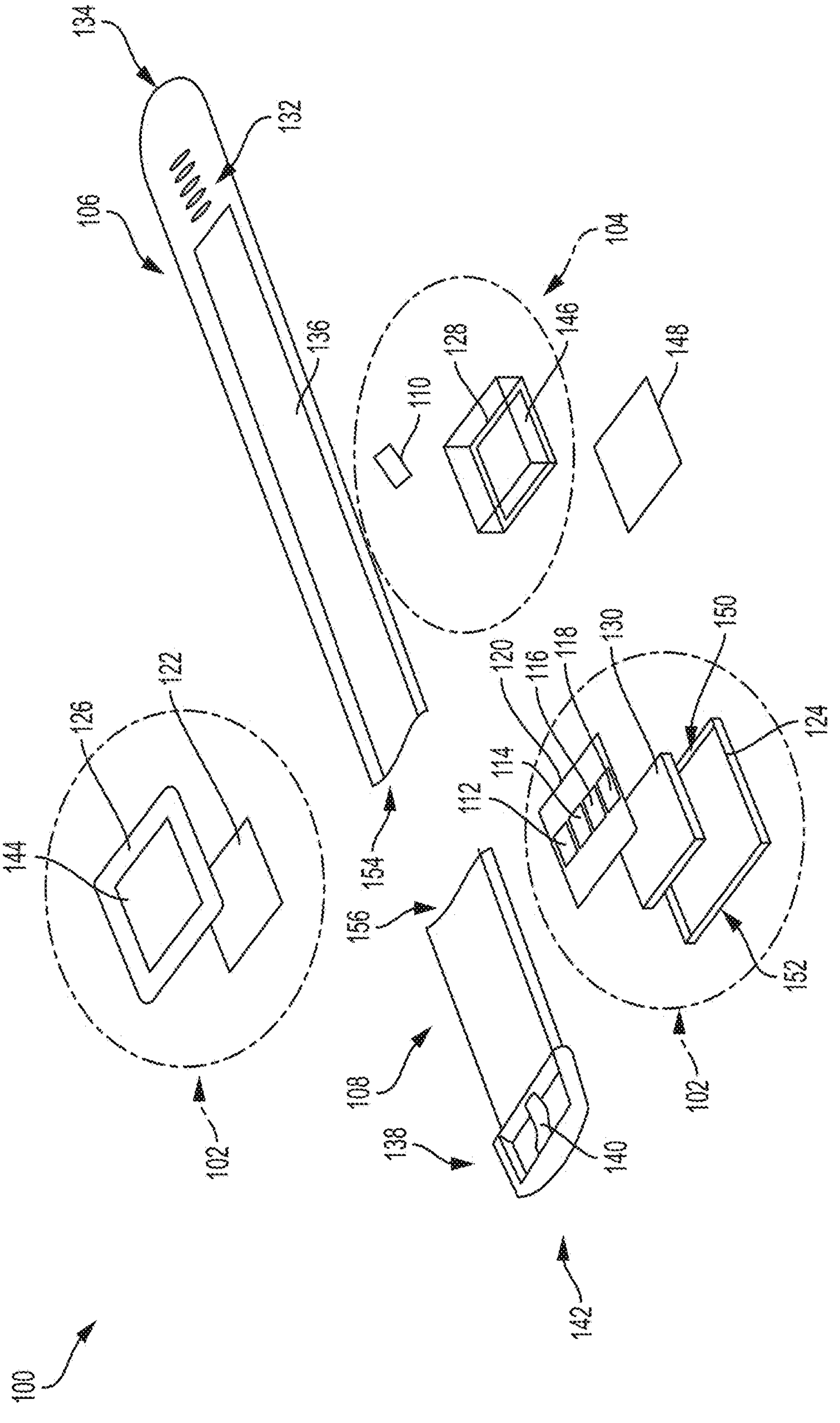

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FIG. 1

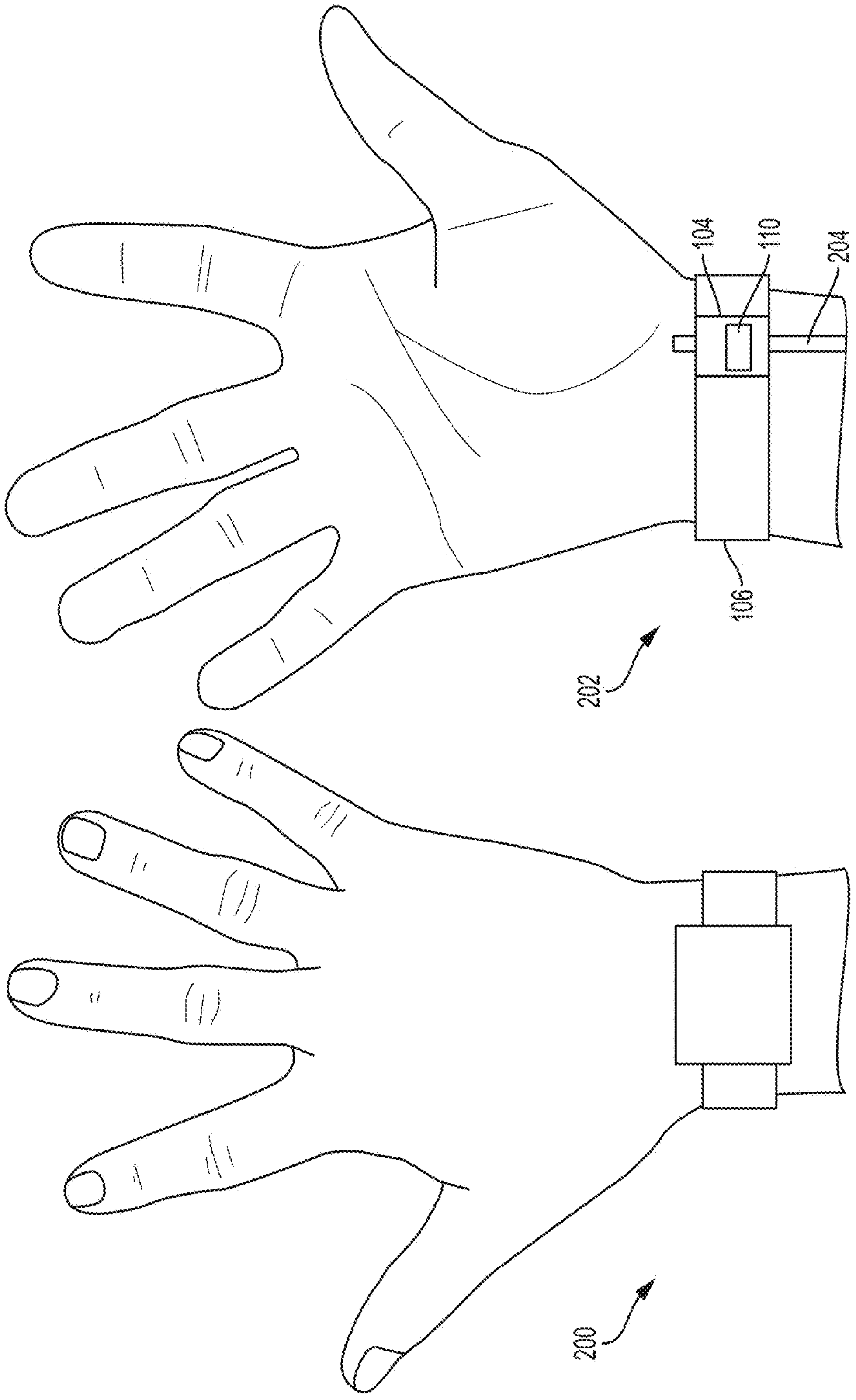

FIG. 2

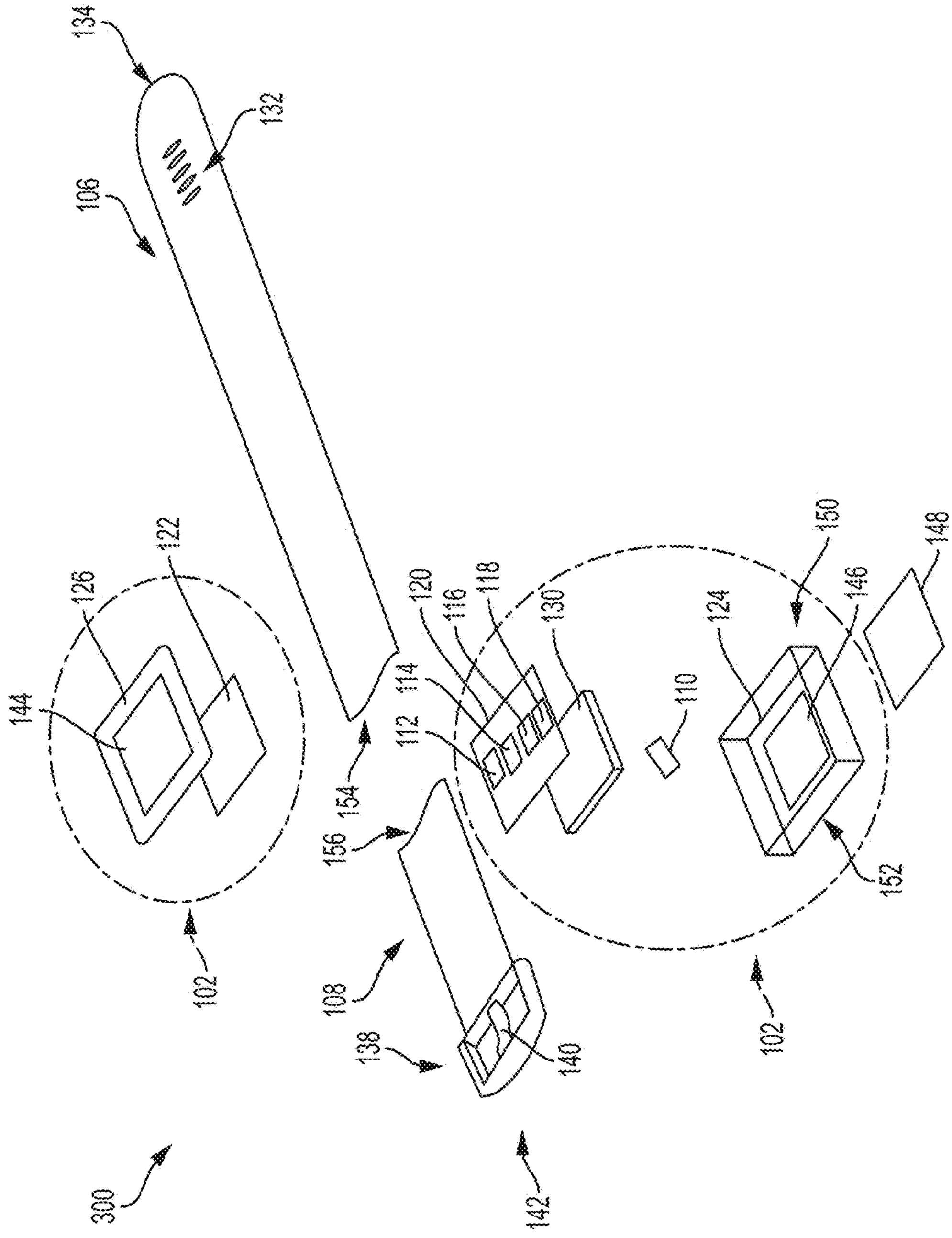
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FIG. 3

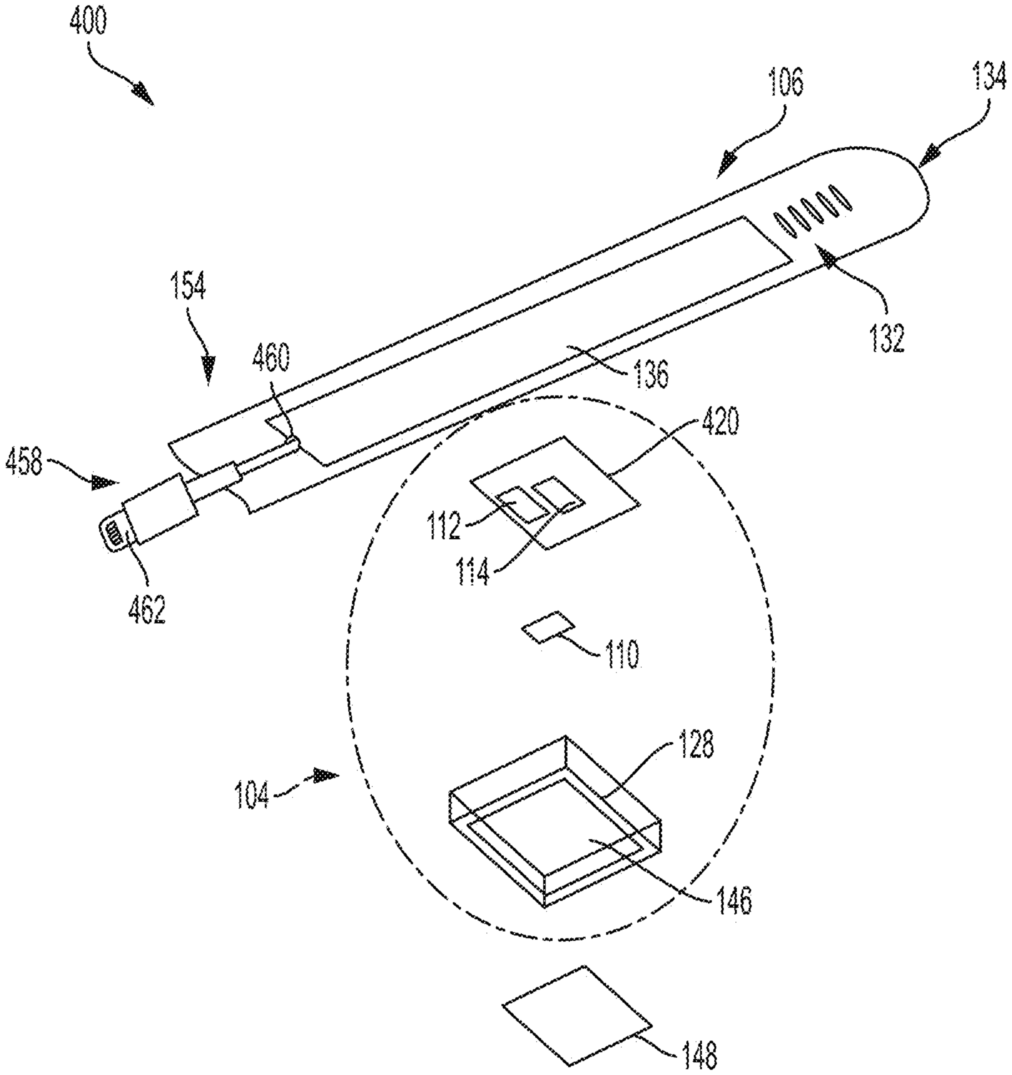
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FIG. 4

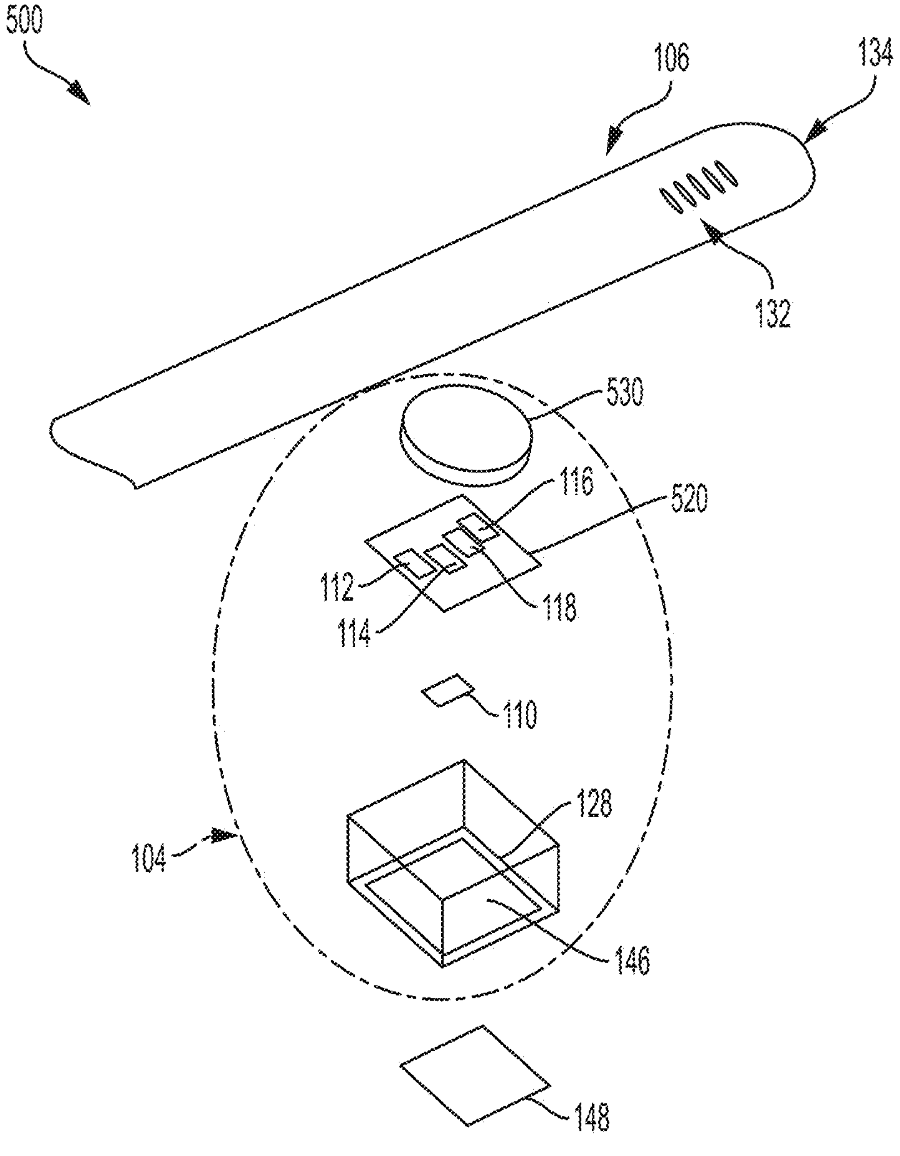

FIG. 5

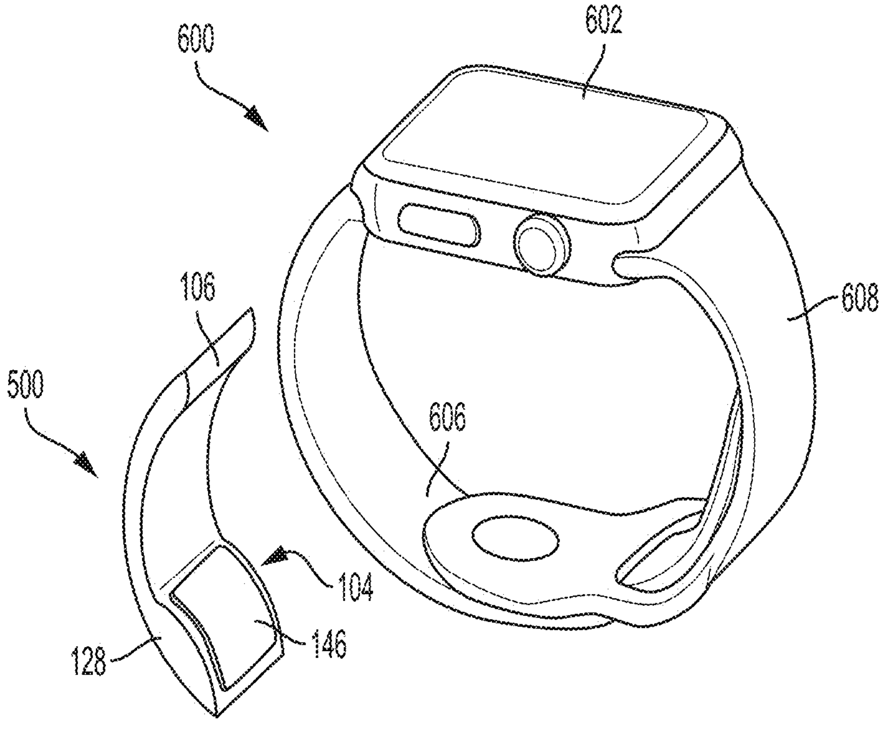

FIG. 6A

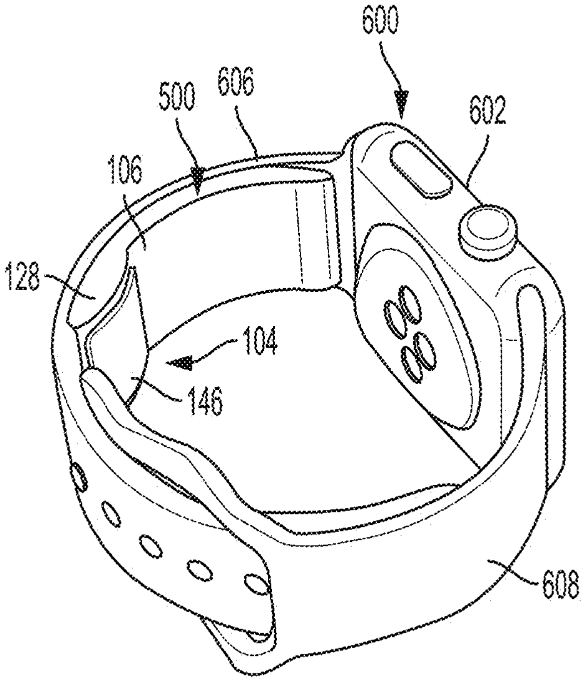

FIG. 6B

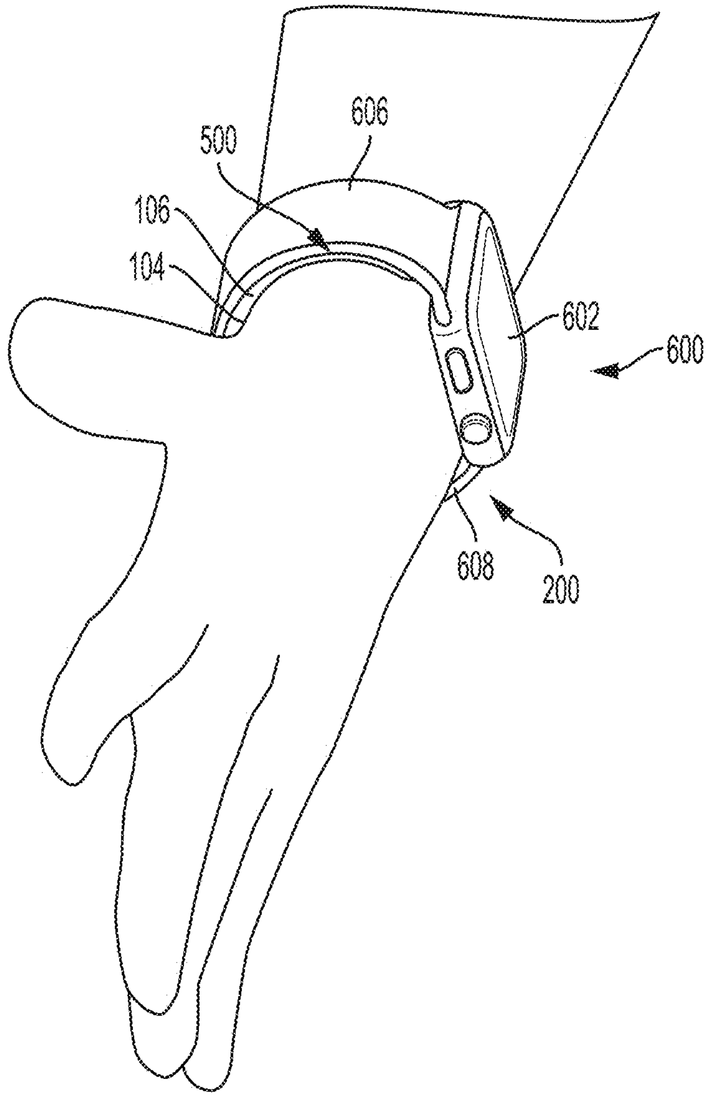

FIG. 6C

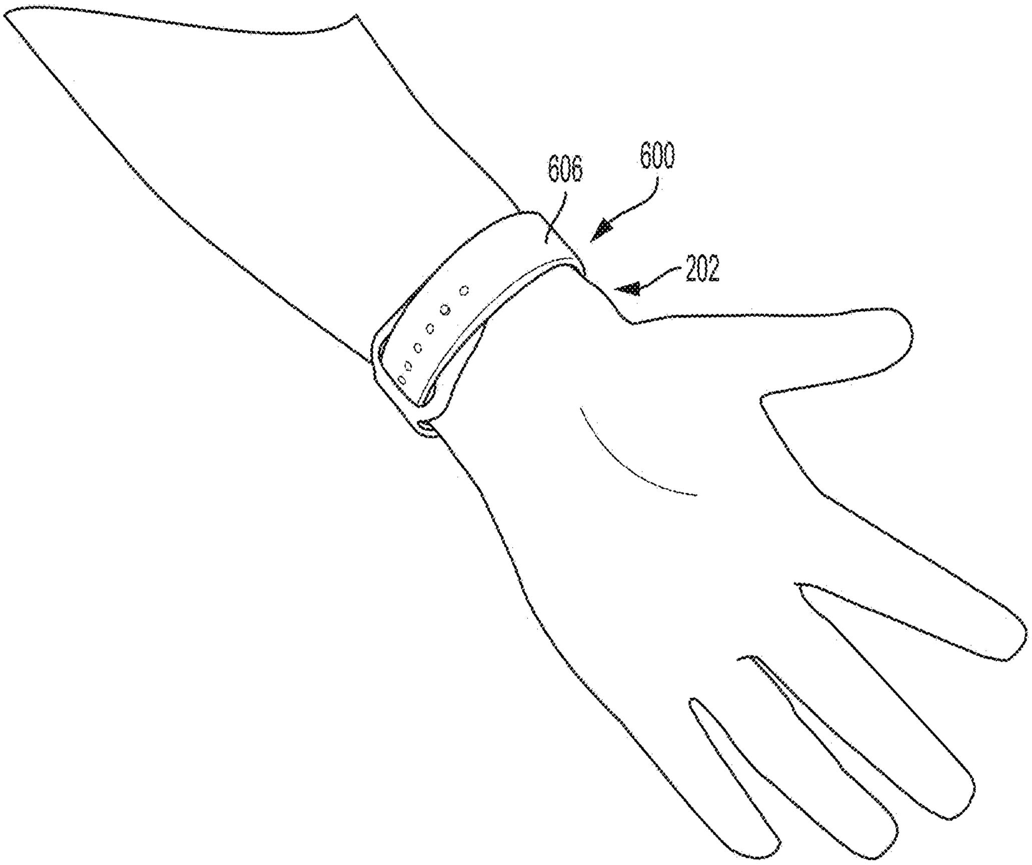

FIG. 6D

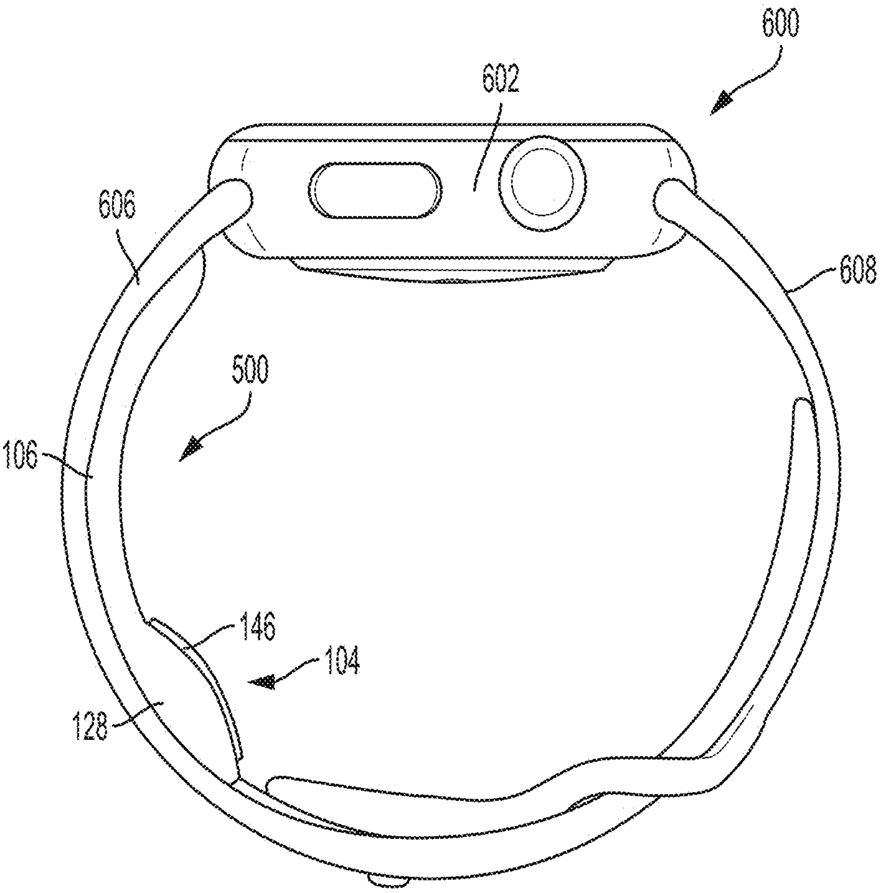

FIG. 6E

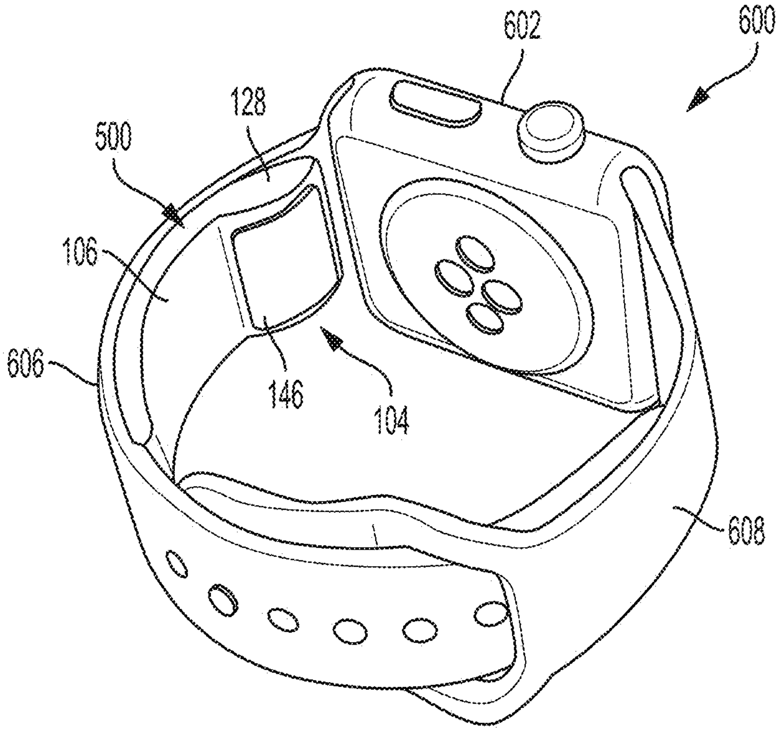

FIG. 6F

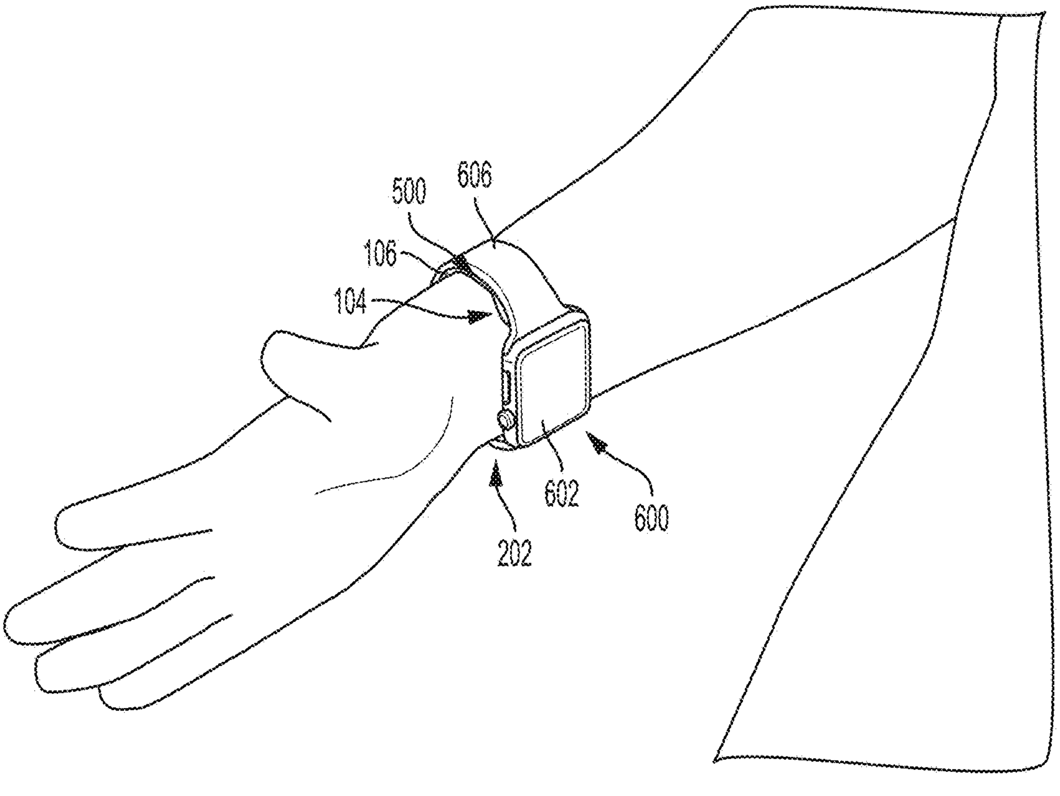

FIG. 6G

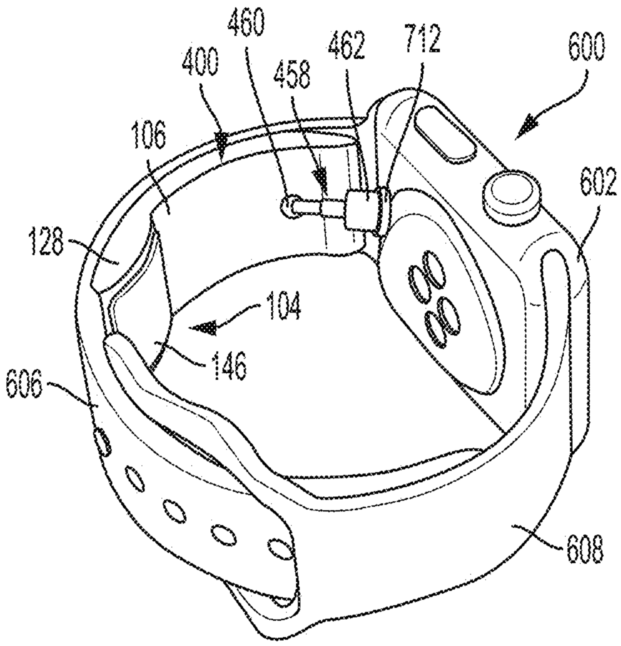

FIG. 7

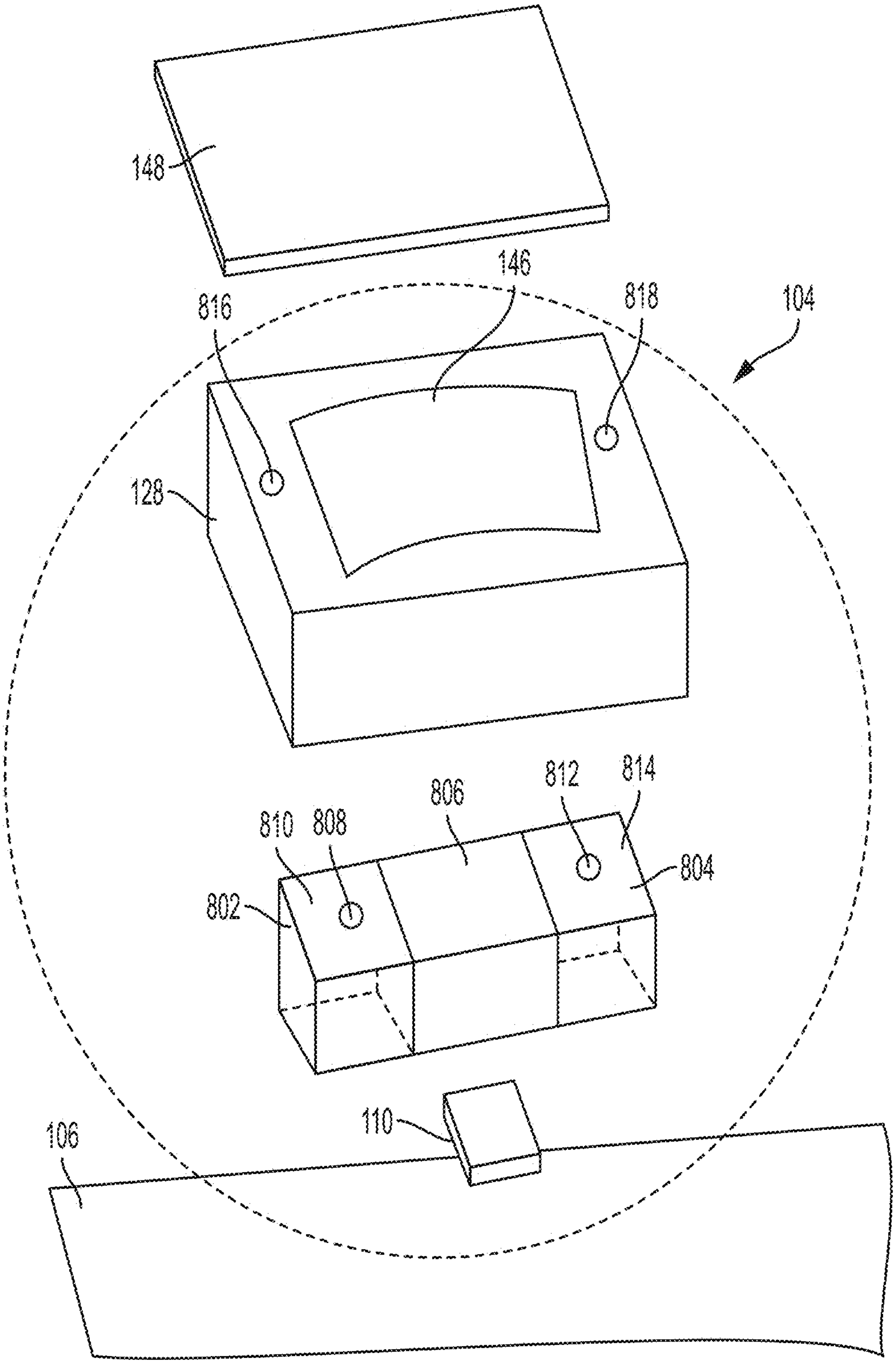

FIG. 8

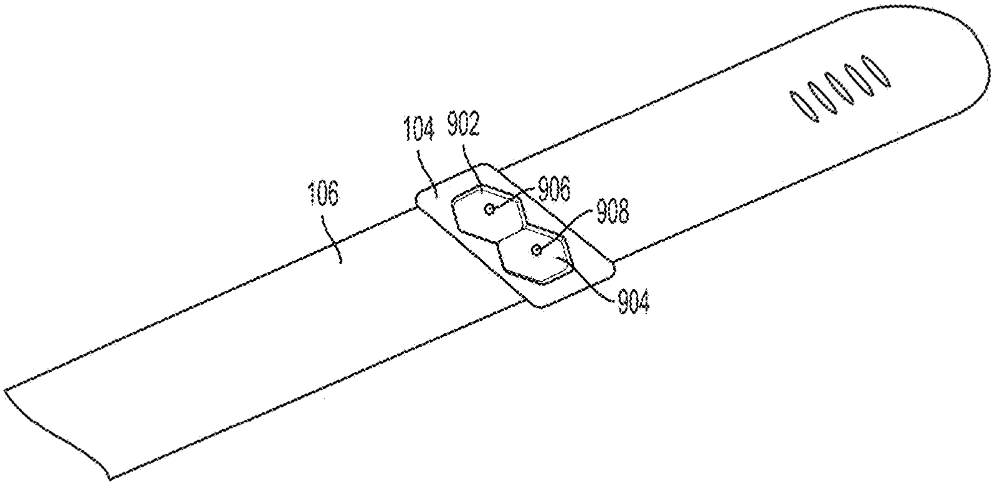

FIG. 9

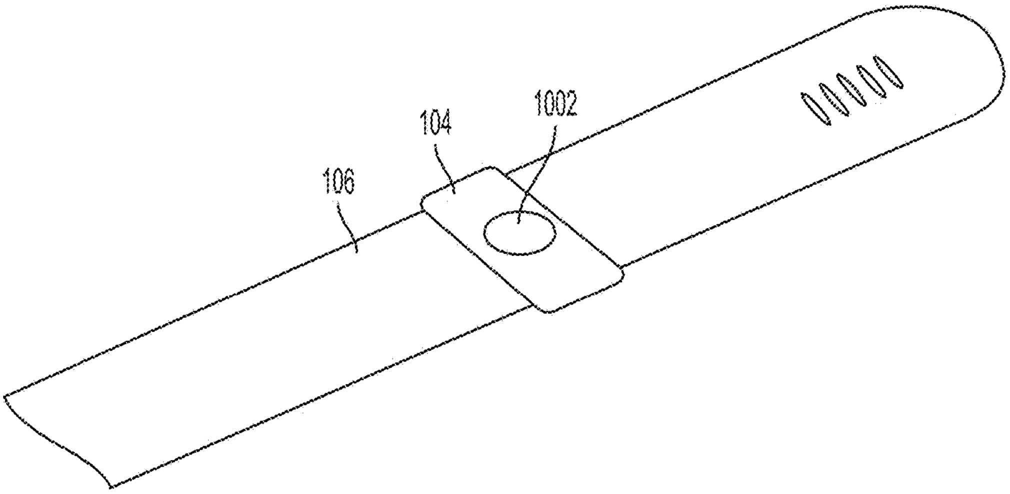

FIG. 10

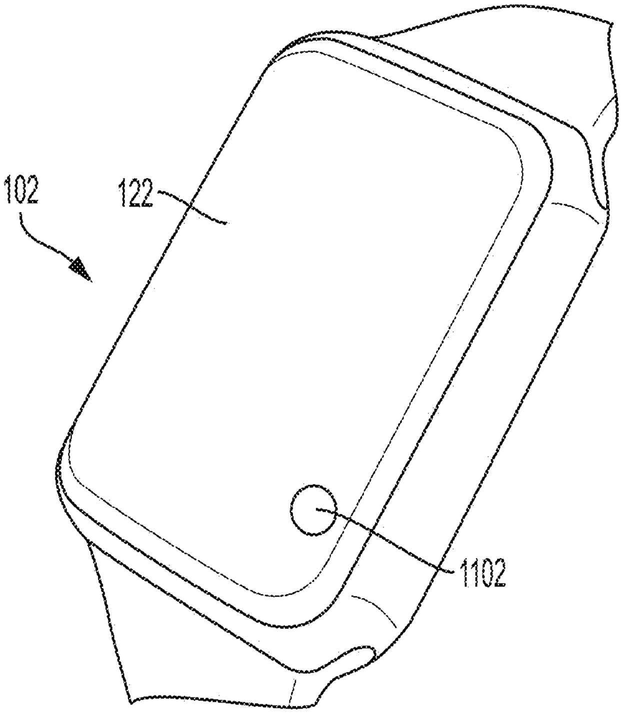

FIG. 11

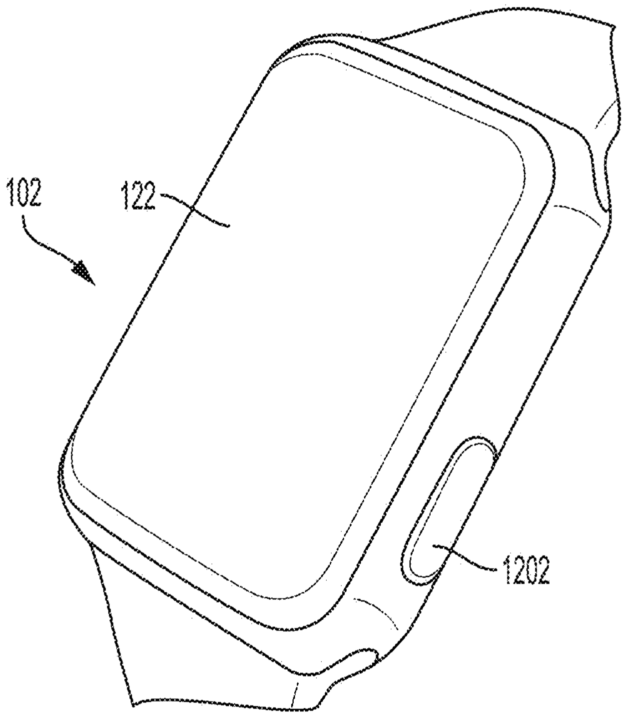

FIG. 12

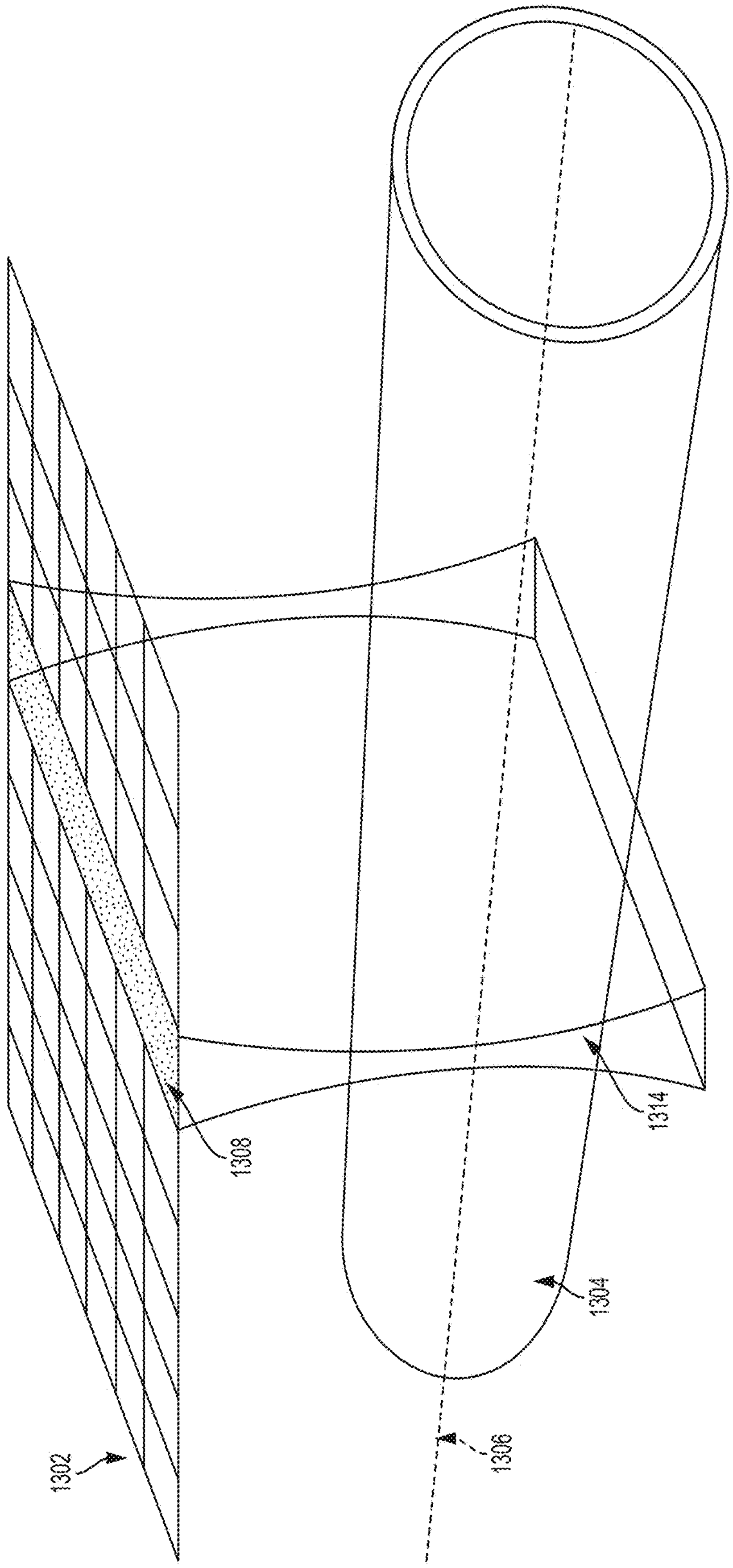

FIG. 13

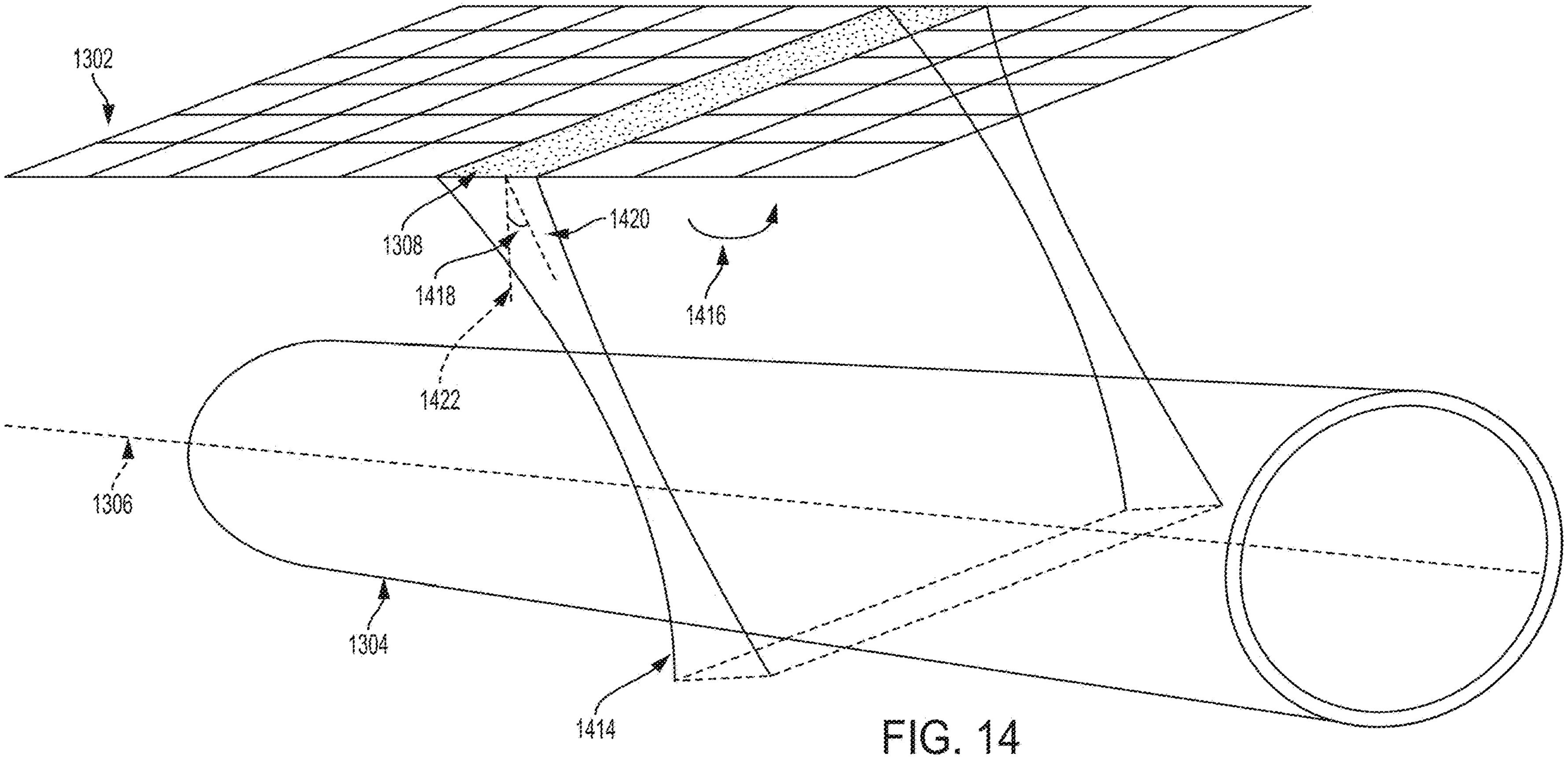

FIG. 14

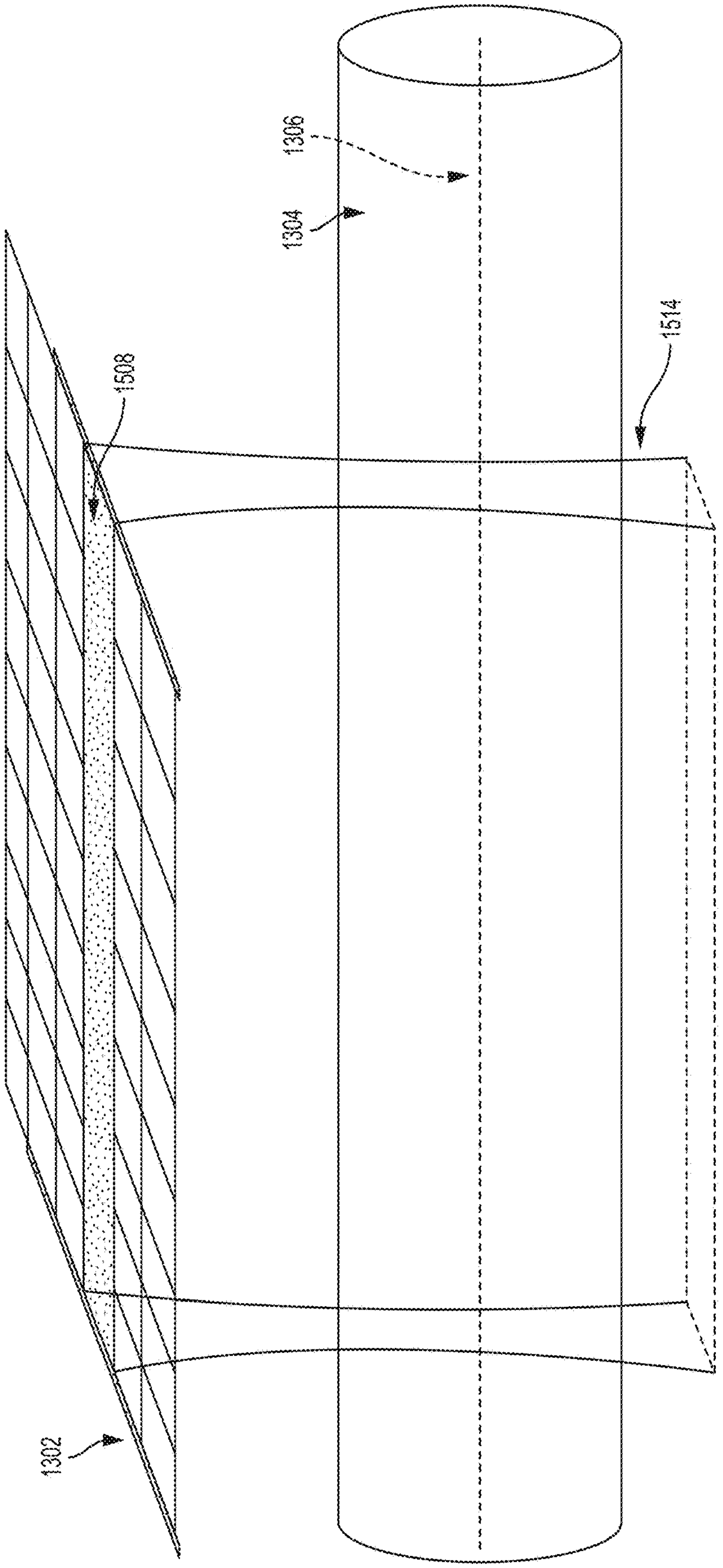

FIG. 15

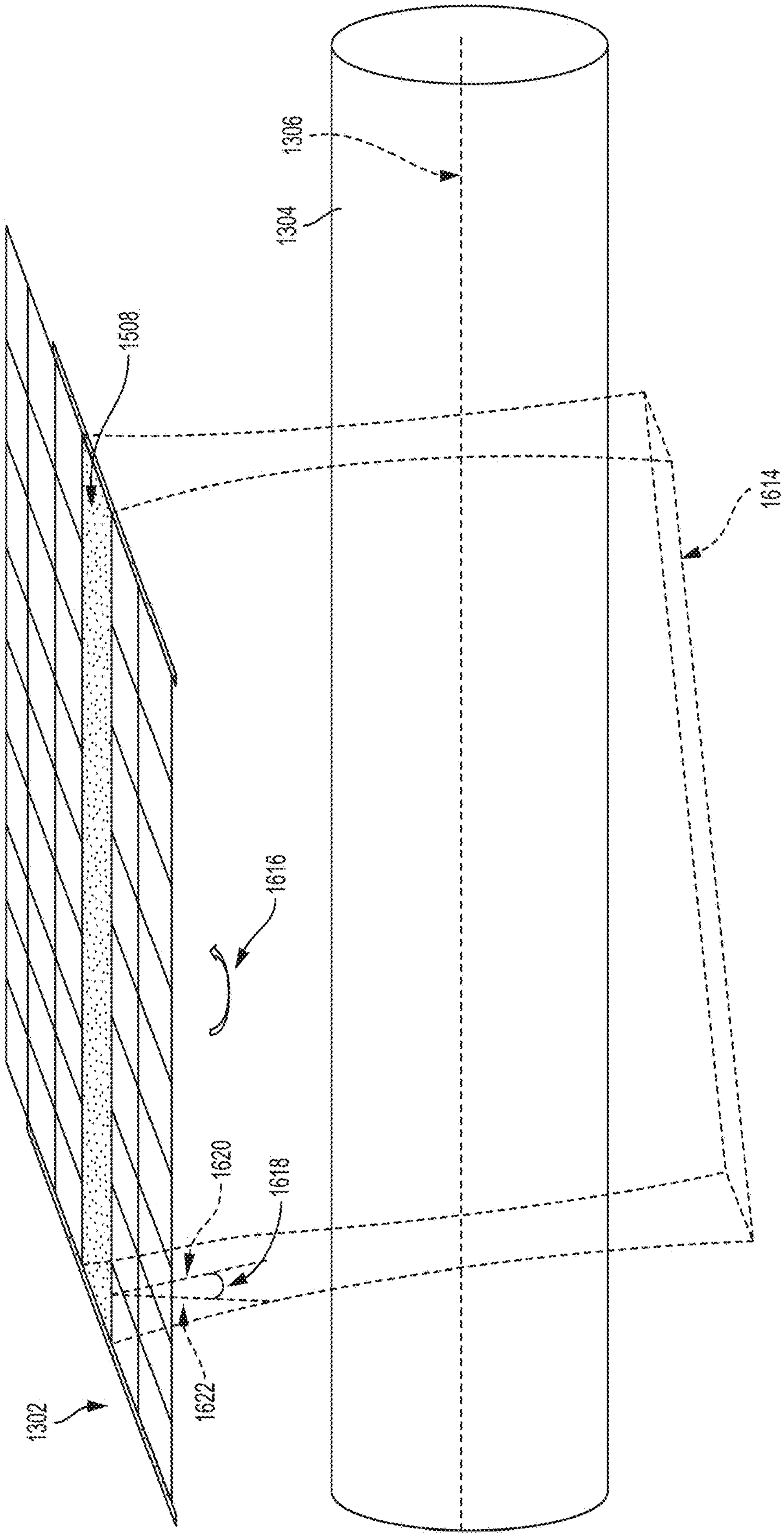

FIG. 16

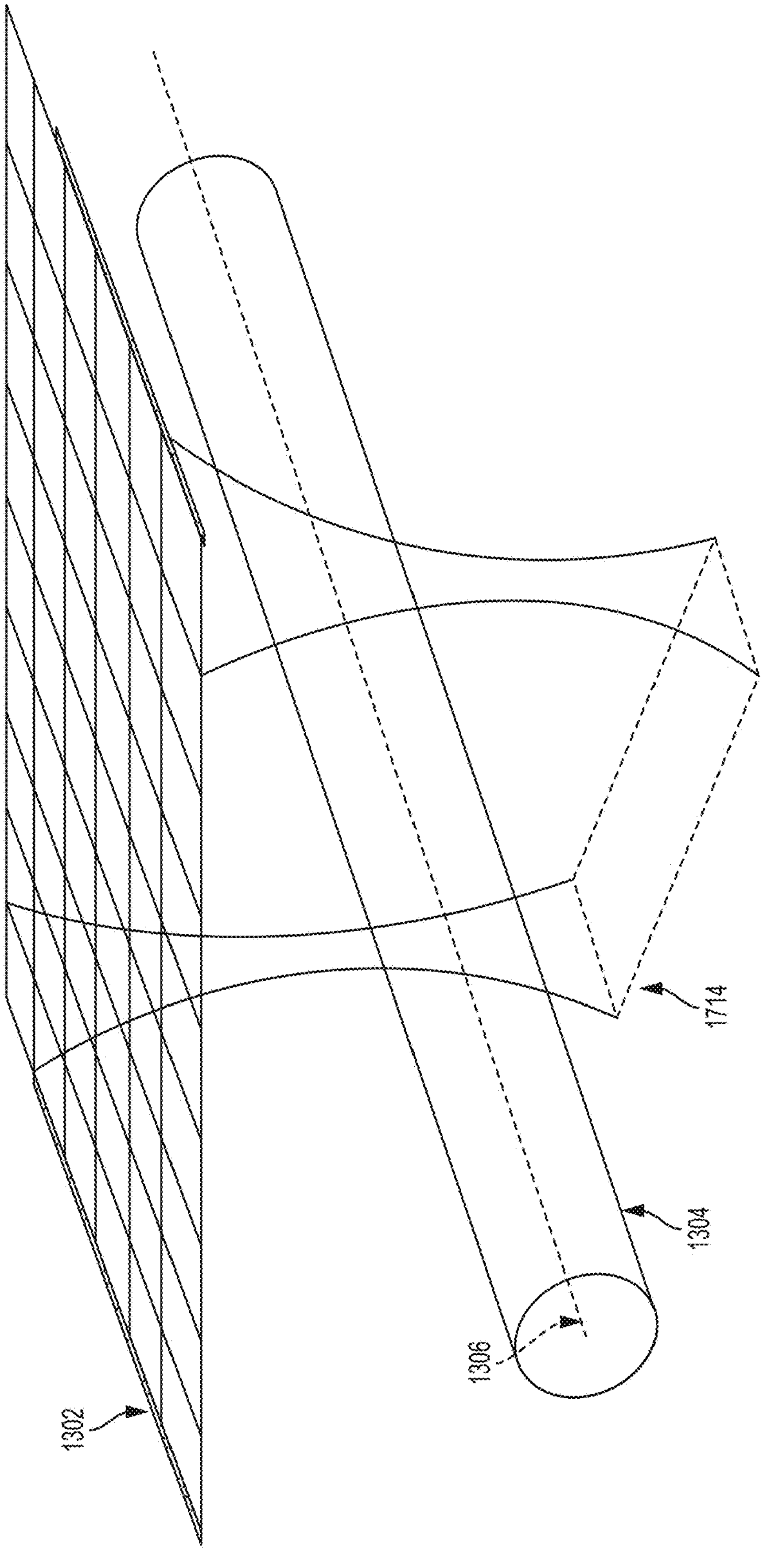

FIG. 17

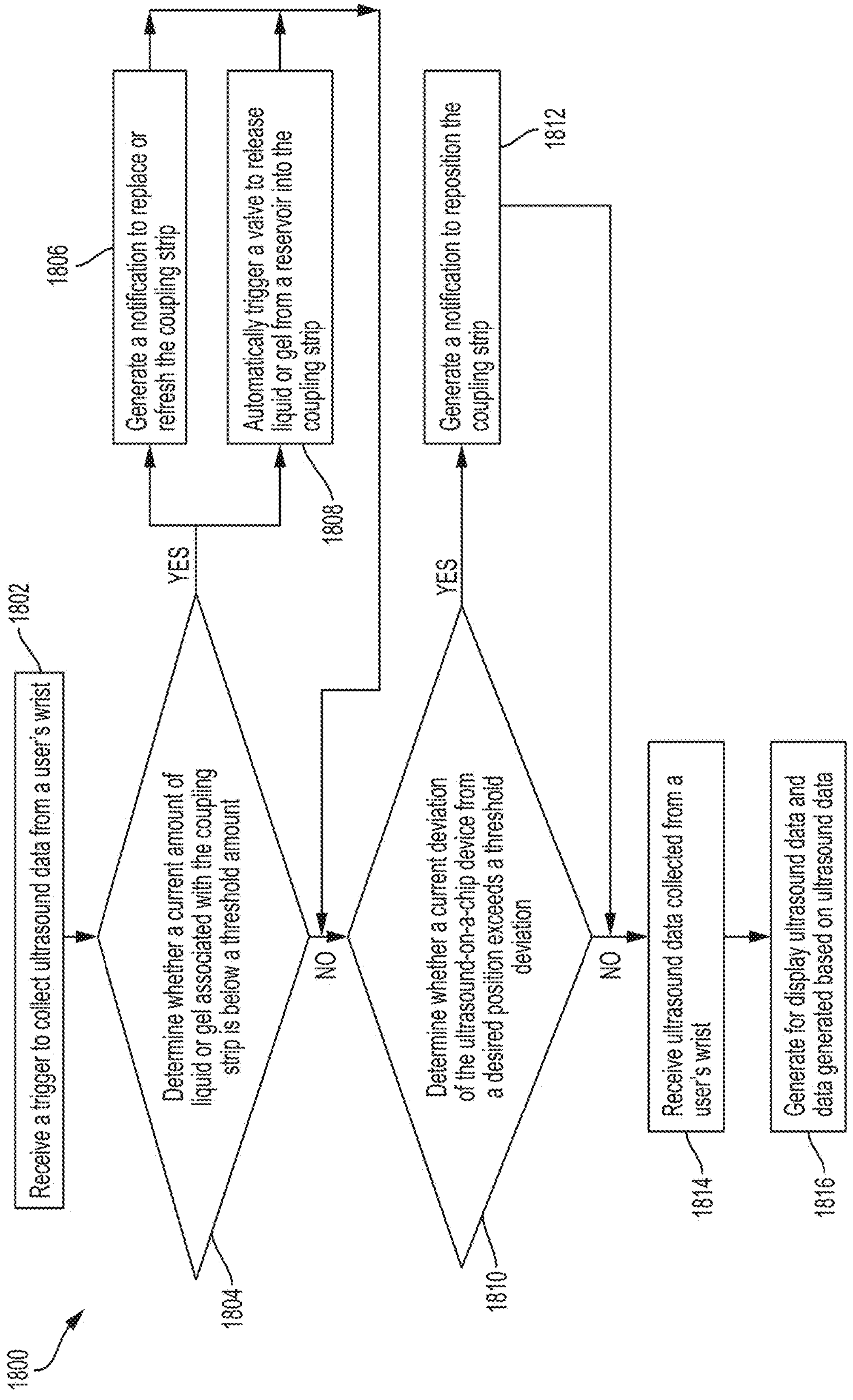
1800
1802
Receive a trigger to collect ultrasound data from a user's wrist
1804
Determine whether a current amount of liquid or gel associated with the coupling strip is below a threshold amount
YES
NO
1806
Generate a notification to replace or refresh the coupling strip
1808
Automatically trigger a valve to release liquid or gel from a reservoir into the coupling strip
1810
Determine whether a current deviation of the ultrasound-on-a-chip device from a desired position exceeds a threshold deviation
YES
NO
1812
Generate a notification to reposition the coupling strip
1814
Receive ultrasound data collected from a user's wrist
1816
Generate for display ultrasound data and data generated based on ultrasound data

FIG. 18

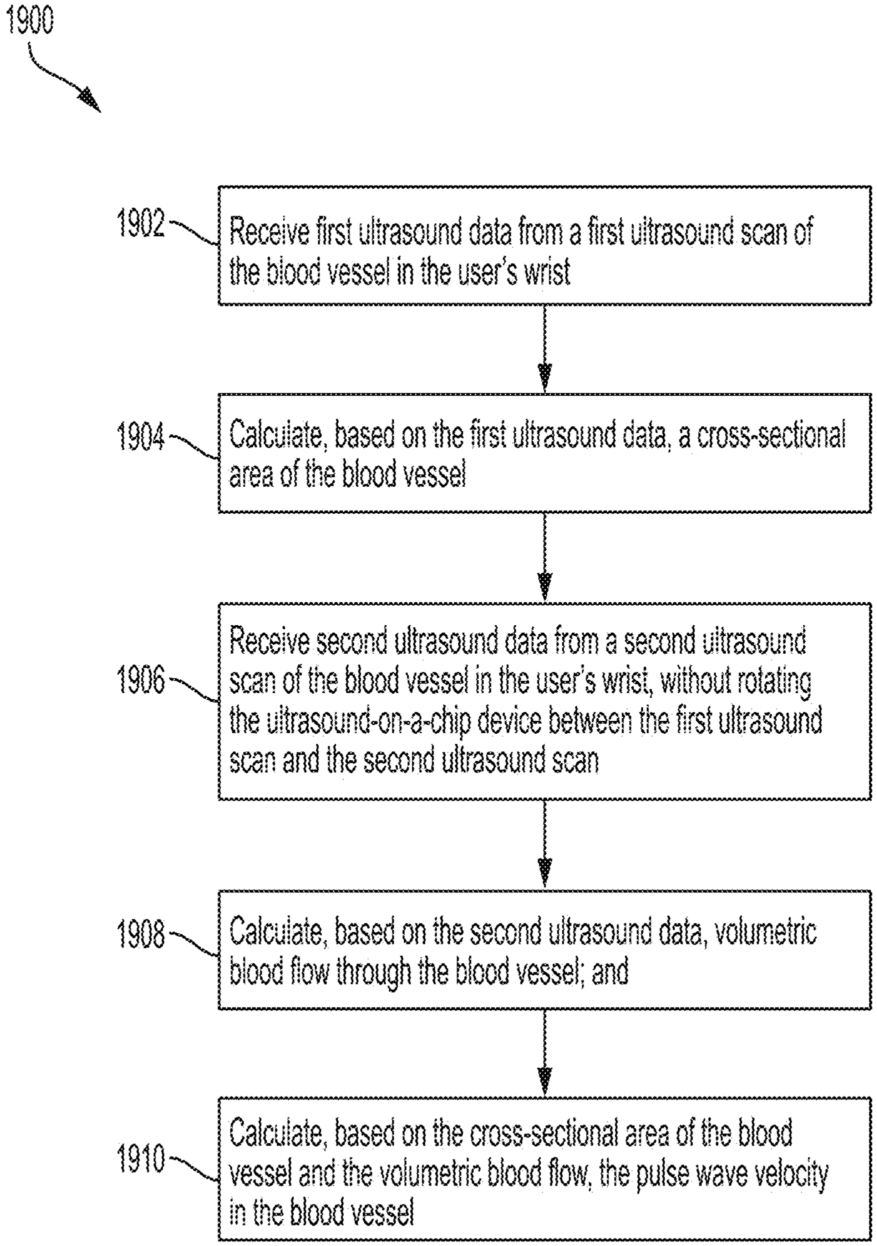
1900
1902
Receive first ultrasound data from a first ultrasound scan of the blood vessel in the user's wrist
1904
Calculate, based on the first ultrasound data, a cross-sectional area of the blood vessel
1906
Receive second ultrasound data from a second ultrasound scan of the blood vessel in the user's wrist, without rotating the ultrasound-on-a-chip device between the first ultrasound scan and the second ultrasound scan
1908
Calculate, based on the second ultrasound data, volumetric blood flow through the blood vessel; and
1910
Calculate, based on the cross-sectional area of the blood vessel and the volumetric blood flow, the pulse wave velocity in the blood vessel

FIG. 19

WRIST BOUND ULTRASOUND-ON-A-CHIP DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit under 35 U.S.C. § 119(e) of U.S. Patent Application Ser. No. 62/555,494, filed Sep. 7, 2017 under Attorney Docket No. B1348.70056US00 and entitled "WRIST BOUND ULTRASOUND-ON-CHIP DEVICE," which is hereby incorporated herein by reference in its entirety.

FIELD

[0002] Generally, the aspects of the technology described herein relate to ultrasound systems. Some aspects relate to wrist bound ultrasound systems.

BACKGROUND

[0003] Ultrasound devices may be used to perform diagnostic imaging and/or treatment, using sound waves with frequencies that are higher with respect to those audible to humans. Ultrasound imaging may be used to see internal soft tissue body structures, for example to find a source of disease or to exclude any pathology. When pulses of ultrasound are transmitted into tissue (e.g., by using a probe), sound waves are reflected off the tissue with different tissues reflecting varying degrees of sound. These reflected sound waves may then be recorded and displayed as an ultrasound image to the operator. The strength (amplitude) of the sound signal and the time it takes for the wave to travel through the body provide information used to produce the ultrasound image. Many different types of images can be formed using ultrasound devices, including real-time images. For example, images can be generated that show two-dimensional cross-sections of tissue, blood flow, motion of tissue over time, the location of blood, the presence of specific molecules, the stiffness of tissue, or the anatomy of a three-dimensional region.

SUMMARY

[0004] According to one aspect, an apparatus includes an ultrasound-on-a-chip device configured to be bound to a user's wrist. In some embodiments, the ultrasound-on-a-chip device is waterproof. In some embodiments, the ultrasound-on-a-chip device is configured to perform both transverse and longitudinal ultrasound scanning of a blood vessel in the user's wrist without being rotated relative to the user's wrist. In some embodiments, the ultrasound-on-a-chip device includes a two-dimensional array of capacitive micromachined ultrasonic transducers (CMUTs). In some embodiments, the ultrasound-on-a-chip device includes a plurality of capacitive micromachined ultrasonic transducers (CMUTs) configured to emit ultrasound waves having a frequency between approximately 5-20 MHz.

[0005] In some embodiments, the apparatus further includes at least one wristband, an ultrasound module containing the ultrasound-on-a-chip device and coupled to the at least one wristband, and a coupling strip coupled to the ultrasound module and configured to couple the ultrasound module to the user's wrist. In some embodiments, the apparatus further includes a primary module coupled to the at least one wristband. In some embodiments, the primary module includes a display screen configured to display at least one of ultrasound data collected by the ultrasound-on-a-chip device, an ultrasound image generated from the ultrasound data, and data generated from the ultrasound data.

[0006] In some embodiments, the apparatus further includes at least one wristband configured to couple to a wristband of a wrist device; an ultrasound module containing the ultrasound-on-a-chip device and coupled to the at least one wristband; and a coupling strip coupled to the ultrasound module and configured to couple the ultrasound module to the user's wrist. In some embodiments, the apparatus further includes a connection cable extending externally from the at least one wristband and configured to electrically connect the ultrasound module to the primary module.

[0007] In some embodiments, the apparatus further includes at least one wristband, a primary module containing the ultrasound-on-a-chip device and coupled to the at least one wristband, and a coupling strip coupled to the primary module and configured to couple the primary module to the user's wrist.

[0008] In some embodiments, the apparatus further includes a reservoir containing liquid or gel and configured to refresh the coupling strip. In some embodiments, the reservoir includes a valve opening from the reservoir into the coupling strip and configured to enable flow of the liquid or gel from the reservoir to the coupling strip. In some embodiments, the valve is configured to enable flow of the liquid or gel from the reservoir to the coupling strip in response to mechanical pressure applied to a portion of the apparatus. In some embodiments, the apparatus further includes processing circuitry configured to automatically trigger the valve to enable flow of the liquid or gel from the reservoir to the coupling strip. In some embodiments, the reservoir further includes an input port configured to enable refilling of the reservoir with the liquid or gel.

[0009] In some embodiments, the apparatus further includes processing circuitry configured to generate a notification to reposition the ultrasound-on-a-chip device. In some embodiments, the apparatus further includes processing circuitry configured to generate a notification to replace the coupling strip or refresh the coupling strip with liquid or gel.

[0010] In some embodiments, the ultrasound-on-a-chip device is configured to transmit ultrasound data collected by the ultrasound-on-a-chip device to processing circuitry that is configured to analyze the ultrasound data using deep learning models. In some embodiments, the processing circuitry is configured to retrieve, from a server, ultrasound data collected by other ultrasound-on-a-chip devices and to use the ultrasound data collected by the other ultrasound-on-a-chip devices when training the deep learning models.

[0011] In some embodiments, the ultrasound-on-a-chip device is configured to transmit ultrasound data of a blood vessel to processing circuitry that is configured to calculate pulse wave velocity in the blood vessel based on the ultrasound data of the blood vessel. In some embodiments, the apparatus further includes a button and processing circuitry configured to trigger collection of ultrasound data by the ultrasound-on-a-chip device upon activation of the button.

[0012] According to another aspect, an apparatus includes a wristband and an ultrasound-on-a-chip device coupled to the wristband. In some embodiments, the wristband includes an interior surface and an exterior surface, and the ultrasound-on-a-chip device is positioned on the interior surface of the wristband.

[0013] According to another aspect, a method includes receiving ultrasound data collected from a user's wrist using an apparatus including at least one wristband, an ultrasound module containing the ultrasound-on-a-chip device and coupled to the at least one wristband, and a coupling strip coupled to the ultrasound module and configured to couple the ultrasound module to the user's wrist.

[0014] In some embodiments, the apparatus further includes a button, and the method further includes triggering collection of the ultrasound data based on activation of the button. In some embodiments, the method further includes determining whether a current amount of liquid or gel associated with the coupling strip is below a threshold amount, and based on determining that the current amount of liquid or gel associated with the coupling strip is below the threshold amount, generating a notification to replace the coupling strip or refresh the coupling strip with liquid or gel.

[0015] In some embodiments, the apparatus further includes a reservoir containing liquid or gel and a valve opening from the reservoir into the coupling strip and configured to enable flow of the liquid or gel from the reservoir to the coupling strip, and the method further includes determining whether a current amount of liquid or gel associated with the coupling strip is below a threshold amount, and based on determining that the current amount of liquid or gel associated with the coupling strip is below the threshold amount, triggering the valve to enable flow of the liquid or gel from the reservoir to the coupling strip. In some embodiments, determining whether the current amount of liquid or gel associated with the coupling strip is below the threshold amount includes performing an ultrasound scan. In some embodiments, determining whether the current amount of liquid or gel associated with the coupling strip is below the threshold amount includes using at least one of a moisture sensor, a capacitive sensor, and a skin conductivity sensor.

[0016] In some embodiments, the method further includes determining whether a current deviation of the ultrasound-on-a-chip device from a desired position exceeds a threshold deviation, and based on determining that the current deviation of the ultrasound-on-a-chip device from the desired position exceeds the threshold deviation, generating a notification to reposition the ultrasound-on-a-chip device.

[0017] In some embodiments, the apparatus further includes a display screen, and the method further includes generating for display, on the display screen, at least one of the ultrasound data, an ultrasound image generated from the ultrasound data, and data generated based on the ultrasound data.

[0018] According to another aspect, a method for calculating pulse wave velocity in a blood vessel includes: receiving, from an ultrasound-on-a-chip device configured to be bound to a user's wrist, first ultrasound data from a first ultrasound scan of the blood vessel in the user's wrist; calculating, based on the first ultrasound data, a cross-sectional area of the blood vessel; receiving, from the ultrasound-on-a-chip device, second ultrasound data from a second ultrasound scan of the blood vessel in the user's wrist, without rotating the ultrasound-on-a-chip device relative to the user's wrist between the first ultrasound scan and the second ultrasound scan; calculating, based on the second ultrasound data, volumetric blood flow through the blood vessel; and calculating, based on the cross-sectional area of the blood vessel and the volumetric blood flow, the pulse wave velocity in the blood vessel.

[0019] In some embodiments, the ultrasound-on-a-chip device is configured to use a two-dimensional array of ultrasound transducers to perform the first and second ultrasound scans. In some embodiments, the first ultrasound scan includes a transverse ultrasound scan of the blood vessel. In some embodiments, the second ultrasound scan includes a longitudinal ultrasound scan with an azimuthal steer towards the blood vessel. In some embodiments, the second ultrasound scan includes a transverse ultrasound scan with an elevational steer towards the blood vessel. In some embodiments, at least one of the first and second ultrasound scans includes using an ultrasound beam profile that is steered along a path that is not perpendicular or parallel to an azimuth or elevation direction of the two-dimensional array of ultrasound transducers. In some embodiments, the method further includes estimating a blood pressure in the blood vessel based on the pulse wave velocity in the blood vessel.

[0020] According to another aspect, a method for estimating blood pressure in a blood vessel includes measuring an elasticity of the blood vessel using an ultrasound-on-a-chip device configured to be bound to a user's wrist.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Various aspects and embodiments will be described with reference to the following exemplary and non-limiting figures. It should be appreciated that the figures are not necessarily drawn to scale. Items appearing in multiple figures are indicated by the same or a similar reference number in all the figures in which they appear.

[0022] FIG. **1** shows an example of an apparatus for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein;

[0023] FIG. **2** shows an example of a user's dorsal wrist and the user's volar wrist when the user wears the assembled apparatus of FIG. **1**;

[0024] FIG. **3** shows another example of an apparatus for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein;

[0025] FIG. **4** shows another example of an apparatus for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein;

[0026] FIG. **5** shows another example of an apparatus for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein;

[0027] FIGS. **6**A-**6**G show examples of an apparatus for an ultrasound-on-a-chip device configured to be bound to a user's wrist when the apparatus is assembled and worn;

[0028] FIG. **7** shows an example of an apparatus when electrically coupled to a user's personal wrist device;

[0029] FIG. **8** shows an example in which an ultrasound module includes reservoirs for refreshing a coupling strip in accordance with certain embodiments described herein;

[0030] FIG. **9** shows an example of recesses incorporated into an ultrasound module in accordance with certain embodiments disclosed herein;

[0031] FIG. **10** shows an example of a mechanical button incorporated into an ultrasound module in accordance with certain embodiments disclosed herein;

[0032] FIG. **11** shows an example of a virtual button on a display screen of a primary module in accordance with certain embodiments disclosed herein;

[0033] FIG. **12** shows an example of a mechanical button on a primary module in accordance with certain embodiments disclosed herein;

[0034] FIG. **13** shows an illustration of performing a transverse ultrasound scan of a blood vessel with a two-dimensional array of ultrasound transducers in accordance with certain embodiments disclosed herein;

[0035] FIG. **14** shows an illustration of performing a transverse ultrasound scan, with an elevational steer, of a blood vessel using the two-dimensional array of ultrasound transducers in accordance with certain embodiments disclosed herein;

[0036] FIG. **15** shows an illustration of performing a longitudinal ultrasound scan of a blood vessel with the two-dimensional array of ultrasound transducers in accordance with certain embodiments disclosed herein;

[0037] FIG. **16** shows an illustration of performing a longitudinal ultrasound scan, with an azimuthal steer, of a blood vessel using the two-dimensional array of ultrasound transducers in accordance with certain embodiments disclosed herein;

[0038] FIG. **17** shows an illustration of performing a transverse ultrasound scan of a blood vessel using the two-dimensional array of ultrasound transducers, when the blood vessel does not lie either perpendicular or parallel to the azimuth direction or the elevation direction, in accordance with certain embodiments disclosed herein;

[0039] FIG. **18** shows an example process for obtaining ultrasound data from a user's wrist, in accordance with certain embodiments disclosed herein; and

[0040] FIG. **19** shows an example process for calculating pulse wave velocity (PWV), in accordance with certain embodiments disclosed herein.

DETAILED DESCRIPTION

[0041] Conventional ultrasound systems are large, complex, and expensive systems that are typically only purchased by large medical facilities with significant financial resources. Recently, cheaper and less complex ultrasound imaging devices have been introduced. Such imaging devices may include ultrasonic transducers monolithically integrated onto a single semiconductor die to form a monolithic ultrasound device. Aspects of such ultrasound-on-a chip devices are described in U.S. patent application Ser. No. 15/415,434 titled "UNIVERSAL ULTRASOUND DEVICE AND RELATED APPARATUS AND METHODS," filed on Jan. 25, 2017 (and assigned to the assignee of the instant application) and published as U.S. Pat. Pub. No. 2017/0360397 A1, which is incorporated by reference herein in its entirety. The reduced cost and increased portability of these new ultrasound devices may make them significantly more accessible to the general public than conventional ultrasound devices.

[0042] Although the reduced cost and increased portability of ultrasound imaging devices make them more accessible to the general populace, people who could make use of such devices may have little to no training for how to use them. The inventors have recognized that a wrist bound ultrasound-on-a-chip device may be helpful in minimizing complexity of collecting ultrasound data. Instead of placing an ultrasound probe on a user every time collection of ultrasound data is needed, the ultrasound-on-a-chip device may be kept bound to the wrist for an extended period of time (e.g., 1 hour, 6 hours, 12 hours, 1 day, 1 week, 1 month, indefinitely, or any suitable length of time), in place for collection of ultrasound data when needed. Instead of a user actively initiating collection of ultrasound data when needed, because the ultrasound-on-a-chip device is kept bound to the wrist for an extended period of time (e.g., 1 hour, 6 hours, 12 hours, 1 day, 1 week, 1 month, indefinitely, or any suitable length of time) and in place for collection of ultrasound data when needed, the ultrasound-on-a-chip device may be able to automatically initiate collection of ultrasound data, without requiring active initiation of data collection by a user. Additionally, it may not be necessary for a medical professional knowledgeable about ultrasound data collection to be involved in collection of ultrasound data with the wrist bound ultrasound-on-a-chip device. The ultrasound data may be collected and sent to one or more servers (also known as a "cloud"), from which a user and/or his or her medical professional can retrieve the ultrasound data and track the progress of ultrasound scans. Furthermore, blood pressure or other metrics may be learned in a deep learning framework applied to aggregated data and an inference can be run on the ultrasound data that has been uploaded to the server(s). The wrist bound ultrasound-on-a-chip device may already be in place at the location on the wrist for ultrasound data collection, and parameters needed for ultrasound data collection may already be programmed into the ultrasound-on-a-chip device or automatically receivable by the ultrasound-on-a-chip from an external source. Because the ultrasound-on-a-chip device may be coupled to a wristwatch device or a bracelet, which the user may already wear, the wrist bound ultrasound-on-a-chip device may not require the user to wear an additional device in order to enable collection of ultrasound data from the wrist. A wrist bound ultrasound-on-a-chip device, with a form factor similar to a normal wristwatch or bracelet, may be comfortable and familiar for a user. When the ultrasound-on-a-chip device is part of an apparatus including a primary module such as a smartwatch, the primary module may provide functionality in combination with the ultrasound-on-a-chip device. For example, the user may view data collected by the ultrasound-on-a-chip device on a display screen of the primary module, the user may receive notifications about the ultrasound-on-a-chip device from the primary module (e.g., on a display screen of the primary module or by an audio speaker of the primary module), and the user may control operation of the ultrasound-on-a-chip device using physical and/or virtual buttons of the primary module.

[0043] The inventors have further recognized that the wrist may be an advantageous location for an ultrasound-on-a-chip device because useful ultrasound data may be collected from the wrist. For example, measurements of blood flow, heart rate, blood pressure, blood vessel diameter, and pulse wave velocity may be measured/calculated/estimated based on ultrasound data collected from the wrist.

[0044] The inventors have further recognized that an ultrasound-on-a-chip device that includes a two-dimensional array of ultrasound transducers may be helpful for applications involving collection of ultrasound data from the wrist. A two-dimensional array of ultrasound transducers can, for example, perform transverse and longitudinal ultrasound scanning and steer ultrasound beam profiles in the azimuthal and elevational directions, as well as steer ultrasound beam profiles in arbitrary orientations. This flexibility can be useful, for example, in applications requiring collection of multiple types of data that may require or be enabled by multiple ultrasound beam profiles and multiple scanning directions. For example, measuring PWV at the wrist may require collecting ultrasound data for measuring blood vessel diameter, spatial mean velocity, and/or blood vessel wall velocity, which may be enabled by the flexibility of a two-dimensional ultrasound transducer array.

[0045] The inventors have further recognized that using capacitive micromachined ultrasonic transducers (CMUTs), which may be integrated with CMOS (complementary metal-oxide-semiconductor) circuitry and referred to as CMOS ultrasonic transducers (CUTs), in a wrist bound ultrasound-on-a-chip device may be advantageous. The ultrasound transducers in the wrist bound ultrasound-on-a-chip device may be configured to emit ultrasound waves having frequencies between 5-20 MHz in order to collect ultrasound data from arteries in the wrist. These frequencies may represent the optimal frequencies in terms of attenuation and resolution based on the depth of the arteries in the wrist below the skin surface. CMUTs may be advantageous compared with piezoelectric micromachined ultrasonic transducers (PMUTs) for applications using high frequencies (e.g., frequencies between 5-20 MHz) for reasons related to manufacturability and sensitivity. In terms of manufacturability, high frequency applications require small elements with tight pitch (i.e., the distance between the centers of adjacent transducers) and narrow kerfs (i.e., the gap between adjacent transducers). Certain manufacturing processes for PMUTs (e.g., using dicing and filling) can make it difficult to produce small elements with tight pitch and narrow kerfs with consistent results because of the small scales involved. In contrast, the manufacturing processes for CMUTs may make it easier to produce small elements with tight pitch and narrow kerfs. CMUTs also have high sensitivity. As discussed further below, CMUTs may include a cavity formed in a substrate with a membrane overlying the cavity. CMUTs may be especially sensitive when their cavities are small and membranes are thick, which is advantageous for high frequency applications.

[0046] The inventors have further recognized that including a coupling strip in the wrist bound ultrasound-on-a-chip device may be helpful for reducing the air gap between the ultrasound-on-a-chip device (more particularly, an ultrasound module containing the ultrasound-on-a-chip device) and the user's wrist. In particular, the coupling strip may be configured to establish acceptable impedance matching coupling for ultrasound signal transmission and reception. To reduce the air gap between the ultrasound-on-a-chip device and the user's wrist, the coupling strip may be configured to be flexible such that the coupling strip conforms to the irregular surface of the user's wrist. Conventionally, ultrasound gel is applied to the user's skin prior to collection of ultrasound data from the user, in order to reduce the air gap between the ultrasound-on-a-chip device and the user's wrist and to establish acceptable impedance matching coupling for ultrasound signal transmission and reception. However, ultrasound gel tends to dry up and consequently may not be effective after a period of time. Accordingly, applications that may require collection of ultrasound data (continuously or periodically) over a period of time longer than the period of time during which ultrasound gel is effective may not be able to use conventional ultrasound gel. For example, a wrist bound ultrasound-on-a-chip device, which may be configured to be worn and used for data collection for an extended period of time (e.g., 1 hour, 6 hours, 12 hours, 1 day, 1 week, 1 month, indefinitely, or any suitable length of time), may benefit from an alternative to ultrasound gel that can function for longer than ultrasound gel. The coupling strip described herein may be helpful in providing benefits of ultrasound gel, such as reducing the air gap between the ultrasound-on-a-chip device and the user's wrist and ensuring proper impedance matching coupling for ultrasound signal transmission and reception, while also avoiding the limited period of time during which ultrasound gel is effective. For example, the coupling strip may not dry up as quickly as conventional ultrasound gel. As another example, the coupling strip may be more easily replaceable (for example, by peeling off an old coupling strip and adhering a new coupling strip to the ultrasound-on-a-chip device and/or the user's skin) than removing old ultrasound gel and applying new ultrasound gel. As another example, the coupling strip may be refreshable by addition of liquid to the coupling strip if the coupling strip dries out.

[0047] The inventors have further recognized that configuring a wrist bound ultrasound-on-a-chip device to be waterproof may be helpful. For example, if the wrist bound ultrasound-on-a-chip device is waterproof, prior to collection of ultrasound data, the user may dip the ultrasound-on-a-chip device in water, run the ultrasound-on-a-chip device over water, and/or take a shower with the ultrasound-on-a-chip device to create a water layer between the ultrasound-on-a-chip device and the user's skin, and thereby establish proper impedance matching coupling for ultrasound signal transmission and reception.

[0048] As used herein, a wrist bound object or an object configured to be bound to the wrist should be understood to mean that the object is configured to remain located at or near a subject's wrist without external application of force. For example, an ultrasound-on-a-chip device coupled to a wristwatch or a bracelet that is worn on a user's wrist may be considered "wrist bound."

[0049] As used herein, an "ultrasound-on-a-chip device" should be understood to mean a device including micromachined ultrasound transducers integrated with a semiconductor die containing integrated circuitry.

[0050] It should be appreciated that the embodiments described herein may be implemented in any of numerous ways. Examples of specific implementations are provided below for illustrative purposes only. It should be appreciated that these embodiments and the features/capabilities provided may be used individually, all together, or in any combination of two or more, as aspects of the technology described herein are not limited in this respect.

[0051] FIG. **1** shows an example of an apparatus **100** for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein. In FIG. **1**, the apparatus **100** is shown disassembled. The apparatus **100** is wearable by a user around the user's wrist and includes a primary module **102**, an ultrasound module **104**, a coupling strip **148**, a first wristband **106**, and a second wristband **108**. It should be understood that as referred to herein, a "wristband" may be any type of band configured to encircle any portion of the wrist, or the entire wrist.

[0052] The ultrasound module **104** includes an ultrasound-on-a-chip device **110** and an ultrasound housing element **128**. The primary module **102** includes a printed circuit board (PCB) **120**, a display screen **122**, a battery **130**, and primary housing elements **124** and **126**. On the PCB **120** is processing circuitry **112**, memory circuitry **114**, communication circuitry **116**, and power management circuitry **118**. The first wristband **106** includes a plurality of holes **132** at its first end portion **134** that are each located at a different distance from the first end portion **134** of the first wristband **106**. Conductors **136** extend through the first wristband **106** and extend into the primary housing elements **124** and **126** to electrically connect the ultrasound module **104** to the PCB **120**. The second wristband **108** includes a buckle **138** at its first end portion **142**. The buckle **138** includes a pin **140**.

[0053] The ultrasound-on-a-chip device **110** includes micromachined ultrasound transducers integrated with a semiconductor die containing integrated ultrasound circuitry. In some embodiments, the ultrasonic transducers may be formed on the same chip as the ultrasound circuitry to form a monolithic ultrasound device. In other embodiments, certain portions of the ultrasound circuitry may be in a different semiconductor chip than the transducers. The ultrasound transducers may be capacitive micromachined ultrasonic transducers (CMUTs). The CMUTs may be integrated with CMOS circuitry. A CMUT may, for example, include a cavity formed in a CMOS wafer, with a membrane overlying the cavity, and in some embodiments sealing the cavity. Electrodes may be provided to create a transducer cell from the covered cavity structure. The CMOS wafer may include integrated circuitry to which the transducer cell may be connected. The transducer cell and CMOS wafer may be monolithically integrated, thus forming an integrated ultrasonic transducer cell and integrated circuit on a single substrate (the CMOS wafer). CMUTs integrated with CMOS circuitry may be referred to as CMOS ultrasonic transducers (CUTs).

[0054] The ultrasound transducers may be arranged in a one-dimensional array or a two-dimensional array, and there may be 1024, 2048, 4096, 8192, 16384, or any other suitable number of transducer elements in the array. The transducers may be arranged with a 50 μm, 100 μm, 130 μm, 200 μm, 250 μm, or any other suitable pitch. The semiconductor die/dice may be 5 mm×5 mm, 10×5 mm, 1×1 cm, 1.5×1 cm, 1.5 cm×1.5 cm, 2×1 cm, 2×1.5 cm, 2×2 cm, or any other suitable size. In some embodiments, the ultrasound-on-a-chip device **110** includes a transducer array having 2048 transducer elements arranged in a 64×32 array with a 130 μm pitch on a semiconductor die that is 10×5 mm in size. In some embodiments, the ultrasound-on-a-chip device **110** includes a transducer array having 4096 transducer elements arranged in a 64×64 array with a 130 μm pitch on a semiconductor die that is 1×1 cm in size. The ultrasound circuitry in the ultrasound-on-a-chip device **110** may include transmit circuitry that transmits a signal to a transmit beamformer in the ultrasound-on-a-chip device **110** which in turn drives the ultrasound transducers to emit pulsed ultrasonic signals into the user's wrist. The pulsed ultrasonic signals may be back-scattered from structures in the user's wrist, such as blood vessels, to produce echoes that return to the transducers. These echoes may then be converted into electrical signals, or ultrasound data, by the transducer elements, and the electrical signals are received by receive circuitry in the ultrasound circuitry. The electrical signals representing the received echoes are sent to a receive beamformer in the ultrasound-on-a-chip device **110** that outputs ultrasound data in response to the received echoes. For further description of examples of ultrasound devices and ultrasound circuitry, see U.S. patent application Ser. No. 15/415,434 titled "UNIVERSAL ULTRASOUND DEVICE AND RELATED APPARATUS AND METHODS."

[0055] In some embodiments, the ultrasound transducers in the ultrasound-on-a-chip device **110** may emit ultrasound waves having frequencies between approximately 5-20 MHz in order to collect ultrasound data from arteries in the wrist. These frequencies may represent the optimal frequencies in terms of attenuation and resolution based on the depth of the arteries in the wrist below the skin surface. In some embodiments, the ultrasound-on-a-chip device **110** may emit ultrasound waves having frequencies up to approximately 21 MHz, 22 MHz, 23 MHz, 24 MHz, 25 MHz, 26 MHz, 27 MHz, 28 MHz, 29 MHz, 30 MHz, >30 MHz, or any suitable frequency. In some embodiments, the ultrasound-on-a-chip device **110** may emit ultrasound waves having frequencies down to approximately 4 MHz, 3 MHz, 2 MHz, 1 MHz, <1 MHz, or any suitable frequency.

[0056] The ultrasound-on-a-chip device **110** is positioned in the ultrasound module **104** such that its longitudinal axis is parallel to the longitudinal axis of the first wristband **106**. In the example of the radial artery, because the ultrasound-on-a-chip device **110** will be transverse to the radial artery when positioned on the wrist, it may be easier to position the ultrasound-on-a-chip device **110** over the radial artery, and not to the left or right of the radial artery, than if the ultrasound-on-a-chip device **110** is positioned with its longitudinal axis perpendicular to the first wristband **106**. In some embodiments, it may be possible to rotate the ultrasound module **104** to a desired orientation relative to the first wristband **106** prior to coupling the ultrasound module **104** to the first wristband **106**.

[0057] The ultrasound-on-a-chip device **110** may transmit collected ultrasound data over the conductors **136** to the processing circuitry **112**. The ultrasound module **104** and the PCB **120** are electrically coupled to the conductors **136** which extend through the first wristband **106** and into the primary module **102**. The conductors **136** may be, for example, in a flexible printed circuit board or a cable.

[0058] The ultrasound housing element **128** and the first wristband **106** enclose the ultrasound-on-a-chip device **110**. The ultrasound housing element **128** has an acoustic lens **146** through which ultrasonic waves can propagate from the ultrasound-on-a-chip device **110** into the user's wrist. In some embodiments, the acoustic lens **146** is a simple opening in the ultrasound housing element **128**. When the apparatus **100** is assembled, the ultrasound housing element **128** faces the user's wrist. In some embodiments, the ultrasound housing element **128** is a protrusion from the first wristband **106** that forms a cavity that contains the ultrasound-on-a-chip device **110**.

[0059] The coupling strip **148** is attached to the surface of the acoustic lens **146** that faces the user's wrist. The coupling strip **148** is configured to reduce the air gap between the ultrasound module **104** and the user's wrist and to establish acceptable impedance matching coupling for ultrasound signal transmission and reception. In some embodiments, therefore, the coupling strip **148** may be considered an impedance matching strip, or an impedance matching coupler. Further examples of the coupling strip **148** are described in more detail hereinafter in the section entitled "Example Coupling Strips."

[0060] In the primary module **102**, the PCB **120** is communicatively coupled to the display screen **122**, for example by internal wires within the primary housing elements **124** and **126**, and includes processing circuitry **112**, memory circuitry **114**, communication circuitry **116**, and power management circuitry **118**, which may be included in one or more semiconductor chips on the PCB **120**. The processing circuitry **112** may be configured to perform any of the functionality described herein. The processing circuitry **112** may include one or more processors (e.g., computer hardware processors) and may be configured to execute one or more processor-executable instructions stored in the memory circuitry **114**. The memory circuitry **114** may be used for storing programs and data and may comprise one or more storage devices such as non-transitory computer-readable storage media. The processing circuitry **112** may control writing data to and reading data from the memory circuitry **114** in any suitable manner. The processing circuitry **112** is configured to receive ultrasound data from the ultrasound-on-a-chip device **110** and includes image reconstructions circuitry for reconstructing the ultrasound data into an ultrasound image (which may be two-dimensional images or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, three-dimensional images). The processing circuitry **112** may also be configured to perform calculations (e.g., anatomical or physiological measurements) based on ultrasound data and/or ultrasound images (which may be two-dimensional images or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, three-dimensional images). The processing circuitry **112** may include specially-programmed and/or special-purpose hardware such as an application-specific integrated circuit (ASIC). For example, the processing circuitry **112** may comprise one or more ASICs specifically designed for machine learning (e.g., deep learning). The ASICs specifically designed for machine learning may be employed to, for example, accelerate the inference phase of a neural network. The processing circuitry **112** also includes control circuitry that is configured to supply control signals that are transmitted over the conductors **136** to control operation of the ultrasound-on-a-chip device **110**, such as operation of the transmit and receive circuitry. The control circuitry is also configured to supply control signals to the display screen **122**, the circuitry on the PCB **120**, and the ultrasound-on-a-chip device **110** to control their operation. The processing circuitry **112** may include a field-programmable gate array (FPGA).

[0061] The battery **130** is electrically connected to the PCB **120** and the display screen **122** to provide power to the circuitry on the PCB **120** and the display screen **122**. The battery **130** is also configured to supply power to the ultrasound-on-a-chip device **110** over the conductors **136**. The battery **130** may be any type of battery, such as a button cell battery (e.g., a zinc air cell battery, type PR48, size A13), a lithium ion battery, or a lithium polymer battery. The battery **130** may be rechargeable. The power management circuitry **118** is configured to manage supply of power from the battery **130** to the PCB **120**, the display screen **122**, and to the ultrasound-on-a-chip device **110**. The power management circuitry **118** may be responsible for converting one or more input voltages from the battery **130** into voltages needed to carry out operation of the ultrasound-on-a-chip device **110**, and for otherwise managing power consumption within the device ultrasound-on-a-chip device **110**. For example, the power management circuitry **118** may step the input voltage up or down, as necessary, using a charge pump circuit or via some other DC-to-DC voltage conversion mechanism.

[0062] The communication circuitry **116** is configured to wirelessly transmit data (e.g., ultrasound data, ultrasound images, calculations based on ultrasound data/images) to an external device, such as external host device, workstation, or server. The communication circuitry **116** may include BLUETOOTH, ZIGBEE, and/or WiFi wireless communication circuitry. In some embodiments, the communication circuitry **116** may be configured to transmit data to the external device over a wired connection, such as a SERDES, DDR, USB, OR MIPI wired connection.

[0063] The primary module **102** may be configured as any type of electronic device and may perform functions unrelated to ultrasound data collection. For example, the primary module **102** may be configured as a smartwatch, and the display screen **122** may be configured to display any type of data, including the time, e-mail, instant messages, and/or the Internet. The display screen **122** may be any type of display screen, such as a low-power light emitting diode (LED) array, a liquid-crystal display (LCD) array, an active-matrix organic light-emitting diode (AMOLED) display, or a quantum dot display. The display screen **122** may be curved. The primary module **102** may include other sensors, such as global positioning, gyroscope, accelerometer, barometer, blood alcohol level, glucose level, blood oxygenation level, microphone, heart rate, ultraviolet, and galvanic skin response sensor, and the display screen **122** may display data from these additional sensors. In some embodiments, the display screen **122** may be absent.

[0064] In some embodiments, the ultrasound module **104** is configured to communicate with the primary module **102** wirelessly. In such embodiments, the ultrasound module **104** may include wireless communication circuitry configured to communicate wirelessly with the communication circuitry **116** of the primary module **102**. The ultrasound module **104** and the primary module **102** may wirelessly communicate ultrasound data from the ultrasound module **104** to the primary module **102** and control signals from the primary module **102** to the ultrasound module **104**. In some embodiments, the ultrasound module **104** includes a battery and does not draw power from the battery **130** in the primary module **102**. In embodiments where the ultrasound module **104** communicates wirelessly with the primary module **102** and has its own battery, the conductors **136** may be absent. In some embodiments the ultrasound module **104** may charge or power itself inductively from the primary module **102** or an auxiliary charger.

[0065] In some embodiments, the ultrasound module **104** may include internal processing circuitry **112**, memory circuitry **114**, communication circuitry **116**, and/or power management circuitry **118**. Portions of the circuitry may be integrated with the ultrasound-on-a-chip device **110**. In such embodiments, the ultrasound module **104** may perform image reconstruction and/or data transmission to an external device using circuitry internal to the ultrasound module **104**, and may not communicate with the primary module **102**. Accordingly, the conductors **136** may be absent.

[0066] The primary housing elements **124** and **126** enclose the PCB **120**, the display screen **122**, and the battery **130**. The display screen **122** is positioned adjacent to the primary housing element **124**, which includes an opening **144** through which the display screen **122** can be seen. When the apparatus **100** is assembled, the primary housing element **124** faces the user's wrist and the primary housing element **126** faces away from the user's wrist. The primary housing element **126** and the display screen **122** are positioned on an opposite surface of the apparatus **100** (i.e., the surface that faces away from the user's wrist) than the PCB **120**, the battery **130**, and the primary housing element **124**. In some embodiments, the primary housing elements **124** and **126** may be a single element. For example, the single primary housing element may have a hinge so that the ultrasound housing element can open the PCB **120**, the display screen **122**, and the battery **130** can be inserted inside. As another example, the single primary housing element may have a slot into which the PCB **120**, the display screen **122**, and the battery **130** can be inserted.

[0067] The first wristband **106** is coupled at its second end portion **154** to a first end portion **150** of the primary housing element **124**. The second wristband **108** is coupled at its second end portion **156** to a second end portion **152** of the primary housing element **124**. The first and second wristbands **106** and **108** may be configured to couple to the primary housing element **124** through any coupling means, such as a clip, a snap, a screw, an adhesive, magnetism, hook and loop fastener (e.g., Velcro), an interlocking fit, etc. In some embodiments, the primary housing element **124** may include pairs of lugs at each of its first and second end portions **134** and **136**, with spring bars bridging each pair of lugs, and the first and second wristbands **106** and **108** may loop around the spring bars. The first and second wristbands **106** and **108** may be made of any material, such as leather, fabric, plastic, and metal. The first and second wristbands **106** and **108** may have any shape and may resemble a conventional band for a wristwatch or a bracelet.

[0068] The apparatus **100** can be bound to the user's wrist by inserting the pin **140** into one of the plurality of holes **132**. Based on which hole of the plurality of holes **132** is used, the circumference of the apparatus **100** can be adjusted so that the apparatus **100** fits around the user's wrist. In some embodiments, the apparatus **100** may be bound to the user's wrist using other mechanisms. For example, instead of the plurality of holes **132** and the buckle **138**, the first and second wristbands **106** and **108** may include a clip, a snap, Velcro, magnets, or an interlocking fit. In some embodiments, the apparatus **100** includes just one wristband, or more than two wristbands.

[0069] The ultrasound module **104** is configured to attach to the first wristband **106**. In some embodiments, the ultrasound module **104** is attached to the first wristband **106** at a position not intended to be moved. For example, the ultrasound module **104** may be positioned at a specific location on the first wristband **106** such that, when the apparatus **100** is worn, the ultrasound module **104** is positioned over a specific region of the user's wrist (e.g., the radial artery). The ultrasound module **104** may be configured to attach to the first wristband **106** through any coupling means. For example, the ultrasound module **104** may attach to the first wristband **106** through complementary Velcro, magnets, or snaps on the ultrasound module and the first wristband **106**. In some embodiments, the apparatus is configured such that the position of the ultrasound module **104** on the first wristband **106** can be changed. In some embodiments, the first wristband **106** may include a plurality of discrete coupling points along its length (e.g., discrete magnets, discrete Velcro elements, discrete snap locations). In other embodiments, the first wristband **106** has a continuous coupling region along its length (e.g., a continuous length of magnetic material or a continuous length of hook and loop fastener (e.g., Velcro) material). In some embodiments, the ultrasound module **104** may include a clip for clipping the ultrasound module **104** to the first wristband **106**. In other embodiments, the first wristband **106** may have a cavity into which the ultrasound-on-a-chip device **110** is placed. In yet other embodiments, the first wristband **106** includes a plurality of holes and the ultrasound module **104** includes a pin, and the ultrasound module **104** may be coupled to the first wristband **106** by inserting the pin into one of the plurality of holes.

[0070] In some embodiments, the primary module **102** may be absent, and the PCB **120**, the processing circuitry **112**, the memory circuitry **114**, the communication circuitry **116**, the power management circuitry **118**, and the battery **130** may be included in the ultrasound module **104**. In such embodiments, the first wristband **106** and the second wristband **108** may be a single continuous wristband.

[0071] FIG. **2** shows an example of a user's dorsal wrist **200** and the user's volar wrist **202** when the user wears the assembled apparatus **100** of FIG. **1**. The ultrasound module **104** is positioned on the first wristband **106** such that the ultrasound-on-a-chip device **110** (visible through the ultrasound module **104**) is positioned above the radial artery **204**. In particular, the ultrasound module **104** is positioned off-center towards the thumb on the portion of the first wristband **106** that contacts the user's volar wrist **202**. At the radial artery, measurements of blood flow, heart rate, blood pressure, blood vessel diameter, and pulse wave velocity may be taken based on ultrasound data collected by the ultrasound-on-a-chip device **110** from the radial artery.

[0072] FIG. **3** shows another example of an apparatus **300** for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein. The apparatus **300** is wearable by a user around the user's wrist. In FIG. **3**, the apparatus **300** is shown disassembled. The following description discusses differences between the apparatus **300** and the apparatus **100**.

[0073] The apparatus **300** lacks the ultrasound module **104**. The ultrasound-on-a-chip device **110** is located in the primary module **102**. The primary housing element **124** includes the acoustic lens **146**, and the first wristband **106** lacks internal conductors to interface with an ultrasound module. The coupling strip **148** is coupled to the surface of the primary housing element **124** that faces the user's wrist. The ultrasound-on-a-chip device **110** and may be able to collect ultrasound data from various blood vessels (e.g., besides the radial artery, such as the anterior interosseous artery) depending on how the primary module **102** is worn (e.g., whether the primary module **102** is worn on the dorsal or volar wrist. Ultrasound data collected from veins may be used, for examine, to examine deep vein thrombosis, blockages to blood flow (such as clots), narrowing of vessels, tumors and congenital vascular malformations, reduced or absent blood flow, and greater than normal blood flow.

[0074] FIG. **4** shows another example of an apparatus **400** for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein. The apparatus **400** is configured as a wristband that the user can physically couple to a wristband of his or her personal smartwatch module and electrically connect to the smartwatch module. In some embodiments, the apparatus **400** may be configured as an interchangeable wristband that the user can couple (physically and electrically) to his or her personal smartwatch module directly, replacing the smartwatch's original wristband. In FIG. **4**, the apparatus **400** is shown disassembled. The following description discusses differences between the apparatus **400** and the apparatus **100**.

[0075] The apparatus **400** lacks the primary module **102**. The ultrasound module **104** includes a printed circuit board (PCB) **420**. On the PCB **420** is the processing circuitry **112** and the memory circuitry **114**. In contrast to apparatus **300**, the ultrasound module **304** has internal processing circuitry **312** and memory circuitry **315**, because the smartwatch to which the apparatus **300** is intended to be coupled may not have processing and memory circuitry capable of interfacing with the ultrasound-on-a-chip device **110** and processing ultrasound data.

[0076] The first wristband **106** includes conductors **136** extending through the first wristband **106** that connect to a connection cable **458** at the second end portion **154** of the first wristband **106**. The connection cable **458** exits from the first wristband **106** through an opening **460** in the first wristband **106** and has a male connector **462** configured to connect to a complementary female port on the user's personal smartwatch. Examples of plugging the male connector **462** into the smartwatch will be illustrated further in FIG. **7**. In some embodiments, the apparatus **400** may include a plate configured to screw into the user's personal smartwatch at the complementary female port and to prevent the male connector **462** from being removed from the female port on the smartwatch during use of the apparatus **400**.

[0077] The conductors **136** and the connection cable **458** electrically connect the ultrasound module **104** to the user's smartwatch. Accordingly, the ultrasound module **104** may use components within the user's smartwatch, and the ultrasound module **104** does not itself need to include these components. For example, in FIG. **400**, the ultrasound module **104** is configured to draw power from the smartwatch's battery to power the ultrasound-on-a-chip device **110** and circuitry on the PCB **420**. Additionally, the ultrasound module **104** is configured to transmit through the conductors **136** and the connection cable **458** data (e.g., ultrasound data, ultrasound images, calculations based on ultrasound images) to communication circuitry within the smartwatch for wireless transmission to an external device, such as external host device, workstation, or server. The user's personal smartwatch may run an application ("app") configured to interface with the ultrasound module **104**. The connection cable **458** may be any type of connection cable, such as a lightning connector or a mini-USB connector.

[0078] The apparatus **400** may be configured to couple along its longitudinal axis to the longitudinal axis of the smartwatch's wristband. The apparatus **400** may couple to the wristband of the user's personal smartwatch using any coupling means. For example, the first wristband **106** may include pins configured to be inserted into holes in the wristband of the user's smartwatch. As other examples, the apparatus **400** may couple to the wristband of the user's smartwatch with screws, hook and loop fastening (e.g., Velcro), adhesive, a snap, a slot and groove, one or more magnets. In embodiments where the apparatus **400** couples directly to the smartwatch module, replacing the smartwatch's wristband, the apparatus **400** may be configured to couple to the smartwatch module through any coupling means, such as a clip, a snap, a screw, an adhesive, magnetism, hook and loop fastening (e.g., Velcro), an interlocking fit, etc. In some embodiments, the smartwatch module may include pairs of lugs at each of its ends, with spring bars bridging each pair of lugs, and the first and second wristbands **106** and **108** may loop around the spring bars.

[0079] In some embodiments, the ultrasound module **104** has an internal battery and is not configured to draw on the battery in the user's smartwatch. In some embodiments, the ultrasound module **104** has communication circuitry internal to the ultrasound module **104** and is not configured to use communication circuitry in the user's smartwatch. In some embodiments, the ultrasound module **104** may transmit ultrasound data collected by the ultrasound-on-a-chip device **110** to processing circuitry in the user's smartwatch that is configured to reconstruct the ultrasound data into ultrasound images (which may be two-dimensional images or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, three-dimensional images), and may receive control signals from control circuitry in the user's smartwatch. For example, an application on the user's smartwatch may include instructions for the processing circuitry to reconstruct ultrasound data into ultrasound images and instructions for the control circuitry to output control signals for the ultrasound-on-a-chip device **110**. In such embodiments, the ultrasound module **104** may lack the processing circuitry **112** and/or the memory circuitry **114**.

[0080] FIG. **5** shows another example of an apparatus **500** for an ultrasound-on-a-chip device configured to be worn on a user's wrist, in accordance with certain embodiments disclosed herein. The apparatus **500** is configured as a wristband that the user can physically couple to a wristband of his or her personal wrist device, which may be a standard analog watch module, a standard digital watch module, or a smartwatch. In some embodiments, the apparatus **500** may be configured as an interchangeable wristband that the user can couple (physically and electrically) to his or her personal wrist device, replacing the wrist device's original wristband. In FIG. **5**, the apparatus **500** is shown disassembled. The following description discusses differences between the apparatus **500** and the apparatus **400**.

[0081] The ultrasound module **104** includes a printed circuit board (PCB) **520** and a battery **530**. On the PCB **520** is the processing circuitry **112**, the memory circuitry **114**, the communication circuitry **116**, and the power management circuitry **118**. Accordingly, in contrast to apparatus **400**, the ultrasound module **104** does not need to use components (e.g., communication circuitry, battery) outside of the ultrasound module **104** (e.g., in the user's personal smartwatch to which the apparatus **500** is coupled) because these components are already include internally in the ultrasound module **104**. Therefore, the first wristband **106** lacks communication means (e.g., conductors internal to the first wristband **106** and a connection cable extending from the first wristband **106**) to interface with the user's personal wristwatch. The battery **530** may be any type of battery, such as a button cell battery (e.g., a zinc air cell battery, type PR48, size A13), a lithium ion battery, or a lithium polymer battery. The battery **530** may be rechargeable. Examples of coupling the apparatus **500** to the wristband of the user's wrist device will be illustrated further in FIGS. **6**A-**6**G.

[0082] FIGS. **6**A-**6**G show examples of an apparatus for an ultrasound-on-a-chip device configured to be bound to a user's wrist when the apparatus is assembled and worn. FIG. **6**A shows the assembled apparatus **500** and a user's personal wrist device **600** prior to coupling the apparatus **500** to the wrist device **600**. The apparatus **500** includes the ultrasound module **104**, the first wristband **106**, the ultrasound housing module **128**, and the acoustic lens **146**. The coupling strip **148** is not shown in FIG. **6**A. The wrist device **600** includes a primary module **602**, a first wristband **606**, and a second wristband **608**. The primary module includes a button that will be discussed further in relation to FIG. **12**. FIG. **6**B shows the apparatus **500** coupled to the wrist device **600**. In particular, the first wristband **106** is coupled along its longitudinal axis to the first wristband **606** along its longitudinal axis. The apparatus **500** is oriented such that the ultrasound module **104** is distal from the primary module **602** of the wrist device **600**. In this orientation, the ultrasound module **104** may be positioned over the radial artery when the wrist device **600** is worn with the primary module **602** on the dorsal wrist. FIGS. **6**C and **6**D show the apparatus **500** coupled to the wrist device **600** while being worn. FIG. **6**C shows the dorsal wrist **200** and FIG. **6**D shows the volar wrist **202**. The apparatus **500** is oriented in the orientation of FIG. **6**B, namely with the apparatus **500** oriented such that the ultrasound module **104** is distal from the primary module **602** of the wrist device **600**. The wrist device **600** is worn with the primary module **602** on the dorsal wrist so that the ultrasound module **104** may be positioned over the radial artery. FIG. **6**E shows a side view of the apparatus **500** coupled to the wrist device **600** in the orientation of FIG. **6**B, namely with the apparatus **500** oriented such that the ultrasound module **104** is distal from the primary module **602** of the wrist device **600**. FIG. **6**F shows the apparatus **500** coupled to the wrist device **600** in a different orientation than in FIG. **6**B. In particular, the apparatus **500** is coupled to the first wristband **606** such that the ultrasound module **104** is proximal to the primary module **602** of the wrist device **600**. In this orientation, the ultrasound module **104** may be positioned over the radial artery when the wrist device **600** is worn with the primary module **602** on the volar wrist. FIG. **6**G shows the apparatus **500** coupled to the wrist device **600** while being worn. The apparatus **500** is oriented in the orientation of FIG. **6**F, namely with the apparatus **500** oriented such that the ultrasound module **104** is proximal to the primary module **602** of the wrist device **600**. The wrist device **600** is worn with the primary module **602** on the volar wrist **202** so that the ultrasound module **104** may be positioned over the radial artery.

[0083] FIG. **7** shows an example of the apparatus **400** when electrically coupled to the user's personal wrist device **600**. The wrist device **600** further includes a female port **712**. The apparatus **400** includes the connection cable **458** that exits from the first wristband **106** through the opening **460** in the first wristband **106**. The connection cable **458** has the male connector **462**, which is plugged into the complementary female port **712** in the wrist device **600**. In some embodiments, the connection cable **458** includes a female connector instead of, or in addition to, the male connector **462**, and the wrist device **600** includes a male port (instead of or in addition to the female port **712**) into which the female connector plugs. In some embodiments, a clasp on the wristband of the wrist device **600** has pins to which the connector (male or female) on the connection cable **458** may electrically couple.

[0084] FIGS. **1**-**7** show the ultrasound module **104** positioned on the apparatuses shown therein to face the user's wrist when the apparatuses are worn. In some embodiments, the ultrasound module is positioned on the apparatus to face away from the user's wrist when the apparatus is worn. For example, the ultrasound module **104** may be positioned on the outer surface of a wristband. Accordingly, a user may be able to move his or her wrist to place the ultrasound module **104** such that the ultrasound module **104** faces a portion of his or her body (e.g., heart, abdomen, uterus, etc.) in order to collect ultrasound data from that portion of the body. In such embodiments, the display screen **122** on the apparatus may display an ultrasound image/data generated based on collected ultrasound data while the user is holding the ultrasound module **104** at the desired location. For example, in the case of positioning the ultrasound module **104** over the heart, the display screen **122** may show an ultrasound image of the heart and/or display medical parameters such as ejection fraction, fractional shortening, ventricle diameter, ventricle volume, end-diastolic volume, end-systolic volume, cardiac output, stroke volume, intraventricular septum thickness, ventricle wall thickness, and pulse rate. The ultrasound image displayed on the display screen **122** may be a two-dimensional image or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, a representation of a three-dimensional image. In some embodiments, the display screen **122** may display instructions for guiding the user to position the ultrasound module **104** at the desired location while the user is moving his or her wrist. For further description of guiding a user in moving an ultrasound-on-a-chip device to a required position, see U.S. patent application Ser. No. 15/626,423 titled "AUTOMATIC IMAGE ACQUISITION FOR ASSISTING A USER TO OPERATE AN ULTRASOUND DEVICE," filed on Jun. 19, 2017 (and assigned to the assignee of the instant application) and published as U.S. Pat. Pub. No. 2017-0360401 A1, which is incorporated by reference herein in its entirety.

[0085] In some embodiments, instead of or in addition to using a wristband to bind the ultrasound-on-a-chip device to the user's wrist, other means such as adhesives or clamps may be used.

[0086] Further description of data collection and processing with any of the apparatuses described herein are presented hereinafter in the section entitled "Example Data Collection and Processing." Further description of system operations involving any of the apparatuses described herein are presented hereinafter in the section entitled "Example System Functions." Further description of processes performed with any of the apparatuses described herein are presented hereinafter in the section entitled "Example Processes." Further description of additional features that may be included in any of the apparatuses described herein are presented hereinafter in the section entitled "Example Apparatus Features."

Example Coupling Strips

[0087] As discussed above, the coupling strip **148** is configured to reduce the air gap between the ultrasound module **104** and the user's wrist. In particular, the coupling strip **148** is configured to couple to the acoustic lens **146** and establish acceptable impedance matching coupling for ultrasound signal transmission and reception. In some embodiments, therefore, the coupling strip **148** may be considered an impedance matching strip, or an impedance matching coupler. To reduce the air gap between the ultrasound module **104** and the user's wrist, the coupling strip **148** may be configured to be flexible such that the coupling strip **148** conforms to the irregular surface of the user's wrist.

[0088] In some embodiments, the coupling strip **148** includes a solid material and liquid absorbed within the solid material to increase the flexibility of the coupling strip **148**. In some embodiments, the liquid includes a hydrophilic solution. In such embodiments, the coupling strip **148** may be configured to be refreshed with addition of water to the coupling strip **148** to reduce drying of the coupling strip and to maintain acceptable conformity of the coupling strip to the user's wrist. For example, the coupling strip **148** may be refreshed with water in a shower, by dipping the coupling strip **148** in water, or by running water over the coupling strip **148**. In some embodiments, the coupling strip **148** includes a porous sponge that stores water and releases the water slowly, and can be refreshed with addition of water to the porous sponge. In some embodiments, the liquid includes a hydrophobic solution. In such embodiments, the coupling strip **148** is configured to be refreshed with oil, gel, or another hydrophobic consumable to reduce drying of the coupling strip **148** and maintain acceptable conformity of the coupling strip **148** to the user's wrist. In some embodiments, the apparatus (in particular, the ultrasound module **104** and the primary module **102**) is configured to be waterproof so that if, for example, the ultrasound module **104** and the primary module **102** become wet while the coupling strip **148** is being refreshed, the ultrasound module **104** and the primary module **102** continue to function. For example, the ultrasound housing element **128** and the primary housing elements **124** and **126** may be waterproof housings.

[0089] In some embodiments, the coupling strip **148** is configured to be replaceable. For example, the coupling strip **148** may include an adhesive layer between the coupling strip **148** and the surface of the ultrasound module **104**, and to replace the coupling strip **148**, a user may peel the coupling strip **148** from the ultrasound module **104** and attach another coupling strip **148** to the ultrasound module **104**.

[0090] Materials used in the coupling strip **148** may include a rubber material (which may be water-absorbent), a rubberized coating material, a silicone-based material, a gel-based material, an agar-based material, and a room-temperature-vulcanization silicone material. In some embodiments, the coupling strip **148** includes a rubbery silicone material that is sufficiently flexible to maintain acceptable contact with the user's wrist without requiring replacement. In some embodiments, the coupling strip **148** may include a spongy material that is capable of absorbing liquid and being refreshed with water (e.g., by splashing the coupling strip **148** with water, by dipping the coupling strip **148** in water, by taking a shower or bath, and/or by cleaning the coupling strip **148** with water) in order to maintain conformity of the coupling strip **148** to the user's wrist. In such embodiments, the spongy material may release the absorbed liquid at an acceptably low rate such that the coupling strip **148** requires refreshing at an acceptably low frequency.

[0091] In some embodiments, the ultrasound module **104** lacks a coupling strip, and the user may wet the wrist area (e.g., by dipping the wrist in water or running water over the first) prior to data collection to establish proper impedance matching coupling for ultrasound signal transmission and reception. Accordingly, the ultrasound module **104** can operate ultrasound gel-less. In such embodiments, the ultrasound module is configured to be waterproof. For example, the ultrasound housing element **128** may be a waterproof housing.

[0092] FIG. **8** shows an example in which the ultrasound module **104** includes reservoirs for refreshing the coupling strip **148** in accordance with certain embodiments described herein. In FIG. **8**, the ultrasound module **104** includes the ultrasound-on-a-chip device **110**, reservoirs **802** and **804**, and cover **806**. The reservoir **802** includes a valve **808** and a door **810**. The reservoir **804** includes a valve **812** and a door **814**. The ultrasound housing element **128** includes openings **816** and **818**.

[0093] The ultrasound housing element **128** and the first wristband **106** enclose the reservoirs **802** and **804**, the ultrasound-on-a-chip device **110**, and the cover **806**. The cover **806**, which is hollow, covers the ultrasound-on-a-chip device **110** and, together with the ultrasound housing element **128**, form an enclosure for the ultrasound-on-a-chip device **110**. The coupling strip **148** is attached to the surface of the ultrasound housing element **128**.

[0094] The valve **808** opens into the opening **816** and the valve **812** opens into the opening **818**. The reservoirs **802** and **804** contain liquid or gel. The valve **808** is configured to release liquid or gel from the reservoir **802**, through the opening **816**, and into the coupling strip **148**. The valve **812** is configured to release liquid or gel from the reservoir **802**, through the opening **818**, and into the coupling strip **148**.

[0095] The liquid or gel in the reservoirs **802** and **804** may be hydrophilic or hydrophobic. As discussed above, the reservoirs **802** and **804** are configured to refresh the coupling strip **148** with the liquid or gel. In particular, the reservoirs **802** and **804** are configured to add the liquid or gel to the coupling strip **148**, which may absorb the liquid or gel. Adding the liquid or gel to the coupling strip **148** may help to reduce drying of the coupling strip **148** and maintain acceptable conformity of the coupling strip **148** to the user's wrist.

[0096] The valves **808** and **812** may be mechanically or electrically activated. In some embodiments, the user may trigger the valves **808** and **812** to release liquid or gel from the reservoirs **802** and **804** into the coupling strip **148**. In some embodiments, the user may apply mechanical pressure to the ultrasound module **104**, either by directly applying mechanical pressure to the ultrasound module **104** or by applying mechanical pressure to another element to which the ultrasound module **104** is coupled (e.g., the first wristband **106**), and the mechanical pressure may trigger the valves **802** and **812** to release at least a portion of the liquid or gel from the reservoirs **802** and **804** into the coupling strip **148**. For example, mechanical pressure applied to the ultrasound module **104** may compress the reservoirs **802** and **804** and cause them to expel liquid or gel through the valves **808**

and **812**. In some embodiments, the user may apply the mechanical pressure to recesses in the first wristband **106**. In some embodiments, the user may place his or her fingers over sensors on the first wristband **106** and the sensors may transmit an electrical signal to the valves **808** and **812** to release the liquid or gel from the reservoirs **802** and **804** into the coupling strip **148**. In some embodiments, the user may activate a button (e.g., a mechanical button or a virtual button) and activation of the button may transmit an electrical signal to the valves **808** and **812** to release liquid or gel from the reservoirs **802** and **804** into the coupling strip **148**.

[0097] In some embodiments, processing circuitry may be configured to automatically trigger the valves **808** and **812** to release the liquid or gel from the reservoirs **802** and **804** into the coupling strip **148**. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server. For example, the processing circuitry may be configured to trigger the valves **808** and **812** to release the liquid or gel from the reservoirs **802** and **804** into the coupling strip **148** periodically. In some embodiments, the processing circuitry may be configured to trigger the valves **808** and **812** to release the liquid or gel from the reservoirs **802** and **804** into the coupling strip **148** based on detecting that the coupling strip **148** needs to be refreshed with liquid or gel. In some embodiments, detecting that the coupling strip **148** needs to be refreshed with liquid or gel includes determining whether a current amount of liquid or gel associated with the coupling strip **148** is below a threshold amount. In some embodiments, to detect that the coupling strip **148** needs to be refreshed with liquid or gel **424**, the processing circuitry may be configured to analyze (continuously or periodically) ultrasound data collected by the ultrasound-on-a-chip device **110** and determine whether the collected ultrasound data shows signs (e.g., decreased quality of images) that the coupling strip **148** is conforming poorly to the user's wrist. In some embodiments, to detect that the coupling strip **148** needs to be refreshed with liquid or gel, the processing circuitry may be configured to receive signals from a moisture sensor in or adjacent to the coupling strip **148** indicating that the moisture level in or adjacent to the coupling strip **148** is below a threshold moisture level. In some embodiments, the processing circuitry may be configured to use other sensors to detect that the coupling strip **148** needs to be refreshed, such as capacitive sensors or skin conductivity sensors. In some embodiments, the processing circuitry may detect that the coupling strip **148** needs to be refreshed with liquid or gel and generate a notification that the user needs to refresh the coupling strip **148** with liquid or gel. In some embodiments, the notification may be displayed on the display screen **122**. In some embodiments, the notification displayed on the display screen **122** may include text, an image, and/or a video. In some embodiments, the notification may include audio output from the primary module **102**.

[0098] The door **810** can be opened to reveal an inside cavity of the reservoir **802** and enable refilling of the reservoir **802** with liquid or gel. The door **814** can be opened to reveal an inside cavity of the reservoir **804** and enable refilling of the reservoir **804** with liquid or gel. To refill the reservoirs **802** and **804**, a user may remove the ultrasound housing element **128** from the first wristband **106**, thereby revealing the reservoirs **802** and **804**. The user may open the doors **810** and **814** and then run liquid or gel over the reservoirs **802** and **804**, dip the reservoirs **802** and **804** into liquid or gel, or take a shower in order to add liquid to the reservoirs **802** and **804**. The ultrasound-on-a-chip device **110** may be protected from damage during the refilling process by the cover **806**, which forms an enclosure for the ultrasound-on-a-chip device **110**, and may be waterproof. In some embodiments, the reservoirs **802** and **804** may be removable in order to allow the user to refill the reservoirs **802** and **804** without risking damage to the ultrasound-on-a-chip device **110**. In some embodiments, the door **810** may be any type of input port.

[0099] In some embodiments, the reservoirs **802** and **804** may be coupled together as a single part, and/or may be connected together such that the reservoirs **802** and **804** constitute one reservoir. In some embodiments, one of the reservoirs **802** and **804** is absent, or there may be more than two reservoirs. In some embodiments, tubes may connect the reservoirs **802** and **804** to the coupling strip **148**. In such embodiments, the reservoirs **802** and **804** may not be located adjacent to the coupling strip **148**. In embodiments in which the ultrasound-on-a-chip device **110** is located within the primary module **102**, the reservoirs **802** and **804** may be located within the primary module **102** as well. In some embodiments, the cover **806** may be absent. In some embodiments, other means for refilling the reservoirs **802** and **804** may be included, such as valves.

[0100] Other embodiments of reservoirs for refreshing the coupling strip **148** with liquid or gel are possible, such as reservoirs without valves. For example, in some embodiments, the reservoir includes an amorphous surface from which gel can be squeezed out like a sponge. In some embodiments, the reservoir includes a sponge-like material coupled through a restriction to the coupling strip **148** such that the reservoir may slowly release liquid or gel to refresh the coupling strip **148**.

Example Apparatus Features

[0101] FIG. **9** shows an example of recesses incorporated into an ultrasound module in accordance with certain embodiments disclosed herein. FIG. **9** shows the ultrasound module **104** and the first wristband **106**. The ultrasound module **104** is coupled to the first wristband **106** and incorporates inward recesses **902** and **904** on the outer surface of the ultrasound module **104** (i.e., the surface that faces away from the user's wrist). A sensor **906** is located within recess **902** and a sensor **908** is located within recess **904**. The coupling strip **148** (not visible in FIG. **9**) is coupled to the opposite surface of the ultrasound module **104** as the recesses **902** and **904**. In some embodiments, a user may apply mechanical pressure with his or her fingers to the recesses **902** and **904**. In such embodiments, the sensors **906** and **908** may be configured to detect the application of the mechanical pressure. For example, the sensors **906** and **908** may be pressure sensors configured to detect mechanical pressure on the sensors **906** and **908**. As another example, the sensors **906** and **908** may be light sensors configured to detect reduction in light incident on the sensors **906** and **908** due to placement of the user's fingers on the sensors **906** and **908** when applying mechanical pressure. As another example, the sensors **906** and **908** may be temperature sensors configured to detect an increase in temperature of the sensors **906** and **908** due to placement of the user's fingers on the sensors **906** and **908** when applying mechanical pressure. In some embodiments, upon detection of the application of mechanical pressure by the sensors **906** and **908**, processing circuitry may be configured to trigger the ultrasound-on-a-chip device **110** in the ultrasound module **104** to collect ultrasound data. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server.

[0102] In some embodiments, the coupling strip **148** may be configured such that it does not establish acoustic coupling between the ultrasound-on-a-chip device **110** and the user's wrist during normal use. In such embodiments, the user may apply light mechanical pressure to the recesses **902** and **904**, and the mechanical pressure may cause the coupling strip **148** opposite the recesses **902** and **904** to establish acoustic coupling between the ultrasound-on-a-chip device **110** and the user's wrist. Accordingly, when the user applies the mechanical pressure, the coupling strip **148** may establish acceptable coupling between the ultrasound module **104** and the user's wrist and enable the ultrasound-on-a-chip device **110** to collect ultrasound data of acceptable quality. In some embodiments, the ultrasound-on-a-chip device **110** may collect ultrasound data (continuously or at intervals), and processing circuitry, such as processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server, may later analyze the collected ultrasound data to detect ultrasound data collected when the mechanical pressure was not applied and delete that ultrasound data. In some embodiments, the ultrasound-on-a-chip device **110** may collect ultrasound data (continuously or at intervals), and the processing circuitry may later analyze the collected ultrasound data to detect ultrasound data collected when the mechanical pressure was applied and transmit that ultrasound data for storage in memory (e.g., memory circuitry **114**, or memory in an external host device, workstation, or server). In such embodiments, to detect ultrasound data collected when mechanical pressure was applied and when mechanical pressure was not applied, the processing circuitry may calculate a measure of quality of the ultrasound data. In this embodiment, the sensors **906** and **908** may be absent. In some embodiments, data from the sensors **906** and **908** may be temporally correlated with ultrasound data (e.g., through the use of timestamps), and the processing circuitry may determine from the sensor data which ultrasound data was collected during periods with and without application of mechanical pressure. It may be helpful for the coupling strip **148** to not establish acoustic coupling between the ultrasound-on-a-chip device **110** and the user's wrist during normal use to avoid discomfort (e.g., due to constant rubbing of the coupling strip **148** against the user's wrist and difficulty in removing the coupling strip **148** from the user's wrist due to adhesion).

[0103] The recesses **902** and **904** may be incorporated into any of the apparatuses discussed herein. In some embodiments, the recesses **902** and **904** may not be located on the ultrasound-on-a-chip device **110**. For example, the recesses **902** and **904** may be incorporated into the primary module **102** or into the first wristband **106**. In some embodiments, there may be one recess or more than two recesses, the recesses **902** and **904** may be absent, and/or the sensors **906** and **908** may not be located in the recesses **902** and **904** and may detect the application of mechanical pressure by detecting signals (e.g., pressure signals) elsewhere in the apparatus. In some embodiments, applying mechanical pressure to the recesses **902** and **904** may compress reservoirs (e.g., reservoirs **802** and **804**) within the ultrasound module **104** and cause them to expel liquid or gel to refresh the coupling strip **148**.

[0104] FIG. **10** shows an example of a mechanical button incorporated into an ultrasound module in accordance with certain embodiments disclosed herein. FIG. **10** shows the ultrasound module **104** and the first wristband **106**. The ultrasound module **104** is coupled to the first wristband **106** and incorporates a mechanical button **1002** on the outer surface of the ultrasound module **104** (i.e., the surface that faces away from the user's wrist). In some embodiments, upon detection of activation of the mechanical button **1002** (e.g., application of mechanical pressure to the mechanical button **1002**), processing circuitry, such as processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server, may be configured to trigger the ultrasound-on-a-chip device **110** to collect ultrasound data. In some embodiments, applying mechanical pressure to the mechanical button **1002** may trigger reservoirs (e.g., reservoirs **802** and **804**) within the ultrasound module **104** to release liquid or gel to refresh the coupling strip **148**. In some embodiments, there may be more than one mechanical button **1002**, or the mechanical button **1002** may be located on the first wristband **106**.

[0105] FIG. **11** shows an example of a virtual button on a display screen of a primary module in accordance with certain embodiments disclosed herein. FIG. **11** shows the primary module **102**. The primary module **102** includes the display screen **122** which displays a virtual button **1102**. In some embodiments, upon detecting that the virtual button **1102** has been activated (e.g., touched), processing circuitry, such as processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server, may be configured to trigger the ultrasound-on-a-chip device **110** to trigger the ultrasound-on-a-chip device **110** to collect ultrasound data. In some embodiments, activating the virtual button **1102** may cause the processing circuitry to trigger reservoirs (e.g., reservoirs **802** and **804**) within the ultrasound module **104** to release liquid or gel to refresh the coupling strip **148**. The virtual button **1102** may be located on any portion of the display screen **122**.

[0106] FIG. **12** shows an example of a mechanical button on a primary module in accordance with certain embodiments disclosed herein. FIG. **12** shows the primary module **102** which includes a mechanical button **1202** in a side wall of the primary module **102**. In some embodiments, upon detecting that the mechanical button **1202** has been activated (e.g., pressed), processing circuitry, such as processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server, may be configured to trigger the ultrasound-on-a-chip device **110** to trigger the ultrasound-on-a-chip device **110** to collect ultrasound data. In some embodiments, activating the mechanical button **1202** may cause the processing circuitry to trigger reservoirs (e.g., reservoirs **802** and **804**) within the ultrasound module **104** to release liquid or gel to refresh the coupling strip **148**. The mechanical button **1202** may be located on any portion of the primary module. One or more of the recesses **902** and **904**, mechanical button **1002**, virtual button **1102**, and mechanical button **1202** may all be included in the apparatus.

Example Data Collection and Processing

[0107] In some embodiments, processing circuitry may be configured to process and/or analyze ultrasound images (which may be two-dimensional images or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, three-dimensional images) reconstructed from ultrasound data collected by the ultrasound-on-a-chip device **110**. In some embodiments, the processing circuitry may be configured to analyze the ultrasound data itself. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server. The processing circuitry may trigger ultrasound data collection by the ultrasound-on-a-chip device **110** and/or analyze ultrasound data/images at a single time, or at time intervals (e.g., every second, every minute, every hour, four times per day, three times per day, two times per day, one a day, or any suitable time interval), or continuously. In some embodiments, the processing circuitry may use deep learning models to analyze ultrasound data/images. In such embodiments, the processing circuitry may be configured to retrieve, from a server, ultrasound data/images from other ultrasound-on-a-chip devices and to use the ultrasound data/images from the other ultrasound-on-a-chip devices when training the deep learning models. For further discussion of deep learning models, see U.S. patent application Ser. No. 15/626,423 titled "AUTOMATIC IMAGE ACQUISITION FOR ASSISTING A USER TO OPERATE AN ULTRASOUND DEVICE.".

[0108] In some embodiments, the processing circuitry may reconstruct ultrasound data collected from the wrist to form an ultrasound image (which may be two-dimensional images or, when the ultrasound-on-a-chip device **110** includes a two-dimensional array, three-dimensional images). The processing circuitry may analyze the ultrasound image to perform segmentation of the ultrasound image to identify contours of anatomical structures displayed in the ultrasound image, such as blood vessels within the wrist (e.g., the radial artery, ulnar artery, and median artery). The processing circuitry may perform various anatomical and physiological measurements using the ultrasound image, such as measuring the diameter of a blood vessel displayed in the ultrasound image; measuring the average, minimum, and/or maximum of the diameter over time of a blood vessel displayed in the ultrasound image; measuring blood pressure; measuring velocity of blood flow within a blood vessel displayed in the ultrasound image; producing a map of velocity of blood flow within a blood vessel; producing a time trace of heart rate; and producing a time trace of velocity of blood flow within a blood vessel displayed in the ultrasound image.

[0109] In some embodiments, the ultrasound-on-a-chip device **110** may be configured to perform Doppler ultrasound imaging, which may include pulsed wave Doppler imaging. The processing circuitry may be configured to form a color Doppler ultrasound image based on ultrasound data collected with pulsed wave Doppler imaging, and may also be configured to form a spectral Doppler velocity trace of blood flow within a blood vessel based on ultrasound data. In some embodiments, the processing circuitry may be configured to measure average velocity, maximum velocity, minimum velocity, and/or acceleration of blood flow within a blood vessel based on ultrasound data collected with Doppler ultrasound imaging over a period of time. In some embodiments, the processing circuitry may be configured to measure blood volume flowing within a blood vessel per heart pulse. In some embodiments, the processing circuitry may be configured to produce a time trace based on M-mode ultrasound imaging.

[0110] In some embodiments, the ultrasound-on-a-chip device **110** may be configured to perform ultrasound elastography (e.g., shear wave elasticity imaging, quasistatic elastography, acoustic radiation force impulse imaging, shear imaging, and transient elastography) and the processing circuitry may be configured to produce data and/or form an image based on the ultrasound data collected. In some embodiments, the data produced from the ultrasound elastography may include measurements of elasticity of a blood vessel wall. In some embodiments, measurement of elasticity of a blood vessel wall may be combined with measurement of blood volume within the blood vessel to calculate blood pressure.

[0111] In some embodiments, the processing circuitry may be configured to calculate pulse wave velocity (PWV) in a blood vessel based on ultrasound data from the blood vessel. PWV may represent a measure of arterial stiffness, which in some cases has been proven to be a predictor of cardiovascular disease. PWV may represent a noninvasive method for measuring arterial blood pressure waveforms, which may contain information for diagnosing and treating cardiovascular disease. In some embodiments, the processing circuitry may be configured to calculate PWV in the blood vessel periodically over time and to output the evolution of PWV calculations over time.

[0112] In some embodiments, the processing circuitry may calculate PWV at a single arterial site based on volumetric flow rate and cross-sectional area measured at the arterial site. The arterial site may be a site along on an artery in the wrist, such as the radial artery, ulnar artery, and median artery. In such embodiments, the processing circuitry may calculate cross-sectional area by receiving, from the ultrasound-on-a-chip device **110** positioned at the wrist, data from a transverse ultrasound scan of the blood vessel in the wrist, measuring the diameter of the blood vessel on an ultrasound image resulting from the transverse scan, and calculating the cross-sectional area from the measured diameter by assuming axisymmetrical geometry. The processing circuitry may calculate volumetric flow rate by multiplying cross-sectional area by spatial mean velocity. The processing circuitry may calculate spatial mean velocity by receiving, from the ultrasound-on-a-chip device **110** positioned at the wrist, pulsed Doppler ultrasound imaging of the blood vessel in the wrist, where the blood vessel is insonated at an angle relative to the longitudinal axis of the blood vessel. The angle may be, for example, <10 degrees, 10 degrees, 20 degrees, 30 degrees, 40 degrees, 50 degrees, 70 degrees, 80 degrees, >80 degrees, or any other suitable angle. In some embodiments, to perform the pulsed Doppler ultrasound imaging at an angle relative to the longitudinal axis of the blood vessel, the ultrasound-on-a-chip device **110** may perform a transverse ultrasound scan with an elevational steer towards the blood vessel. In some embodiments, to perform the pulsed Doppler ultrasound imaging at an angle relative to the longitudinal axis of the blood vessel, the ultrasound-on-a-chip device **110** may perform a longitudinal ultrasound scan steered at an angle towards the blood vessel. PWV may be calculated from the volumetric flow rate and cross-sectional area measurements by measuring the slope of a linear portion of a volumetric flow rate vs. cross-sectional area plot. Furthermore, blood pressure may be estimated based on PWV and the cross-sectional area of the blood vessel. As discussed above, PWV is a measure of arterial stiffness, or conversely, arterial elasticity, and thus other methods for measuring elasticity using ultrasound imaging may be used to estimate blood pressure. Other methods for measuring elasticity using ultrasound may include, for example, shear wave elasticity imaging, quasistatic elastography, acoustic radiation force impulse imaging, shear imaging, and transient elastography. For further description of measuring PWV based on volumetric flow rate and cross-sectional area measured at an arterial site, and estimating blood pressure using PWV/elasticity, see Seo, Joohyun, et al. "Noninvasive arterial blood pressure waveform monitoring using two-element ultrasound system." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 62.4 (2015): 776-784, which is hereby incorporated by reference herein in its entirety. In some embodiments, the ultrasound-on-a-chip device **110** may perform a bi-planar acquisition, where the diameter of the blood vessel is measured using transverse scanning and the spatial mean velocity is measured using longitudinal scanning. When the ultrasound-on-a-chip device **110** includes a two-dimensional array of ultrasound transducers, the ultrasound-on-a-chip device **110** may be configured to perform both transverse ultrasound scanning and longitudinal ultrasound scanning, with or without azimuthal and/or elevational steering, without requiring rotation of the ultrasound-on-a-chip device **110** relative to the user's wrist.

[0113] In some embodiments, the processing circuitry may calculate PWV by receiving, from the ultrasound-on-a-chip device **110** positioned at the wrist, pulse wave imaging of blood vessel. For example, the blood vessel may be an artery in the wrist, such as the radial artery, ulnar artery, and median artery, or a vein in the wrist. In such embodiments, the processing circuitry may calculate cross-sectional area by receiving, from the ultrasound-on-a-chip device **110** positioned at the wrist, longitudinal ultrasound scanning at an acceptably high frame rate for detecting a pulse wave. The frame rate may be, for example, 500 Hz, 1000 Hz, 1500 Hz, 2000 Hz, or any suitable frame rate. The processing circuitry may analyze interframe axial displacements of the blood vessel to obtain velocities of the blood vessel wall, and PWV can be calculated based on the obtained velocities. For further description of measuring PWV using pulse wave imaging, see Luo, Jianwen, Ronny X. Li, and Elisa E. Konofagou. "Pulse wave imaging of the human carotid artery: an in vivo feasibility study." *IEEE transactions on ultrasonics, ferroelectrics, and frequency control* 59.1 (2012): 132-181, which is hereby incorporated by reference herein in its entirety.

[0114] FIG. **13** shows an illustration of performing a transverse ultrasound scan of a blood vessel **1304** with a two-dimensional array of ultrasound transducers **1302** in accordance with certain embodiments disclosed herein. The blood vessel **1304** has a longitudinal axis **1306**. The two-dimensional array of ultrasound transducers **1302** includes a set of ultrasound transducers **1308**. In FIG. **13**, the set of ultrasound transducers **1308** represents a column of the two-dimensional array of ultrasound transducers **1302**. The set of ultrasound transducers **1308** is configured to perform a transverse ultrasound scan of the blood vessel **1304** by producing an ultrasound beam profile **1314** along a plane that is orthogonal to the longitudinal axis **1306** of the blood vessel **1304**. It will be appreciated that the ultrasound beam profile **1314** (and the ultrasound beam profiles discussed in FIGS. **14-17**) is a conceptual representation, and is shown as an approximation of multiple (e.g., up to hundreds of) transmit events that may overlap in space and may progressively advance in one direction and are used to form a cross-sectional ultrasound image slice. Thus, the ultrasound beam profile **1314** need not represent spatial locations for a single beam, but may display total spatial illumination that may be used to form a cross-sectional ultrasound image slice. The ultrasound beam profile **1314** also shows approximate intensity threshold bounds. By performing the transverse ultrasound scan of the blood vessel **1304**, the set of ultrasound transducers **1308** may collect ultrasound data from which the diameter of the blood vessel **1304** can be measured. As discussed above, measuring the diameter of the blood vessel **1304** may be useful, for example, for calculating the cross-sectional area of the blood vessel **1304**, which in turn can be useful for calculating PWV.

[0115] FIG. **14** shows an illustration of performing a transverse ultrasound scan, with an elevational steer, of the blood vessel **1304** using the two-dimensional array of ultrasound transducers **1302** in accordance with certain embodiments disclosed herein. The set of ultrasound transducers **1308** is configured to perform a transverse ultrasound scan, steered in the elevation direction, of the blood vessel **1304** by producing an ultrasound beam profile **1414** along a plane that is orthogonal to the longitudinal axis **1306** of the blood vessel **1304**, similar to the ultrasound beam profile **1314**. The set of ultrasound transducers **1308** is further configured to steer the ultrasound beam profile **1414** in an elevation direction **1416** such that the ultrasound beam profile **1414** forms an angle **1418** with a plane orthogonal to the longitudinal axis **1306** of the blood vessel **1304**. (The angle **1418** is shown between a line **1420** parallel to a plane through the ultrasound beam profile **1414** and a line **1422** that is orthogonal to the longitudinal axis **1306**). Performing the transverse ultrasound scan, steered in the elevation direction, of the blood vessel **1304** may be useful, for example, for performing pulsed Doppler ultrasound imaging of the blood vessel **1304**, with which the spatial mean velocity of blood flow through the blood vessel **1304** may be measured. As discussed above, measuring the spatial mean velocity of blood flow through the blood vessel **1304** may be useful, for example, for calculating PWV.

[0116] FIG. **15** shows an illustration of performing a longitudinal ultrasound scan of a blood vessel **1304** with the two-dimensional array of ultrasound transducers **1302** in accordance with certain embodiments disclosed herein. The two-dimensional array of ultrasound transducers **1302** includes a set of ultrasound transducers **1408**. In FIG. **15**, the set of ultrasound transducers **1508** represents a row of the two-dimensional array of ultrasound transducers **1302**. The set of ultrasound transducers **1508** is configured to perform a longitudinal ultrasound scan of the blood vessel **1304** by producing an ultrasound beam profile **1514** along a plane that is parallel to the longitudinal axis **1306** of the blood vessel **1304**. By performing the longitudinal ultrasound scan of the blood vessel **1304**, the set of ultrasound transducers **1508** may be able to perform pulse wave imaging. As discussed above, performing pulse wave imaging may be useful, for example, for calculating blood vessel velocities, which can in turn be useful for calculating PWV.

[0117] FIG. **16** shows an illustration of performing a longitudinal ultrasound scan, with an azimuthal steer, of a blood vessel **1304** using the two-dimensional array of ultrasound transducers **1302** in accordance with certain embodiments disclosed herein. The set of ultrasound transducers **1508** is configured to perform a longitudinal ultrasound scan of the blood vessel **1304** by producing an ultrasound beam profile **1614** along a plane that is parallel to the longitudinal axis **1306** of the blood vessel **1304**, similar to the ultrasound beam profile **1514**. The set of ultrasound transducers **1508** is further configured to steer the ultrasound beam profile **1614** in an azimuthal direction **1616** such that the ultrasound beam profile forms an angle **1618** with a plan that is orthogonal to the longitudinal axis **1306** of the blood vessel **1304**. (The angle **1618** is shown between a line **1620** parallel to a plane through the ultrasound beam profile **1614** and a line **1622** that is orthogonal to the longitudinal axis **1306**). Performing the longitudinal ultrasound scan of the blood vessel **1304** with an azimuthal steer may be useful, for example, for performing pulsed Doppler ultrasound imaging of the blood vessel **1304**, with which the spatial mean velocity of blood flow through the blood vessel **1304** may be measured. As discussed above, measuring the spatial mean velocity of blood flow through the blood vessel **1304** may be useful, for example, for calculating PWV.

[0118] FIG. **17** shows an illustration of performing a transverse ultrasound scan of a blood vessel **1304** using the two-dimensional array of ultrasound transducers **1302**, when the blood vessel does not lie either perpendicular or parallel to the azimuth direction or the elevation direction, in accordance with certain embodiments disclosed herein. In FIG. **17**, all of the transducers in the two-dimensional array of ultrasound transducers **1302** are used to produce an ultrasound beam profile **1714** along a plane that is perpendicular to the longitudinal axis **1306** of the blood vessel **1304**. However, in some embodiments, a subset of the transducers in the two-dimensional array of ultrasound transducers **1302** are used. While a transverse ultrasound scan is shown in FIG. **17**, the two-dimensional array of ultrasound transducers **1302** may be configured to perform a longitudinal ultrasound scan, or steer an ultrasound beam profile in any arbitrary direction, even when the blood vessel does not lie perpendicular or parallel to the azimuth direction or the elevation direction. Thus, the two-dimensional array of ultrasound transducers **1302** can perform a transverse or longitudinal scan on the blood vessel **1304** without rotating the two-dimensional array of ultrasound transducers **1302**, as the scanning direction can be rotated about the normal axis of two-dimensional array of ultrasound transducers **1302** such that a transverse scan or longitudinal scan can be performed with any relative orientations between the two-dimensional array of ultrasound transducers **1302** and the blood vessel **1304**. This may be helpful, for example, if the wrist bound ultrasound-on-a-chip device **110** moves during normal use and does not maintain a constant orientation relative to the blood vessel **1304**.

[0119] In the examples of FIGS. **13**-**17**, the two-dimensional array of ultrasound transducers **1302** may be nonuniform (e.g., the transducers may be arranged in a configuration that is not a regular rectangular grid) in some embodiments. In some embodiments, more than one column of transducers may be configured to produce the ultrasound beam profiles, or any group of transducers in the two-dimensional array of ultrasound transducers **1302** (e.g., all the transducers) may be configured to produce the ultrasound beam profiles. In some embodiments, the ultrasound beam profiles may be formed from cylindrical beams and/or plane waves, and the ultrasound beam profiles may have sector profiles and may be formed from focused beams.

[0120] As illustrated by FIGS. **13**-**17**, the two-dimensional array of ultrasound transducers **1302** may be helpful in a wrist bound ultrasound-on-a-chip device, as the two-dimensional array of ultrasound transducers **1302** can, for example, perform transverse and longitudinal ultrasound scanning and steer ultrasound beam profiles in the azimuth and elevational directions, or rotate/steer ultrasound beam profiles in any other arbitrary direction, without requiring rotation of the ultrasound-on-a-chip device relative to the user's wrist between scans. In some embodiments, the two-dimensional array of ultrasound transducers **1302** may use a set of transducers (e.g., set of ultrasound transducers **1308**) in a first direction to form ultrasound beam profiles in a traverse direction (e.g., ultrasound beam profiles **1314** and **1414**) and another set of transducers (e.g., set of ultrasound transducers **1508**) in a second direction that is orthogonal to the first direction to form ultrasound beam profiles in a longitudinal direction (e.g., ultrasound beam profiles **1514** and **1614**). This flexibility can be useful, for example, in applications requiring collection of multiple types of data that may require or be enabled by multiple ultrasound beam profiles and multiple scanning directions. For example, measuring PWV at the wrist may require collecting data for measuring blood vessel diameter, spatial mean velocity, and/or blood vessel wall velocity, which may be enabled by the flexibility of a two-dimensional ultrasound transducer array.

Example System Functions

[0121] Processing circuitry may be configured to perform functions related to the apparatuses described herein. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or one or more servers (also known as a "cloud"). In some embodiments, the processing circuitry may be configured to detect when the ultrasound-on-a-chip device **110** needs to be repositioned. In some embodiments, detecting when the ultrasound-on-a-chip device **110** needs to be repositioned includes determining whether a current deviation of the ultrasound-on-a-chip device **110** from a desired position exceeds a threshold deviation. For example, the ultrasound-on-a-chip device **110** may be positioned over a specific portion of the wrist from which an ultrasound image containing a target anatomical view may be collected, but due to movement of the user's wrist, the ultrasound-on-a-chip device **110** may move away from the specific portion of the wrist. In some embodiments, to detect when the ultrasound-on-a-chip device **110** needs to be repositioned, the processing circuitry may be configured to analyze (continuously or at intervals) data collected by the ultrasound-on-a-chip device and determine whether the collected data matches the desired collected data. For example, the processing circuitry may collect ultrasound data, form an ultrasound image, and determine whether the ultrasound image contains a target anatomical view (e.g., a view of a specific anatomical structure, such as a specific blood vessel). In some embodiments, the processing circuitry may use deep learning to detect when the ultrasound-on-a-chip device needs to be repositioned.

[0122] In some embodiments, the processing circuitry may be configured to generate a notification to reposition the ultrasound-on-a-chip device **110**. The notification may include instructions to the user to move the ultrasound-on-a-chip device **110** to the required position, and the instructions may guide the user in moving the ultrasound-on-a-chip device **110** to the required position. For further description of guiding a user in moving an ultrasound-on-a-chip device **110** to a required position, see U.S. patent application Ser. No. 15/626,423 titled "AUTOMATIC IMAGE ACQUISITION FOR ASSISTING A USER TO OPERATE AN ULTRASOUND DEVICE." In some embodiments, the notification may be displayed on the display screen **122**, and may include text, an image, and/or a video. In some embodiments, the notification may include audio output from the primary module **102**.

[0123] In some embodiments, the processing circuitry may be configured to detect when the coupling strip **148** needs to be refreshed with liquid or gel or replaced. In some embodiments, detecting that the coupling strip **148** needs to be refreshed with liquid or gel includes determining whether a current amount of liquid or gel associated with the coupling strip **148** is below a threshold amount. For example, the liquid or gel absorbed in the coupling strip **148** may evaporate, which can cause the coupling strip **148** to conform poorly to the user's wrist, and thereby cause the ultrasound-on-a-chip device **110** to collect poor quality ultrasound images. In some embodiments, the processing circuitry may be configured to analyze collected data (continuously or at intervals) and determine whether the collected data shows signs (e.g., decreased quality of images) that the coupling strip **148** is conforming poorly to the user's wrist. To detect that the coupling strip **148** needs to be refreshed with liquid or gel or replaced, the processing circuitry may be configured to receive signals from a moisture sensor in or adjacent to the coupling strip **148** indicating that the moisture level in or adjacent to the coupling strip **148** is below a threshold moisture level. In some embodiments, the processing circuitry may be configured to use other sensors to detect that the coupling strip **148** needs to be refreshed, such as capacitive sensors or skin conductivity sensors. In some embodiments, the processing circuitry may use deep learning to detect when the coupling strip needs to be refreshed or replaced.

[0124] In some embodiments, the processing circuitry may be configured to generate a notification to replace the coupling strip **148** or refresh the coupling strip **148** with liquid or gel. The notification may include instructions to the user to refresh the coupling strip **148**. The notification may be displayed on the display screen **122** and may include text, an image, and/or a video. In some embodiments, the notification may include audio output from the primary module **102**.

[0125] In some embodiments, the processing circuitry may be configured to generate for display data and/or images generated based on ultrasound data collected from the user's wrist. The processing circuitry may generate for display the data/images on the display screen **122** or on a display screen of an external host device (e.g., smartphone, tablet, or laptop), workstation, or server. In some embodiments, the user may access a software application ("app") installed on a host device or workstation for viewing the data/images. In some embodiments, the processing circuitry may receive the data/images from a remote server.

Example Processes

[0126] FIG. **18** shows an example process **1800** for obtaining ultrasound data from a user's wrist, in accordance with certain embodiments disclosed herein. The ultrasound data may be received from the ultrasound-on-chip device **110** in any of the apparatuses described herein. The process **1800** may be performed by, for example, processing circuitry. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server.

[0127] In act **1802**, the processing circuitry may receive a trigger to collect ultrasound data from a user's wrist. In some embodiments, the trigger may be passage of a fixed period of time (e.g., one second, one minute, one hour, 6 hours, 8 hours, 12 hours, one day, or any suitable period of time). In some embodiments, the trigger may be activation of a button (e.g., virtual button **1102** or mechanical button **1202**) or a sensor (e.g., sensors **924** and **925**) on the apparatus. The process **1800** may then proceed to act **1804**.

[0128] In act **1804**, the processing circuitry may determine whether a current amount of liquid or gel associated with the coupling strip **148** is below a threshold amount. In some embodiments, to determine whether the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount, the processing circuitry may be configured to analyze (continuously or periodically) ultrasound data collected by the ultrasound-on-a-chip device **110** and determine whether the collected ultrasound data shows signs (e.g., decreased quality of images) that the coupling strip **148** is conforming poorly to the user's wrist. In some embodiments, to determine whether the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount, the processing circuitry may be configured to receive signals from a moisture sensor in or adjacent to the coupling strip **148** indicating that the moisture level in or adjacent to the coupling strip **148** is below a threshold moisture level. In some embodiments, the processing circuitry may be configured to use other sensors to determine whether the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount, such as capacitive sensors or skin conductivity sensors. If the current amount of liquid or gel associated with the coupling strip **148** is not below the threshold amount, the process **1800** may proceed to act **1810**. If the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount, the process **1800** may proceed to act **1806** and/or to act **1808**. Processor-executable instructions (e.g., stored in memory circuitry **114**) may determine whether the process **1800** proceeds to act **1806** and/or to act **1808**.

[0129] In act **1806**, the processing circuitry may generate a notification to replace or refresh the coupling strip **148**. In some embodiments, the notification may be displayed on the display screen **122**, or on a display screen of an external host device (e.g., a smartphone, tablet, or a computer) local to the user, and may include text, an image, and/or a video. In some embodiments, the notification may include audio output from the primary module **102** or from an external host device. The process may then proceed to act **1810**.

[0130] In act **1808**, the processing circuitry may automatically trigger a valve (e.g., valves **808** and **812**) to release liquid or gel from a reservoir (e.g., reservoirs **802** and **804**) into the coupling strip **148**. The process **1800** may then proceed to act **1810**.

[0131] In act **1810**, the processing circuitry may determine whether a current deviation of the ultrasound-on-a-chip device **110** from a desired position exceeds a threshold deviation. In some embodiments, the processing circuitry may analyze collected data (continuously or at intervals) and determine whether the collected data matches the desired collected data. For example, the processing circuitry may receive ultrasound data, form an ultrasound image, and determine whether the ultrasound image contains a target anatomical view (e.g., a view of a specific anatomical structure, such as a specific blood vessel). If the current deviation of the ultrasound-on-a-chip device **110** from the desired position does not exceed the threshold deviation, the process **1800** may proceed to act **1814**. If the current deviation of the ultrasound-on-a-chip device **110** from the desired position exceeds the threshold deviation, the process **1800** may proceed to act **1812**.

[0132] In act **1812**, the processing circuitry may generate a notification to reposition the ultrasound-on-a-chip device **110**. In some embodiments, the notification may include instructions to the user to move the ultrasound-on-a-chip device **110** to the required position, and may include instructions that guide the user in moving the ultrasound-on-a-chip device to the required position. For further description of guiding a user in moving an ultrasound-on-a-chip device to a required position, see U.S. patent application Ser. No. 15/626,423 titled "AUTOMATIC IMAGE ACQUISITION FOR ASSISTING A USER TO OPERATE AN ULTRASOUND DEVICE." In some embodiments, the notification may be displayed on the display screen **122** or a display screen of an external host device (e.g., a smartphone, tablet, or a computer) local to the user, and may include text, an image, and/or a video. In some embodiments, the notification may include audio output from the primary module **102** or an external host device local to the user. The process may then proceed to act **1814**.

[0133] In act **1814**, the processing circuitry may receive ultrasound data collected from the user's wrist. In some embodiments in which the processing circuitry is external to the ultrasound-on-a-chip device **110**, the processing circuitry may receive the ultrasound data over conductors **136**/connection cable **376** or over a wireless communication link such as a BLUETOOTH, WiFi, or ZIGBEE wireless communication link using communication circuitry (e.g., communication circuitry **116**). The process may then proceed to act **1816**.

[0134] In act **1816**, the processing circuitry may generate for display the ultrasound data, an ultrasound image generated based on the ultrasound data, and/or data generated based on the ultrasound data. For example, the data generated based on the ultrasound data may include calculations of blood flow, heart rate, blood pressure, blood vessel diameter, and pulse wave velocity based on the ultrasound data. The processing circuitry may generate for display the ultrasound data, ultrasound image, and/or data generated based on the ultrasound data on the display screen **122** or on a display screen of an external host device (e.g., a smartphone, a tablet, or a computer) local to the user. In some embodiments, the user may access a software application ("app") installed on the primary module **102** or host device for viewing the data and/or images.

[0135] In some embodiments, certain steps in process **1800** may be omitted. For example, the process **1800** may not determine whether the current deviation of the ultrasound-on-a-chip device **110** from the desired position exceeds a threshold deviation, may not determine whether the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount, and/or may not generate for display the ultrasound data/data generated based on the ultrasound data. In some embodiments, certain steps may be performed in a different order than shown in FIG. **18**. For example, the process **1800** may including determining whether the current deviation of the ultrasound-on-a-chip device **110** from the desired position exceeds a threshold deviation before determining whether the current amount of liquid or gel associated with the coupling strip **148** is below the threshold amount.

[0136] FIG. **19** shows an example process **1900** for calculating pulse wave velocity (PWV), in accordance with certain embodiments disclosed herein. PWV may represent a measure of arterial stiffness, which in some cases, such as aortic stiffness, has been proven to be a predictor of cardiovascular disease. PWV may represent a noninvasive method for measuring arterial blood pressure waveforms, which may contain information for diagnosing and treating cardiovascular disease. The ultrasound data may be received from the ultrasound-on-chip device **110** in any of the apparatuses described herein. The process **1900** may be performed by, for example, processing circuitry. The processing circuitry may be processing circuitry **112** or processing circuitry in an external host device (e.g., a smartphone, tablet, or laptop), workstation, or server. In some embodiments, the processing circuitry may calculate PWV at a single arterial site based on volumetric flow rate and cross-sectional area measured at the arterial site. The arterial site may be a site along on an artery in the wrist, such as the radial artery, ulnar artery, and median artery.

[0137] In act **1902**, the processing circuitry may receive first ultrasound data from a first ultrasound scan of the blood vessel in the user's wrist. In some embodiments, the first ultrasound scan of the blood vessel may be a transverse ultrasound scan of the blood vessel. The process **1900** may then proceed to act **1904**.

[0138] In act **1904**, the processing circuitry may calculate, based on the first ultrasound data, a cross-sectional area of the blood vessel. In some embodiments, the processing circuitry may measure the diameter of the blood vessel on an ultrasound image resulting from a transverse ultrasound scan, and calculating the cross-sectional area from the measured diameter involves assuming axisymmetrical geometry. In some embodiments, processing circuitry may use deep learning to measure the diameter of the blood vessel based on the first ultrasound data. The process **1900** may then proceed to act **1906**.

[0139] In act **1906**, the processing circuitry may receive second ultrasound data from a second ultrasound scan of the blood vessel in the user's wrist, without rotating the ultrasound-on-a-chip device **110** relative to the user's wrist between the first ultrasound scan and the second ultrasound scan. In some embodiments, the second ultrasound scan may include performing pulsed Doppler ultrasound imaging of the blood vessel in the wrist, where the blood vessel is insonated at an angle relative to the longitudinal axis of the blood vessel. The angle may be, for example, <10 degrees, 10 degrees, 20 degrees, 30 degrees, 40 degrees, 50 degrees, 70 degrees, 80 degrees, >80 degrees, or any other suitable angle. In some embodiments, to perform the pulsed Doppler ultrasound imaging at an angle relative to the longitudinal axis of the blood vessel, the ultrasound-on-a-chip device may perform a transverse ultrasound scan with an elevational steer. In some embodiments, to perform the pulsed Doppler ultrasound imaging at an angle relative to the longitudinal axis of the blood vessel, the ultrasound-on-a-chip device may perform a longitudinal ultrasound scan steered at an angle. In some embodiments, to perform the second ultrasound scan without rotating the ultrasound-on-a-chip device relative to the user's wrist between the first ultrasound scan and the second ultrasound scan, the ultrasound-on-a-chip device **110** may include a two-dimensional array of ultrasound transducers. In some embodiments, the ultrasound-on-a-chip device **110** may use a one-dimensional array of ultrasound transducers to perform the first and second ultrasound scans. The process **1900** may then proceed to act **1908**.

[0140] In act **1908**, the processing circuitry may calculate, based on the second ultrasound data, volumetric blood flow through the blood vessel. In some embodiments, the processing circuitry may calculate spatial mean velocity from the second ultrasound data and multiply cross-sectional area of the blood vessel by spatial mean velocity to calculate the volumetric blood flow. In some embodiments, the processing circuitry may use deep learning to calculate spatial mean velocity from the second ultrasound data. The process **1900** may then proceed to act **1910**.

[0141] In act **1910**, the processing circuitry may calculate, based on the cross-sectional area of the blood vessel and the volumetric blood flow, the pulse wave velocity in the blood vessel. PWV may be calculated from the volumetric flow rate and cross-sectional area measurements by measuring the slope of a linear portion of a volumetric flow rate vs. cross-sectional area plot. In some embodiments, instead of/in addition to calculating PWV based on volumetric flow rate and cross-sectional area measured at an arterial site, the processing circuitry may calculate PWV using pulse wave imaging. Further description of measuring PWV has already been presented herein in the section entitled "Example Data Collection and Processing."

[0142] Various inventive concepts may be embodied as one or more processes, of which examples have been provided. The acts performed as part of each process may be ordered in any suitable way. Thus, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments. Further, one or more of the processes may be combined and/or omitted.

[0143] The terms "program," "application," or "software" are used herein in a generic sense to refer to any type of computer code or set of processor-executable instructions that may be employed to program a computer or other processor to implement various aspects of embodiments as discussed above. Additionally, according to one aspect, one or more computer programs that when executed perform methods of the disclosure provided herein need not reside on a single computer or processor, but may be distributed in a modular fashion among different computers or processors to implement various aspects of the disclosure provided herein.

[0144] Processor-executable instructions may be in many forms, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc., that perform particular tasks or implement particular abstract data types. Typically, the functionality of the program modules may be combined or distributed.

[0145] Also, data structures may be stored in one or more non-transitory computer-readable storage media in any suitable form. For simplicity of illustration, data structures may be shown to have fields that are related through location in the data structure. Such relationships may likewise be achieved by assigning storage for the fields with locations in a non-transitory computer-readable medium that convey relationship between the fields. However, any suitable mechanism may be used to establish relationships among information in fields of a data structure, including through the use of pointers, tags or other mechanisms that establish relationships among data elements.

[0146] Various aspects of the present disclosure may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described in one embodiment may be combined in any manner with aspects described in other embodiments.

[0147] Further, some actions are described as taken by a "operator" or "subject." It should be appreciated that a "operator" or "subject" need not be a single individual, and that in some embodiments, actions attributable to an "operator" or "subject" may be performed by a team of individuals and/or an individual in combination with computer-assisted tools or other mechanisms. Further, it should be appreciated that, in some instances, a "subject" may be the same person as the "operator." For example, an individual may be imaging themselves with an ultrasound device and, thereby, act as both the "subject" being imaged and the "operator" of the ultrasound device.

[0148] Use of ordinal terms such as "first," "second," "third," etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[0149] The terms "approximately" and "about" may be used to mean within ±20% of a target value in some embodiments, within ±10% of a target value in some embodiments, within ±5% of a target value in some embodiments, and yet within ±2% of a target value in some embodiments. The terms "approximately" and "about" may include the target value.

[0150] As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0151] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having," "containing," "involving," and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

[0152] Having described above several aspects of at least one embodiment, it is to be appreciated various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be object of this disclosure. Accordingly, the foregoing description and drawings are by way of example only.

What is claimed is:

1. An apparatus comprising an ultrasound-on-a-chip device configured to be bound to a user's wrist.

2. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device is waterproof.

3. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device is configured to perform both transverse and longitudinal ultrasound scanning of a blood vessel in the user's wrist without being rotated relative to the user's wrist.

4. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device comprises a two-dimensional array of capacitive micromachined ultrasonic transducers (CMUTs).

5. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device comprises a plurality of capacitive micromachined ultrasonic transducers (CMUTs) configured to emit ultrasound waves having a frequency between approximately 5-20 MHz.

6. The apparatus of claim **1**, further comprising:

at least one wristband;

an ultrasound module containing the ultrasound-on-a-chip device and coupled to the at least one wristband; and

a coupling strip coupled to the ultrasound module and configured to couple the ultrasound module to the user's wrist.

7. The apparatus of claim **6**, further comprising a primary module coupled to the at least one wristband.

8. The apparatus of claim **7**, wherein the primary module comprises a display screen configured to display at least one of ultrasound data collected by the ultrasound-on-a-chip device, an ultrasound image generated from the ultrasound data, and data generated from the ultrasound data.

9. The apparatus of claim **1**, further comprising:

at least one wristband configured to couple to a wristband of a wrist device;

an ultrasound module containing the ultrasound-on-a-chip device and coupled to the at least one wristband; and

a coupling strip coupled to the ultrasound module and configured to couple the ultrasound module to the user's wrist.

10. The apparatus of claim **9**, further comprising a connection cable extending externally from the at least one wristband and configured to electrically connect the ultrasound module to the primary module.

11. The apparatus of claim **1**, further comprising:

at least one wristband;

a primary module containing the ultrasound-on-a-chip device and coupled to the at least one wristband; and

a coupling strip coupled to the primary module and configured to couple the primary module to the user's wrist.

12. The apparatus of claim **11**, further comprising a reservoir containing liquid or gel and configured to refresh the coupling strip.

13. The apparatus of claim **12**, wherein the reservoir comprises a valve opening from the reservoir into the coupling strip and configured to enable flow of the liquid or gel from the reservoir to the coupling strip.

14. The apparatus of claim **13**, wherein the valve is configured to enable flow of the liquid or gel from the reservoir to the coupling strip in response to mechanical pressure applied to a portion of the apparatus.

15. The apparatus of claim **13**, further comprising:

processing circuitry configured to automatically trigger the valve to enable flow of the liquid or gel from the reservoir to the coupling strip.

16. The apparatus of claim **12**, wherein the reservoir further comprises an input port configured to enable refilling of the reservoir with the liquid or gel.

17. The apparatus of claim **1**, further comprising processing circuitry configured to generate a notification to reposition the ultrasound-on-a-chip device.

18. The apparatus of claim **17**, further comprising processing circuitry configured to generate a notification to replace the coupling strip or refresh the coupling strip with liquid or gel.

19. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device is configured to transmit ultrasound data collected by the ultrasound-on-a-chip device to processing circuitry that is configured to analyze the ultrasound data using deep learning models.

20. The apparatus of claim **19**, wherein the processing circuitry is configured to retrieve, from a server, ultrasound data collected by other ultrasound-on-a-chip devices and to use the ultrasound data collected by the other ultrasound-on-a-chip devices when training the deep learning models.

21. The apparatus of claim **1**, wherein the ultrasound-on-a-chip device is configured to transmit ultrasound data of a blood vessel to processing circuitry that is configured to calculate pulse wave velocity in the blood vessel based on the ultrasound data of the blood vessel.

22. The apparatus of claim **1**, wherein the apparatus further comprises:

a button; and

processing circuitry configured to trigger collection of ultrasound data by the ultrasound-on-a-chip device upon activation of the button.

23. An apparatus, comprising:

a wristband; and

an ultrasound-on-a-chip device coupled to the wristband.

24. The apparatus of claim **23**, wherein the wristband comprises an interior surface and an exterior surface, and wherein the ultrasound-on-a-chip device is positioned on the interior surface of the wristband.

25.-**39**. (canceled)

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当前申请(专利权)人(译)	蝶形网络，INC.		
[标]发明人	ROTHBERG JONATHAN M FIFE KEITH G RALSTON TYLER S SANCHEZ NEVADA J ZAHORIAN JAIME SCOTT CHEN KAILIANG		
发明人	ROTHBERG, JONATHAN M. FERGUS, GREGG FIFE, KEITH G. RALSTON, TYLER S. SANCHEZ, NEVADA J. ZAHORIAN, JAIME SCOTT CHEN, KAILIANG MCNULTY, CHRISTOPHER THOMAS		
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摘要(译)

这里描述的技术的各方面涉及一种装置，该装置包括被配置为绑定到用户手腕的芯片上超声设备。片上超声设备可以包括二维超声换能器阵列。换能器可以是电容微机械超声换能器（CMUT），并且可以配置成发射频率在大约5-20MHz之间的超声波。耦合条可以耦合到芯片上超声设备，以减小芯片上超声设备和用户手腕之间的气隙。片上超声设备可以是防水的并且可以在不旋转的情况下执行横向和纵向超声扫描。片上超声设备可以被配置为计算通过用户手腕中的血管的脉搏波速度。