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(54) Title: WEARABLE DIAGNOSTIC PLATFORM USING DIRECT MAGNETIC DETECTION OF MAGNETIC NANOPARTICLES IN VIVO

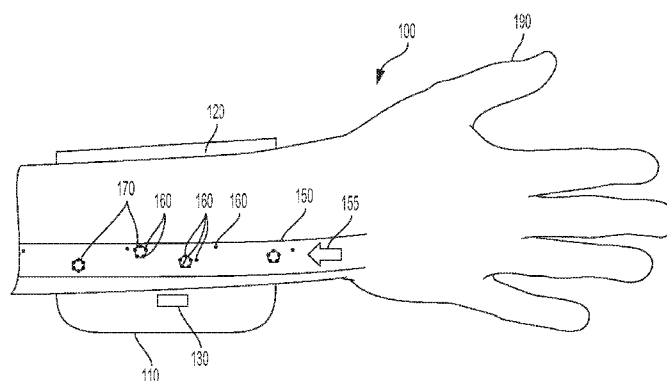


FIG. 1A

(57) Abstract: Wearable devices configured to detect the presence, concentration, number, or other properties of magnetic nanoparticles disposed in subsurface vasculature of a person are provided. The wearable devices are configured to detect, using one or more magnetometers, magnetic fields produced by the magnetic nanoparticles. In some embodiments, the magnetometer(s) are atomic magnetometers. In some embodiments, the wearable devices include magnets or other means to magnetize the magnetic nanoparticles. In some embodiments, the wearable devices produce a time-varying magnetic field, and the magnetometer(s) are configured to detect a time-varying magnetic field responsively produced by the magnetic nanoparticles. In some embodiments, the magnetic nanoparticles are configured to bind to an analyte of interest and detected properties of the magnetic nanoparticles can be used to determine the presence, concentration, or other properties of the analyte. Detecting magnetic fields produced by the magnetic nanoparticles can include detecting the fields directly or indirectly.



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**WEARABLE DIAGNOSTIC PLATFORM USING DIRECT MAGNETIC
DETECTION OF MAGNETIC NANOPARTICLES IN VIVO**

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Application No. 62/144,646, filed April 8, 2015, and to U.S. Patent Application No. 14/788,882, filed July 1, 2015, the disclosures of which are hereby incorporated by reference in their entireties.

BACKGROUND

[0002] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0003] A number of scientific methods have been developed to detect, measure, and/or affect one or more analytes in a biological or other environment (e.g., a person's body). The one or more analytes could be any analytes that, when present in or absent from a person's body, or present at a particular concentration or range of concentrations, may be indicative of a medical condition or health state of the person. The one or more analytes could be substances whose distribution, action, or other properties, interactions, or activities throughout an animal's body is of scientific or medical interest. The one or more analytes could include pharmaceuticals or other substances introduced into the biological or other environment to effect some chemical or biological process. The one or more analytes could be present in living or nonliving human or animal tissue, and could be detected, measured, or affected in an in vivo, ex vivo, in vitro, or some other type of sample. The one or more analytes could include enzymes, reagents, hormones, proteins, drugs, nanoparticles, pharmaceuticals, cells or other molecules.

SUMMARY

[0004] Some embodiments of the present disclosure provide a device including: (i) a magnetometer, wherein the magnetometer is configured to be positioned proximate to a biological environment, and wherein the magnetometer is configured to detect magnetic fields produced by magnetic nanoparticles in the biological environment that are proximate the magnetometer; and (ii) a controller operably coupled to the magnetometer, wherein the controller includes a computing device programmed to perform controller operations

including: (a) operating the magnetometer to detect a magnetic field; and (b) determining a property of magnetic nanoparticles in the biological environment based on the detected magnetic field.

[0005] Some embodiments of the present disclosure provide a system including: (i) means for detecting a magnetic field proximate to a biological environment, wherein the means for detecting a magnetic field are configured to be positioned proximate to the biological environment, and wherein the means for detecting a magnetic field are configured to detect magnetic fields produced by magnetic nanoparticles in the biological environment that are proximate the means for detecting a magnetic field; and (ii) controller means operably coupled to the means for detecting a magnetic field, wherein the controller means include a computing device programmed to perform controller operations including: (a) operating the means for detecting a magnetic field to detect a magnetic field; and (b) determining a property of magnetic nanoparticles in the biological environment based on the detected magnetic field.

[0006] Some embodiments of the present disclosure provide a method including: (i) detecting, using a magnetometer, a magnetic field proximate to a biological environment, wherein detecting a magnetic field proximate to a biological environment includes detecting a magnetic field produced by magnetic nanoparticles in the biological environment that are proximate the magnetometer; and (ii) determining a property of magnetic nanoparticles in the biological environment based on the detected magnetic field.

[0007] Some embodiments of the present disclosure provide a device including: (i) a magnetometer that is configured to be positioned proximate to a first location of subsurface vasculature and that is configured to detect magnetic fields at the first location; (ii) a magnetic flux source that is configured to be positioned proximate to a second location of the subsurface vasculature and that is configured to magnetize nanoparticles in the in the subsurface vasculature that are proximate the second location, wherein the second location is located upstream from the first location relative to a direction of blood flow in the subsurface vasculature; and (iii) a controller that is operably coupled to the magnetometer and that includes a computing device programmed to perform controller operations. The controller operations include: (a) operating the magnetometer to detect a magnetic field at the first location; and (b) determining a property of magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the second location and that traveled to the first location.

[0008] Some embodiments of the present disclosure provide a device including: (i) means for detecting magnetic fields at a first location of subsurface vasculature; (ii) means for magnetizing nanoparticles that are proximate a second location of the subsurface vasculature, wherein the second location is located upstream from the first location relative to a direction of blood flow in the subsurface vasculature; and (iii) controller means that are operably coupled to the means for detecting magnetic fields. The controller means are configured to perform controller operations including: (a) operating the means for detecting magnetic fields to detect a magnetic field at the first location; and (b) determining a property of magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the second location and that traveled to the first location.

[0009] Some embodiments of the present disclosure provide a method including: (i) magnetizing, using a magnetic flux source, nanoparticles in a first location of subsurface vasculature; (ii) detecting, using a magnetometer, a magnetic field at a second location of the subsurface vasculature, wherein the second location is located downstream from the first location relative to a direction of blood flow in the subsurface vasculature; and (iii) determining a property of magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the first location and that traveled to the second location.

[0010] These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1A is a side cross-sectional view of magnetic particles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0012] Figure 1B illustrates an example output over time of a magnetic sensor of the device of Figure 1A as magnetic particles in the portion of subsurface vasculature of Figure 1A move through the portion of subsurface vasculature.

[0013] Figure 2A is a side cross-sectional view of magnetic particles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0014] Figure 2B illustrates example outputs over time of two magnetic sensors of the device of Figure 2A as magnetic particles in the portion of subsurface vasculature of Figure 2A move through the portion of subsurface vasculature.

[0015] Figure 2C illustrates an example signal related to the motion of magnetic particles in the portion of subsurface vasculature of Figure 2A based on the example outputs illustrated in Figure 2B

[0016] Figure 3A is a side cross-sectional view of magnetic particles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0017] Figure 3B illustrates an example output over time of a magnetic sensor of the device of Figure 3A, an example magnetic field generated by a magnetic coil of the device of Figure 3A, and an example magnetic field generated by magnetic particles in the portion of subsurface vasculature of Figure 3A.

[0018] Figure 4 illustrates an example frequency spectrum of an output of a magnetic sensor.

[0019] Figure 5 is a side cross-sectional view of magnetic particles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0020] Figure 6 is a side cross-sectional view of nanoparticles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0021] Figure 7 is a side cross-sectional view of nanoparticles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature, in accordance with an example embodiment.

[0022] Figure 8A is a side cross-sectional view of magnetic particles in a portion of subsurface vasculature and a device positioned proximate to the portion of subsurface vasculature during a first period of time, in accordance with an example embodiment.

[0023] Figure 8B is a side cross-sectional view of the magnetic particles in the portion of subsurface vasculature of Figure 8A and the device positioned proximate to the portion of subsurface vasculature of Figure 8A during a second period of time, in accordance with an example embodiment.

[0024] Figure 9 is a side cross-sectional view of nanoparticles in a system configured to separate the nanoparticles according to a magnetic property of the nanoparticles

[0025] Figure 10 is perspective view of an example device.

[0026] Figure 11 is an illustration of a number of wearable devices in communication with a server.

[0027] Figure 12 is a block diagram of an example system.

[0028] Figure 13 is a flowchart of an example method.

[0029] Figure 14 is a flowchart of an example method.

DETAILED DESCRIPTION

[0030] In the following detailed description, reference is made to the accompanying figures, which form a part hereof. In the figures, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, figures, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

I. Overview

[0031] Magnetic nanoparticles can be intrinsically magnetic and/or can be magnetizable (e.g., can be configured to develop a magnetic moment in response to an external magnetic field and to retain such a magnetic moment for some specified period of time). Further, such magnetic nanoparticles can be configured to selectively bind with an analyte of interest. Magnetic nanoparticles configured in this way can enable manipulation of, detection of, or other interactions with the analytes by applying magnetic forces to the magnetic nanoparticles. Additionally or alternatively, an analyte of interest could be intrinsically magnetic and/or magnetizable, or could be an engineered analyte (e.g., a pharmaceutical) that includes a magnetic property and/or that is bound to a magnetic nanoparticle and that can be introduced into an environment according to an application. Detecting the magnetic field produced by such magnetic nanoparticles could allow for the determination of the amount (e.g., concentration, number), distribution, or other properties of the analyte of interest in the biological environment. For example, the magnetic field produced by such analyte-binding magnetic nanoparticles in a portion of subsurface vasculature could be detected (e.g., using one or more magnetometers disposed in a wearable

device mounted proximate to the portion of subsurface vasculature) and used to determine the number and/or concentration of the analyte in the blood in the portion of subsurface vasculature.

[0032] Magnetic nanoparticles as described herein (e.g., magnetizable and/or intrinsically magnetized nanoparticles) may be made of and/or wholly or partially coated by an inert material, such as polystyrene, and can have a diameter that is less than about 20 micrometers. In some embodiments, the nanoparticles have a diameter on the order of about 5 nm to 1 μ m. In further embodiments, one or more particles of magnetic and/or magnetizable material of a magnetic nanoparticle (e.g., particles of superparamagnetic iron oxide) may be embedded in a substrate of non-magnetic material (e.g., polystyrene). In some examples, the size and/or a distribution of sizes of such magnetic nanoparticles and/or particles of magnetic and/or magnetizable material thereof could be specified to control a magnetic or other property of the magnetic nanoparticles, e.g., to control a magnetic relaxation time, coercivity, remanence, susceptibility, type of magnetic behavior (e.g., superparamagnetism, ferromagnetism, ferrimagnetism, paramagnetism), hysteresis, or other property of the magnetic nanoparticles. For example, a particle of magnetic material of a magnetic nanoparticle could have a size between approximately 10 nanometers and approximately 20 nanometers e.g., such that the particle of magnetic and/or magnetizable material comprises a single magnetic domain. In another example, a particle of magnetizable material could have a size of approximately 20 nanometers such that the particle of magnetizable material has a magnetic relaxation time of approximately 1 second. The magnetic nanoparticles and/or particles of magnetic and/or magnetizable material thereof may be formed from a paramagnetic, ferri-magnetic, ferro-magnetic, or super-paramagnetic material or any other material that responds to a magnetic field. Such a material may be chosen according to a specified magnetic relaxation rate, e.g., such that any magnetization exhibited by the material decreases over time.

[0033] Those of skill in the art will understand a “particle” in its broadest sense and that it may take the form of any fabricated material, a molecule, cryptophane, a virus, a phage, etc. Further, a magnetic nanoparticle may be of any shape, for example, spheres, rods, non-symmetrical shapes, etc. Further, the magnetic nanoparticles can be configured to selectively bind to one or more analytes (e.g., chemicals, hormones, peptides, DNA or RNA fragments, cells). Such particles could be introduced into an environment that contains the one or more analytes (e.g., into the blood of a body, into a portion of subsurface vasculature of a body, into a fluid of a natural environment, water treatment process, pharmaceutical

process, or some other environment of interest). Alternatively, the one or more analytes and/or a fluid or other material containing the one or more analytes could be extracted (e.g., from an environment of interest) and introduced into another environment into which the magnetic nanoparticles have been or could be introduced.

[0034] Detection of magnetic fields produced by magnetic nanoparticles could provide a variety of applications. The magnetic nanoparticles could be configured to selectively interact with (e.g., to bind to) one or more analytes of interest. Detection of the magnetic fields produced by the magnetic nanoparticles could allow for the determination of one or more properties of the analytes of interest, e.g., an amount of the analytes, a concentration of the analytes, a number of the analytes (e.g., a number of cancer cells in a portion of subsurface vasculature and/or in the blood circulation of a body), a property of the analytes, or some other information about the analytes. Detection of magnetic fields produced by magnetic nanoparticles could allow the determination of the orientation and/or location of the magnetic nanoparticles (e.g., by detecting a magnitude and/or direction of the produced magnetic field at one or more locations proximate to (e.g., outside of) the environment of interest, e.g., outside skin proximate a portion of subsurface vasculature), a degree of aggregation of the magnetic nanoparticles (e.g., by detecting a magnitude of the produced magnetic field, by detecting a property of change over time of the produced magnetic field), or the detection of some other property of the magnetic nanoparticles.

[0035] Such determined properties of the magnetic nanoparticles could be related to properties of the analytes of interest. For example, multiple magnetic nanoparticles could bind to a single instance of an analyte (e.g., to a single cancer cell) such that detection of an aggregate of magnetic nanoparticles (e.g., detection of a large amplitude magnetic field produced by such aggregated magnetic nanoparticles) allows for the determination that the single instance of the analyte is present (e.g., that a cancer cell is present in a portion of subsurface vasculature). Other properties of a detected magnetic field produced by magnetic nanoparticles could be used in similar or different ways to determine properties of one or more analytes in an environment of interest.

[0036] One or more properties of the analyte could be related to a medical condition of a human or animal containing the analyte. In some examples, the analyte could have a medical or other effect on the human or animal (e.g., the analyte is a toxin, the analyte is a pharmaceutical, the analyte is a cancer cell), and detecting magnetic fields produced by magnetic nanoparticles bound to the analyte could allow detection or determination of a medical condition of the human or animal. For example, the analyte could be a cancer cell,

and detection of the magnetic fields produced by magnetic nanoparticles in the blood could allow the detection of an amount of the cancer cells in the blood, a stage of the cancer, that the cancer has entered or left remission, or some other information or health state.

[0037] In some examples, magnetic nanoparticles could be used to collect an analyte (e.g., by exerting a magnetic force to collect magnetic nanoparticles bound to the analyte), to control a rate of administration of a drug (e.g., by producing magnetic fields to manipulate magnetic nanoparticles bound to the drug), to modify or destroy an analyte (e.g., by applying RF energy to the magnetic particles such that analytes bound to the magnetic particles are modified or destroyed), or to provide some other function. Other applications and environments containing magnetic nanoparticles are anticipated.

[0038] Magnetic nanoparticles could be detected in a variety of ways. A direction, magnitude, property of change over time, or some other property of the produced magnetic fields could be detected. Such detection could include operating one or more magnetometers (i.e., devices or components configured to detect one or more properties of a magnetic field, e.g., magnitude, direction, magnitude in a specified direction, of a magnetic field) to directly detect produced magnetic fields at one or more respective locations proximate to (e.g., outside of) an environment of interest that contains the magnetic nanoparticles. For example, a body-mountable device including one or more magnetometers could be mounted to a skin surface proximate a portion of subsurface vasculature such that the one or more magnetometers can detect magnetic fields produced by the magnetic nanoparticles in the portion of subsurface vasculature. In some examples, the detected produced magnetic field could be produced in response to an oscillating or otherwise time-varying field produced in the environment of interest. For example, an oscillating magnetic field could be produced, and an oscillating magnetic field responsively produced by the magnetic nanoparticles in the environment (e.g., an oscillating magnetic field at a harmonic of the produced oscillating magnetic field) could be detected.

[0039] In some examples, magnetic field produced by magnetic nanoparticles (e.g., by magnetized nanoparticles) could be detected indirectly, e.g., by magnetically or otherwise detecting a property that is related to and/or affected by the magnetic field produced by the magnetic nanoparticles. For example, a precession frequency or other information about magnetic spins of atomic nuclei in the environment (e.g., a $T2^*$ spin relaxation time of packets of atomic nuclei having polarized magnetic spins) that is related to the magnetic nanoparticles (e.g., that is changed by inhomogeneities in the Earth's magnetic field that are produced by the magnetic nanoparticles) could be detected. This could include polarizing the

magnetic spins of hydrogen atoms or other nuclei in a first location of vasculature (e.g., using a permanent magnet or other magnetic flux source located at a second location of vasculature that is upstream from the first location of vasculature), rotating the magnetic spins of atomic nuclei in the first location of vasculature by producing a time-varying magnetic field in the first location (e.g., using coils of a pulse emitter), and detecting time-varying magnetic fields produced by atomic nuclei in the first location in response to the rotation of the magnetic spins of the atomic nuclei (e.g., using a magnetometer).

[0040] Magnetometers used to detect magnetic fields as described herein could be configured to detect magnetic fields that have very small magnitudes. For example, a magnetometer used to detect magnetic fields produced by magnetic nanoparticles could be configured to have a sensitivity such that the magnetometer can detect changes in a measured magnetic field (e.g., a magnetic field at a location less than approximately 1 centimeter outside a portion of subsurface vasculature) of less than approximately 10 femtoteslas.

[0041] Magnetometers could include superconducting quantum interference devices (SQUIDs), spin-exchange relaxation-free (SERF) magnetometers, multi-pass optical atomic magnetometers, inductive loops or coils or other antenna structures, spin precession magnetometers, or some other magnetic-field-detecting components or devices. Further, the magnetic fields (e.g., magnetic fields produced by magnetic nanoparticles) could be detected at more than one location (e.g., by more than one magnetometer) to allow for detection of properties of the magnetic nanoparticles (e.g., to detect a speed of movement of the nanoparticles in a portion of subsurface vasculature) and/or to allow a background magnetic field (e.g., a magnetic field present in the environment of interest that is not produced by and/or related to the magnetic nanoparticles, e.g., that is produced by the Earth, that is produced by electronic devices, that is produced by other magnetic and/or magnetized materials in or proximate to the environment of interest).

[0042] The magnetic nanoparticles could produce a magnetic field intrinsically, e.g., the magnetic nanoparticles could include magnetized ferromagnetic materials and/or the magnetic nanoparticles could include superparamagnetic materials that become spontaneously magnetized. In such examples, this intrinsically produced magnetic field could be detected (e.g., by a magnetometer) and used to determine one or more properties of an analyte to which the magnetic nanoparticles are configured to bind. Additionally or alternatively, the magnetic field produced by the magnetic nanoparticles could be induced by an external static and/or time-varying magnetic field or other applied energy or field. For example, a permanent magnet, electromagnet, or other magnetic field producing component

could produce a magnetic field in an environment of interest (e.g., in a portion of subsurface vasculature) sufficient to magnetize the magnetic nanoparticles, and the magnetic field produced by the magnetized magnetic nanoparticles could be detected. In another example, an alternating (e.g., sinusoidal) magnetic field could be produced (e.g., by an electronically driven coil) in an environment of interest containing the magnetic nanoparticles, and magnetic fields reflected, phase-shifted, frequency-shifted, frequency-multiplied, or otherwise produced by the magnetic nanoparticles could be detected.

[0043] In some examples, one or more properties of the analyte could be determined and/or detected by collecting the magnetic nanoparticles such that a magnitude of the magnetic field produced by the magnetic particles and detected by a magnetometer is increased. Such collection could include producing a magnetic field in an environment of interest such that a magnetic force is exerted on the magnetic nanoparticles to collect the magnetic nanoparticles. In some examples, an electromagnet, permanent magnet, or other magnetic field-producing component could be operated to collect the magnetic nanoparticles and subsequently to release the collected magnetic nanoparticles (e.g., to provide detection of a magnetic field produced by the magnetic nanoparticles without interference by the magnetic field produced by the electromagnet, permanent magnet, or other magnetic field-producing component).

[0044] In some examples, permanently magnetic nanoparticles in vasculature of a body (e.g., nanoparticles that include ferromagnetic material or other material capable of being permanently magnetized) could, as a result of mutual magnetic attraction, aggregate into clumps. Such clumps could have a sufficient size or other properties such that the clumps of magnetized nanoparticles block small-diameter blood vessels. Further, in examples wherein such permanently magnetized nanoparticles are configured to selectively interact with (e.g., to reversibly bind to) an analyte, clumping of the nanoparticles could prevent interaction between the nanoparticles and the analyte.

[0045] In some examples, magnetic nanoparticles in vasculature of a body could be magnetizable and further could be configured such that magnetization of the magnetic nanoparticles (e.g., by application of an external magnetic field) is temporary, i.e., that the magnetization of such a magnetic nanoparticle could decay, reverse, or otherwise diminish or change over time. For example, such magnetic nanoparticles could include paramagnetic materials, superparamagnetic materials, or other materials or structures such that a state of magnetization of the magnetic nanoparticles decreases over time. Such magnetic nanoparticles could be configured to have a specified magnetic relaxation time (e.g., a

magnetic relaxation time within a specified range of relaxation times, e.g., between approximately 1 second and approximately 2 seconds) or to have specified some other measure of the time-dependence of the decrease of the magnetization of such a magnetic nanoparticle over time subsequent to being magnetized.

[0046] In such examples, the magnetic nanoparticles could be magnetized and a property (e.g., a direction, magnitude, or other property of a magnetic field produced by) of the magnetized nanoparticles could be detected. For example, the magnetic nanoparticles could be magnetized (e.g., by a permanent magnet or other magnetic flux source) in an upstream location of vasculature (upstream relative to a flow of blood in the vasculature) and the magnetized nanoparticles could be detected (e.g., by a magnetometer) in a second, downstream location of vasculature after the magnetized nanoparticles have flowed, with the blood in the vasculature, from the upstream location to the downstream location. The magnetization of the magnetized nanoparticles could subsequently decrease such that the magnetic nanoparticles substantially do not clump.

[0047] Magnetic nanoparticles having a magnetic relaxation time (or some other measure of the decrease of the magnetization of magnetized nanoparticles over time) within a specified range of relaxation times could be produced in a variety of ways. In some examples, a plurality of individual magnetic nanoparticles having a range of relaxation times could be sorted or partitioned such that individual magnetic nanoparticles having relaxation times within the specified range are separated from the remainder of the plurality of individual magnetic nanoparticles. In some examples, this could include disposing the plurality of individual magnetic nanoparticles in a flowing carrier fluid, magnetizing the plurality of individual magnetic nanoparticles (e.g., using a permanent magnet) in an upstream location, applying a separating magnetic force to the magnetized nanoparticles (e.g., using a permanent magnet) in a downstream location, and collecting and/or partitioning the separated magnetic nanoparticles (e.g., using a forked tube or other means for separating a fluid flow). As a result, individual magnetic nanoparticles of the plurality of individual magnetic nanoparticles that have a relaxation time greater than a specified value (e.g., a specified value related to a distance between the upstream location and the downstream location and a rate of flow of the carrier fluid) could be separated from magnetic nanoparticles of the plurality of individual magnetic nanoparticles that have a relaxation time less than the specified value. Such a separation could be performed a number of times, e.g., to first separate magnetic nanoparticles having relaxation times less than an upper end of a specified range of relaxation times and to second separate magnetic nanoparticles having

relaxation times greater than a lower end of the specified range of relaxation times. Additionally or alternatively, a relaxation time of the magnetic nanoparticles could be related to a size (e.g., diameter) of the magnetic nanoparticles, and the magnetic nanoparticles could be separated according to size to provide separation of individual magnetic nanoparticles having specified relaxation times.

[0048] Such magnetic nanoparticles having specified magnetic relaxation times or otherwise configured to be temporarily magnetizable could be used as described herein to be detected subsequent to being magnetized while generally being non-magnetized, e.g., to prevent clumping of the magnetic nanoparticles. Further, detection of such magnetic nanoparticles could be provided by the magnetic nanoparticles having such specified magnetic relaxation times. For example, a change in magnetization of such magnetic nanoparticles over time could be detected (e.g., using two magnetometers configured to detect magnetic fields in respective different locations of vasculature downstream from a magnetic flux source configured to magnetize the magnetic nanoparticles) and used to provide an improved measure of the number or amount of the magnetized nanoparticles in the vasculature. This could include, for example, comparing a magnetic field detected at a first location at which the magnetized nanoparticles remain magnetized (e.g., due to proximity to an upstream magnetic flux source) to a magnetic field detected at a second location at which the magnetized nanoparticles have become de-magnetized (e.g., due to a greater distance from the upstream magnetic flux source). In some examples, first and second pluralities of magnetic nanoparticles having magnetic relaxation times within respective first and second non-overlapping ranges of relaxation times could be detected in such a way (i.e., by detecting magnetic fields in multiple different locations of vasculature downstream from a nanoparticle-magnetizing magnetic flux source). For examples, this could provide for the detection of amounts of first and second analytes with which the first and second pluralities of magnetic nanoparticles are, respectively, configured to selectively interact (e.g., bind)

[0049] The effects of a background magnetic field (e.g., a magnetic field produced by electronics or magnetic materials proximate to and/or within an environment of interest, a magnetic field produced by the Earth) could be mitigated or compensated for in a variety of ways. In some examples, a system could include two or more magnetometers configured to detect magnetic fields at two or more respective locations. In such examples, a magnetic field produced by magnetic particles in the environment of interest could be determined by determining a difference between the magnetic fields detected by two of the two or more magnetometers. In some examples, a system could include magnetic shims, magnetic

shielding materials, permanent magnets, electromagnets, or other means for changing and/or controlling a magnetic field detected by a magnetometer. Such means could be used to reduce a background magnetic field detected at a location by the magnetometer (e.g., to cancel a magnetic field produced by the Earth and detected by the magnetometer) and/or to cancel and/or reduce an inhomogeneity of a magnetic field produced by a component of the system or by some other system (e.g., a magnetic field produced by an electromagnet that is configured to magnetize and/or collect magnetic nanoparticles). Such means could be operated based on a magnetic field detected by a magnetometer (e.g., to zero the output of the magnetometer), based on a magnetic field detected by another magnetometer (e.g., to reduce the magnetic field present at the location of a SERF magnetometer based on a magnetic field detected by a Hall effect magnetometer located proximate to the SERF magnetometer), or based on some other information or consideration.

[0050] Magnetometers and magnetic flux sources configured as described herein could be included as part of a variety of systems or devices and configured magnetize magnetic nanoparticles and/or to detect magnetic fields produced by magnetic nanoparticles (e.g. by magnetized magnetic nanoparticles) present in a variety of environments according to a variety of applications. In some examples, one or more magnetometers, magnetic flux sources, or other components could be included in a body-mountable device configured to be mounted to a skin surface and to magnetize nanoparticles and/or to detect magnetic fields produced by magnetic nanoparticles in a portion of subsurface vasculature proximate the skin surface. Additionally or alternatively, magnetometers and/or magnetic flux sources as described herein could be included in handheld, desktop, wall- or floor-mounted devices, or some other type of device or system. Such systems could be configured to magnetize nanoparticles and/or to detect magnetic fields produced by magnetic nanoparticles disposed in natural environments (e.g., portions of subsurface vasculature, fluids of a lake, stream, or other natural outdoor environment), *ex vivo* and/or *in vitro* environments (e.g., fluids contained in a sample container), artificial environments (e.g., a fluid or other volume of a pharmaceutical or industrial process), or some other environment of interest. Magnetic nanoparticles could be disposed in a flowing fluid or otherwise moving environment and/or disposed in a substantially static fluid or otherwise nonmoving environment. Magnetic nanoparticles could be disposed in a flowing fluid or otherwise moving environment and/or disposed in a substantially static fluid or otherwise nonmoving environment. Magnetic nanoparticles could be introduced into the environment of interest (e.g., injected into a portion of subsurface vasculature), naturally present in the environment of interest,

introduced into a sample extracted from an environment of interest, or otherwise disposed relative to an environment of interest.

[0051] Further, note that methods described herein to detect properties (e.g., presence, location, orientation, number, degree of aggregation, state of binding to an analyte) of magnetized magnetic nanoparticles could be applied to detect such properties of magnetic nanoparticles that are permanently magnetic, e.g., that maintain a magnetic dipole moment without being recently exposed to a magnetic flux source. Such permanently magnetized magnetic nanoparticles could include magnetic materials that are permanently magnetizable, could include particles of a ferromagnetic, ferromagnetic, or otherwise magnetic material that includes multiple magnetic domains or that is otherwise configured to be permanently magnetized or to otherwise maintain a magnetic moment for a protracted period of time.

[0052] It should be understood that the above embodiments, and other embodiments described herein, are provided for explanatory purposes, and are not intended to be limiting.

[0053] Further, the term “medical condition” as used herein should be understood broadly to include any disease, illness, disorder, injury, condition or impairment—e.g., physiologic, psychological, cardiac, vascular, orthopedic, visual, speech, or hearing—or any situation requiring medical attention.

II. Illustrative Magnetic Particles and Detection of Magnetic Fields Thereof

[0054] Magnetic fields produced by magnetic nanoparticles in an environment of interest can be detected (e.g., by one or more magnetometers located within and/or proximate to the environment of interest) and used to determine the location, amount (e.g., number, concentration), orientation, velocity, degree of aggregation, or other properties of the magnetic nanoparticles in the environment of interest and/or to determine properties of the environment of interest. Such magnetic nanoparticles could produce a magnetic field intrinsically, e.g., could be composed of permanently magnetized materials. Additionally or alternatively, the magnetic nanoparticles could be magnetizable. Such magnetizable magnetic nanoparticles could be magnetized in the environment of interest (e.g., a magnetic flux source could generate a magnetic flux sufficient to magnetize the magnetic nanoparticles). Alternatively, the nanoparticles could be magnetized in a location that is different from the region of the environment of interest where the magnetic field is detected (e.g., the nanoparticles could be magnetized in a first portion of subsurface vasculature that is upstream from a second portion of subsurface vasculature proximate to which a

magnetometer is disposed to detect magnetic fields produced by magnetized nanoparticles that have flowed from the first location to the second location).

[0055] The environment of interest could include artificial environments (e.g., a fluid of an industrial process, a fluid of a chemical or pharmaceutical process) or natural environments (e.g., a lake, a river, a marsh, blood in vasculature of an animal). For example, the magnetic nanoparticles could be disposed in blood in a portion of subsurface vasculature of a human. The magnetic nanoparticles could be permanently magnetized (e.g., could include particles of ferromagnetic material having multiple magnetic domains) or could be magnetizable when exposed to a magnetic field (e.g., could be paramagnetic or superparamagnetic) or to some other factor. In some examples, the magnetic nanoparticles can be configured to bind to an analyte of interest and magnetic fields produced by the magnetic nanoparticles could be detected to determine the location, amount (e.g., number, concentration), state of binding to one or more magnetic nanoparticles, or other properties of the analyte of interest.

[0056] The magnetic field produced by one or more magnetic nanoparticles can be detected at one or more locations in space. The direction, magnitude, and/or other properties of the produced magnetic field at a particular location can be related to the location and/or orientation of the one or more magnetic nanoparticle relative to the particular location, the magnitude of the permanent and/or induced magnetic dipole moment of the magnetic nanoparticle, magnetic properties of materials proximate the particular location, or other factors. A magnetic field at the particular location (e.g., a direction and/or magnitude of a magnetic field detected by, e.g., a magnetometer) could be related to the magnetic field of the earth, magnetic fields produced by electronics or other devices proximate the particular location, magnetic and/or electromagnetic fields produced by atomic magnetic spins that are precessing in a magnetic field (e.g., a magnetic field produced by the Earth and/or by one or more magnetized nanoparticles), magnetized or otherwise magnetic materials proximate the particular location, or other factors in addition to the magnetic field produced by the one or more magnetic nanoparticles.

[0057] The magnetic nanoparticles could produce a magnetic field intrinsically. For example, each magnetic nanoparticle could include magnetized ferromagnetic, ferrimagnetic, paramagnetic, superparamagnetic, or otherwise magnetized materials and/or each magnetic nanoparticle could include superparamagnetic materials that become spontaneously magnetized. In such examples, this produced magnetic field could be detected at one or more locations (e.g., by a magnetometer) and used to determine one or more properties of the

magnetic nanoparticles. For example, detecting a magnetic field (e.g., detecting a magnitude, direction, change over time, or other properties of the magnetic field) at a particular location could provide information about the location, orientation, number, state of binding to an analyte, degree of magnetization or other magnetic state, degree of aggregation (e.g., aggregation proximate to an instance of an analyte to which the nanoparticles are configured to bind), or some other information about magnetic nanoparticles proximate the particular location. Additionally or alternatively, the magnetic field produced by the magnetic nanoparticles could be induced by an external static and/or time-varying magnetic field or other applied energy or field. The magnetic nanoparticles could include a coating and/or be composed of a material that is biocompatible and/or specified to interact in some way with biological and/or chemical elements in an environment of interest (e.g., to interact specifically with an analyte of interest).

[0058] The magnetic nanoparticles may each include magnetic materials having a coercivity, remanence, susceptibility, permanent magnetic moment, or other magnetic property such that the magnetic nanoparticles can produce a magnetic field (e.g., by being magnetized, by reflecting or otherwise interacting with a time-varying electromagnetic field) that could be detected by a magnetometer proximate to the magnetic nanoparticles. In some examples, this could include the magnetic nanoparticles each including a single piece of magnetic material, e.g., a single particle or crystal of a ferromagnetic, ferrimagnetic, paramagnetic, superparamagnetic, or otherwise magnetic material. Such a magnetic material of a magnetic nanoparticle could be coated by an inert material, such as polystyrene. The magnetic nanoparticles could be similar (e.g., could each be similarly sized) or could vary, e.g., the size of the magnetic nanoparticles or some other properties of the magnetic nanoparticles could vary according to a distribution. For example, the nanoparticles could be configured to be magnetized by an external magnetic field and to have a degree of magnetization that decreases and/or reverses over time. For example, the nanoparticles could have magnetic relaxation times that are within a specified range of relaxation times (e.g., between approximately 100 milliseconds and approximately 1 second, or between approximately 1 second and approximately 2 seconds).

[0059] The magnetic nanoparticles could have an overall size and/or shape specified according to an application. For example, the magnetic nanoparticles could have a size and/or shape such that the magnetic nanoparticles can be transported in blood in the vasculature of a body without causing blockages and/or such that the magnetic nanoparticles, when magnetized (e.g., by an intrinsic magnetization and/or by application of a magnetic

field by a magnetic flux source), produce a magnetic field having a sufficiently high magnitude to be detected by one or more magnetometers proximate the magnetic nanoparticles (e.g., to be detected by a magnetometer located outside of a portion of subsurface vasculature containing the magnetic nanoparticles, e.g., from approximately a millimeter to approximately a centimeter away from the magnetic nanoparticles). In some examples, the magnetic nanoparticles can have a diameter that is less than about 20 micrometers. In some embodiments, the magnetic nanoparticles have a diameter on the order of about 5 nm to 1 μ m.

[0060] In some examples, the magnetic nanoparticles could have a magnetic relaxation time that is less than some specified value such that the magnetization decays, changes orientation, changes sign, or otherwise decreases in an amount of time related to the magnetic relaxation time. For example, the nanoparticles could have magnetic relaxation times between approximately 1 second and approximately 2 seconds. In another example, the nanoparticles could have magnetic relaxation times between approximately 100 milliseconds and approximately 1 second. In some examples, the magnetic relaxation time could be specified to be sufficiently long that the nanoparticles could substantially remain magnetized during a time required to flow from a first region at which the nanoparticles are magnetized (e.g., by a magnetic flux source) to a second region at which a magnetometer detects, directly or indirectly, a magnetic field produced by the still-magnetized nanoparticles. Such a specified magnetic relaxation time could be specified based on a distance between a magnetometer and a magnetic flux source configured to magnetize the nanoparticles, a flow rate or velocity of the nanoparticles (e.g., a flow rate of blood in a portion of subsurface vasculature, e.g., approximately 1 centimeter per second).

[0061] In some examples, the size of the magnetic nanoparticles could be related to the magnetic relaxation time, such that specifying a range of magnetic relaxation times of the nanoparticles could include specifying a size of the nanoparticles and/or of elements of magnetic material (e.g., a particle of superparamagnetic iron oxide) thereof. For example, a range of sizes of the nanoparticles (and/or of an element of magnetic material thereof) between approximately 10 nanometers and approximately 20 nanometers could correspond to a range of magnetic relaxation times between approximately 1 nanosecond and approximately 1 second.

[0062] In further embodiments, nanoparticles of magnetic material (e.g., particles of ferromagnetic, paramagnetic and/or superparamagnetic material) and/or other small particles on the order of 10-100 nanometers in diameter may be assembled to form

larger “clusters” or “assemblies” on the order of 1-10 micrometers. Further, the a magnetic relaxation time(s), arrangement, relative location and/or orientation, number, or other properties of such particles of magnetic material comprising a nanoparticle could be specified such that the nanoparticle is magnetizable and has a magnetic relaxation time within some specified range of relaxation times.

[0063] Those of skill in the art will understand a “particle” in its broadest sense and that it may take the form of any fabricated material, a molecule, cryptophan, a virus, a phage, etc. Further, a magnetic nanoparticle may be of any shape, for example, spheres, rods, non-symmetrical shapes, etc. In some examples, a magnetic material of the magnetic nanoparticles can include a paramagnetic, super-paramagnetic or ferromagnetic material or any other material that responds to a magnetic field. In some examples, the magnetic nanoparticles can include a magnetic moiety (e.g., an organic molecule that has a magnetic and/or magnetizable molecular orbital). Further, the particles can be configured to selectively bind to one or more analytes (e.g., chemicals, hormones, peptides, DNA or RNA fragments, cells). In some examples, the magnetic nanoparticles could be considered to include other elements (e.g., analytes, other magnetic or non-magnetic particles) bound to the magnetic nanoparticles. Other embodiments of magnetic nanoparticles are anticipated.

[0064] In some examples, the magnetic nanoparticles are functionalized to selectively interact with an analyte of interest. The magnetic nanoparticles can be functionalized by covalently attaching a bioreceptor designed to selectively bind or otherwise recognize a particular analyte (e.g., a clinically-relevant analyte, e.g., a cancer cell). For example, magnetic nanoparticles may be functionalized with a variety of bioreceptors, including antibodies, nucleic acids (DNA, siRNA), low molecular weight ligands (folic acid, thiamine, dimercaptosuccinic acid), peptides (RGD, LHRD, antigenic peptides, internalization peptides), proteins (BSA, transferrin, antibodies, lectins, cytokines, fibrinogen, thrombin), polysaccharides (hyaluronic acid, chitosan, dextran, oligosaccharides, heparin), polyunsaturated fatty acids (palmitic acid, phospholipids), or plasmids. The functionalized magnetic nanoparticles can be introduced into a portion of subsurface vasculature of a person or other environment of interest by injection, ingestion, inhalation, transdermal application, or in some other manner.

[0065] A clinically-relevant analyte could be any substance that, when present in the blood of a person or animal, or present at a particular concentration or range of concentrations and/or in a certain amount, may be indicative and/or causative of an adverse medical condition. For example, the clinically-relevant analyte could be an enzyme,

hormone, protein, other molecule, or even whole or partial cells. In one relevant example, certain proteins have been implicated as a partial cause of Parkinson's disease. Thus, the development of Parkinson's disease might be prevented or retarded by providing magnetic nanoparticles functionalized with a bioreceptor that will selectively bind to this target. The nanoparticles could be magnetic and/or could be magnetized, and a magnetic field produced by the magnetic nanoparticles may then be detected, using one or more systems or devices as described herein (e.g., a magnetometer in a wearable device mounted to an external body surface proximate to a portion of subsurface vasculature), to detect a property (e.g., a concentration, a presence) of the bound protein (e.g., to inform a treatment, to adjust a dosage of a drug). As a further example, the analyte could be a cancer cell. By detecting a magnetic field produced by magnetic particles configured to selectively interact with the cancer cells, the progress of cancer (e.g., remission, stage) may be quantified and used to inform some treatment or other action (e.g., to begin chemotherapy, to set a dosage of a chemotherapy drug).

[0066] In some examples, magnetic nanoparticles configured to selectively interact with (e.g., bind to) an analyte of interest could be used to provide some additional applications. For example, an attractive magnetic force could be applied to the magnetic nanoparticles to collect, extract, or otherwise manipulate the analyte. Additionally or alternatively, the magnetic nanoparticles could be used to modify or destroy the analyte of interest, e.g., by transducing an electromagnetic energy directed toward the magnetic nanoparticles (e.g., RF energy) into heat to denature or otherwise modify or destroy the analyte. In some examples, such operations (e.g., emission of an optical, RF, thermal, acoustical, or other type of energy to modify or destroy an analyte of interest) could be performed in response to determining some information about the analyte (e.g., determining that an instance of the analyte is proximate to a magnetometer of a device, and further within an area of effect of an energy emitter of the device) based on a detected magnetic field produced by the magnetic nanoparticles.

[0067] Magnetic fields produced by magnetic nanoparticles and detected at one or more locations (e.g., by magnetometers disposed at the one or more locations) can be used in a variety of ways to detect properties of the magnetic nanoparticles and/or to detect properties of an analyte of interest with which the magnetic nanoparticles are configured to selectively interact. For example, a direction, velocity, orientation, angular velocity, magnetic moment, degree of magnetization, degree of aggregation, or other properties of one or more magnetic nanoparticles could be determined based on a magnetic field detected at one or more

locations. Further, the presence, concentration, location, velocity, or other properties of the analyte could be determined based on the detected magnetic field and/or based on the determined properties of the magnetic nanoparticles. For example, the magnetic nanoparticles could be configured such that a plurality of magnetic nanoparticles could selectively interact with (e.g., bind to) a single instance of the analyte of interest. In such examples, the detection and/or determination that a plurality of the magnetic nanoparticles are aggregated (e.g., proximate each other) could be used to determine that an instance of the analyte is located proximate the aggregated magnetic nanoparticles. Other properties of a detected magnetic field and/or determined properties of the magnetic nanoparticles could be used to determine properties (e.g., location, number, concentration) of the analyte. For example, a velocity, angular velocity, magnetic property, or other property of the magnetic nanoparticles could be related to interaction between the magnetic nanoparticles and the analyte.

[0068] Figure 1A illustrates example magnetic particles 160 and an analyte of interest 170 with which the magnetic particles 160 are configured to selectively interact disposed in a blood vessel 150 (i.e., a portion of subsurface vasculature). In this example, disposed in blood vessel 150 are instances of an analyte 170 (e.g., a cell), in which each instance of analyte 170 is bound to several nanoparticles 160. Also disposed in blood vessel 150 are unbound nanoparticles 160. The blood vessel 150 is located in an arm 190 and contains blood that is flowing (direction of flow indicated by the arrow 155). A body-mountable device 100 includes a housing 110 mounted outside of or otherwise proximate to the blood vessel 150 by a mount 120 configured to encircle the arm 190. The body-mountable device 100 includes a magnetometer 130 disposed in the housing 110 and configured to detect a magnetic field at a location outside of the arm 190 (e.g., at a location within the magnetometer 130). The magnetic field detected by the magnetometer 130 could include magnetic fields produced by the magnetic nanoparticles 160 that are proximate the magnetometer 130, a magnetic field produced by the Earth, a magnetic field produced by electronics and/or electrical wiring (e.g., a magnetic field produced by an electromagnet, by other electronics of the body-mountable device 100, a magnetic field produced by a nearby automobile), an electromagnetic and/or magnetic field produced by precessing atomic magnetic moments (e.g., a time-varying magnetic field produced by precessing magnetic spins of hydrogen nuclei in water or other molecules in the blood vessel 150), a magnetic field produced and/or affected by a magnet or other magnetic material, and or some other magnetic fields and/or combinations of magnetic fields.

[0069] The body-mountable device 100 may further include a magnetic flux source (not shown), for example, a permanent magnet or an electromagnet, that is configured to magnetize the nanoparticles 160 in the blood vessel 150 that are proximate the magnetic flux source (e.g., that are within a first location of subsurface vasculature that is proximate the magnetic flux source). The location of the magnetic field detected by the magnetometer 130 may be downstream, relative the flow of blood 155, from the location at which the nanoparticles 160 are magnetized by the magnetic flux source (e.g., a second location of subsurface vasculature that is proximate the magnetometer 130 and that is downstream from the first location of subsurface vasculature).

[0070] A distance between such a magnetic flux source and the magnetometer 130 could be specified based on a variety of factors according to an application. In some examples, a distance between the magnetic flux source and the magnetometer 130 could be specified to be greater than a specified distance such that a degree of interference in the operation of the magnetometer 130 by magnetic fields (e.g., fringe fields) produced by the magnetic flux source is below some specified level. For example, the distance between the magnetic flux source and the magnetometer 130 could be specified to minimize a degree of magnetic field inhomogeneity in the blood vessel 150 proximate the magnetometer 130 (e.g., in examples wherein the magnetometer 130 is configured to detect magnetic fields produced by magnetic nanoparticles 160 by detecting precession frequencies of atomic nuclei proximate the magnetic nanoparticles 160 using nuclear magnetic resonance). Additionally or alternatively, the distance between the magnetic flux source and the magnetometer 130 could be specified to be less than a specified maximum distance such that a specified amount of nanoparticles 160 that are magnetized by the magnetic flux source and subsequently flow downstream to be proximate the magnetometer 130 are still magnetized when they flow proximate the magnetometer 130. Such a maximum distance could be related to a magnetic relaxation time of the nanoparticles, a flow rate of blood in the blood vessel 150, or some other factors.

[0071] The analyte 170 and magnetic nanoparticles 160 are configured and distributed in the blood vessel 150 such that multiple magnetic nanoparticle 160 can bind to a single instance of the analyte 170 (e.g., to a single cancer cell). Further, magnetic nanoparticles 160 that are not bound to the analyte 170 are generally singly distributed throughout the blood in the blood vessel 150. As a result, the existence of an aggregate of magnetic nanoparticles 160 located proximate to each other could be related to the presence of one or more instances of the analyte 170 proximate the aggregate of nanoparticles.

Additionally or alternatively, the velocity, angular velocity, magnetic properties (e.g., magnetic moment, coercivity, type of magnetic behavior (e.g., ferromagnetism, paramagnetism, superparamagnetism)), or other properties of the magnetic particles 160 could be related to binding to the analyte 170 and/or to some other properties of the analyte 170, magnetic nanoparticles 160, and/or the blood vessel 150.

[0072] The magnetometer 130 could be configured to detect the magnitude, direction, magnitude parallel to a specified direction, frequency, rate of change, or other properties of the magnetic field at a particular location. The particular location could be a location on or within the magnetometer. The particular location could be a volume of space within the magnetometer, e.g., the magnetometer could be configured to detect the average magnitude of the magnetic field across a sensing volume within the magnetometer (e.g., a sensing volume that contains a high-temperature, high-density gas of alkali metal atoms that is optically interrogated by the magnetometer).

[0073] The magnetometer could be configured and/or operated to detect a magnitude or other properties of a time-varying magnetic field within a specified range of frequencies (e.g., the magnetometer 130 could be a radio frequency atomic magnetometer). For example, the magnetometer 130 could be tuned to detect time-varying magnetic fields at frequencies approximately equal to a harmonic of a time-varying magnetic field to which the nanoparticles are exposed (e.g., a time-varying magnetic field produced in an environment proximate the magnetometer 130). In some examples, the magnetometer 130 could be configured to rotate magnetic spins of atomic nuclei (e.g., using one or more pulse emitters configured to emit pulses of electromagnetic radiation at the Larmor frequency of the atomic nuclei) and to detect magnetic and/or electromagnetic fields emitted by the rotated magnetic spins of the atomic nuclei as they responsively precess. The magnetometer 130 could be configured to detect the magnetic field with a specified sensitivity such that the magnetometer can detect magnetic fields produced by the magnetic nanoparticles 160 proximate the magnetometer (e.g., magnetic nanoparticle located less than approximately 1 centimeter from a sensing volume of the magnetometer). For example, the magnetometer could have a sensitivity that is less than approximately 10 femtoteslas.

[0074] Figure 1B illustrates an example signal 131 detected by the magnetometer 130 over time. The signal 131 represents a property of a magnetic field detected by the magnetometer 130 and/or a property or variable determined therefrom. For example, signal 131 could represent the magnitude of the detected magnetic field over time. In another example, the signal 131 could represent the amplitude of the detected magnetic field at a

specified frequency (e.g., a harmonic of a frequency of a magnetic field emitted by the device 100 to excite the magnetic nanoparticles 160). In a further example, the signal 131 could be related to a nuclear magnetic time constant determined from magnetic or electromagnetic fields detected by the magnetometer 130 (e.g., a T1, T2, T2*, or other time constant related to the behavior of the magnetic moments of atomic nuclei proximate the magnetometer 130). The signal 131 is intended to represent any detected or determined property of a magnetic field that could be detected by a magnetometer as described herein and that is related to an amount of magnetic and/or magnetized nanoparticles proximate such a magnetometer.

[0075] As shown in Figure 1B, the signal 131 includes a number of pulses 133a, 133b related to respective increases in the signal that is related to and/or determined from one or more properties of the magnetic field detected by the magnetometer 130. These pulses are related to the flow of blood 155 in the blood vessel 150 causing one or more magnetic nanoparticles 160 (e.g., single magnetic nanoparticles, aggregates of magnetic nanoparticles bound to the analyte 170) to become proximate to the magnetometer 130 (e.g., to become sufficiently proximate that the magnetic field produced by the one or more magnetic nanoparticles and or an effect thereof can be detected by the magnetometer 130) and subsequently to move away from the magnetometer 130.

[0076] The signal 131 includes lower-amplitude pulses 133b corresponding to the motion of individual magnetic nanoparticles 160 (e.g., magnetic nanoparticles that are not bound to the analyte 170) through the blood vessel 150 proximate the magnetometer 130. The signal 131 additionally includes higher-magnitude pulses 133a corresponding to the motion of aggregates of magnetic nanoparticles 160 (e.g., the aggregates may include magnetic nanoparticles bound to the analyte 170) through the blood vessel 150 proximate the magnetometer 130. The body-mountable device 100 could determine and/or detect the presence or other properties of the analyte 170 and/or of the magnetic nanoparticles 160 in the blood vessel 150 based on the width, amplitude, timing, or other properties of the detected pulses 133a, 133b. For example, a number of magnetic nanoparticles 160 proximate the magnetometer 130 at a particular time corresponding to a particular pulse detected in the signal 131 could be determined based on the amplitude of the particular pulse. For example, it could be determined that a single magnetic nanoparticle 160 is proximate to the magnetometer 130 at points in time corresponding to the lower-amplitude pulses 133b and that a plurality of magnetic nanoparticles 160 are proximate to the magnetometer 130 at points in time corresponding to the higher-amplitude pulses 133a. Related to this, it could be determined that an instance of the analyte 170 (e.g., a cancer cell) is proximate to the

magnetometer at particular points in time corresponding to the higher-amplitude pulses 133a (e.g., related to the aggregation of the magnetic nanoparticles 160 by the analyte 170 causing an increase in the amplitude of the detected magnetic field).

[0077] Further, a size, number, or other properties of the analyte 170 could be determined based on the amplitude, width, shape, or other properties of the higher-amplitude pulses 133a and/or based on some other property of a signal that is related to and/or determined from one or more properties of the magnetic field that is detected by the magnetometer. For example, an amplitude of a pulse in the signal 131 (e.g., an amplitude of a pulse in a detected magnetic field magnitude signal) could be related to a surface area of an instance of the analyte 170 (e.g., a greater surface area could permit more magnetic nanoparticles 160 to bind to the instance of analyte 170), a number of available nanoparticle-binding sites of the analyte 170, and/or a number of instances of the analyte 170. A amount of the analyte 170 (e.g., a concentration of the analyte, a number of instances of the analyte) in a body could be determined based on a rate of detection of instances of the analyte (e.g., a rate of higher-amplitude pulses in the detected signal 131), a mass flow rate of blood in the blood vessel 150, and/or other factors. A velocity of the analyte 170 and/or magnetic nanoparticles 160 could be related to a width of pulses in the signal 131. Other properties of the analyte 170, the magnetic nanoparticles 160, the blood vessel 150, and/or the arm 190 could be detected and/or determined based on other features of a signal that is related to and/or determined from one or more properties of a magnetic field that is detected by a magnetometer 130.

[0078] The signal 131 could represent the magnitude of the magnetic field detected by the magnetometer 130, the magnitude of the detected magnetic field in a particular direction, the amplitude or intensity of a time-varying (e.g., oscillating) magnetic field, the amplitude or intensity of a time-varying magnetic field within a range of frequencies, a time constant (e.g., T_1 , T_2 , T_2^*) or other property of magnetic spins of atomic nuclei proximate the magnetometer 130 that is detected or determined from a magnetic field detected by the magnetometer 130, or some other detected and/or determined property of a magnetic field detected by the magnetometer 130. Further, a detected and/or determined property of the detected magnetic field over time could be similar or different from the illustrated example signal 131. Binding of the magnetic nanoparticles 160 to instances of the analyte 170 could be determined and/or detected based on other detected properties of the magnetic field detected by the magnetometer 130 and/or by additional or alternative features thereof. For example, a velocity, an angular velocity, or some other property of motion of one or more

magnetic nanoparticles 160 could be related to whether the magnetic nanoparticle is bound to one or more instances of the analyte 170. That is, magnetic nanoparticles 160 bound to the analyte 170 could be hindered from rotating by the analyte 170, could be sped or slowed in the flow 155 of blood in the blood vessel 150 by the analyte 170 (e.g., due to a drag coefficient of the analyte 170), or could exhibit some other property or behavior that is related to binding to the analyte 170 and that can be detected using the magnetometer 130.

[0079] Magnetic nanoparticles could be magnetized by a magnetic flux source that is proximate to a magnetometer (e.g., 130) that is configured to detect a magnetic field produced by and/or related to such magnetized magnetic nanoparticles. In such examples, the magnetic flux source could act to produce a magnetizing flux during a first period of time and to produce less magnetic flux (e.g., to produce substantially no magnetic flux) during a second period of time. For example, the magnetic flux source could be operated in such a way to reduce a magnitude of an interfering magnetic field (e.g., a magnitude of fringe fields produced by the magnetic flux source at the location of the magnetometer, a degree of inhomogeneity in the background magnetic field proximate the magnetometer) produced by the magnetic flux source, e.g., to permit the magnetometer to more accurately detect fields related to magnetic fields produced by magnetic nanoparticles. In some examples, this could include reducing a current applied to an electromagnet of the magnetic flux source. Additionally or alternatively, this could include mechanically actuating one or more elements of the magnetic flux source, e.g., to rotate a permanent magnet, to move a magnetic shim, to move the magnetic flux source away from the magnetometer, or to actuate one or more elements of the magnetic flux source and/or magnetometer in some other way.

[0080] Further, a magnitude or other properties of a magnetic field produced by such a magnetic flux source could be controlled over time (e.g., according to a square wave or some other time-varying pattern or waveform) to increase an accuracy or to otherwise improve the detection of properties of the nanoparticles and/or an analyte bound thereto based on magnetic fields detected using the magnetometer. For example, a magnetic flux source could produce a magnetic field having a magnitude that varies according to a square wave having a frequency of approximately 10 Hertz. In such an example, a magnetic field that is related to properties of the nanoparticles (e.g., a magnitude of the magnetic field produced by nanoparticles proximate the magnetometer, an amplitude of a time-varying magnetic field produced by the nanoparticles in response to exposure to an exciting time-varying magnetic field) could be detected by the magnetometer and demodulated or otherwise operated on based on the frequency of the time-varying magnetic field produced by

the magnetic flux source.

[0081] Note that the use of the magnetometer 130 to detect magnetic fields produced by magnetic nanoparticles 160 in a flow 155 of blood in a blood vessel 150 (e.g., magnetic nanoparticles that have been magnetized by an upstream magnetic flux source) and further to determine properties of the magnetic nanoparticles 160 and/or an analyte 170 to which the magnetic nanoparticles 160 are configured to bind is intended as a non-limiting illustrative example of embodiments described herein. Magnetic nanoparticles could be disposed in a variety of different environments (e.g., other bodily fluids, fluids of an animal, fluids of a natural environment, fluids of a medical, scientific, or industrial process). The magnetic nanoparticles could be disposed in a flowing fluid or in a substantially static fluid. The magnetic nanoparticles could be disposed in a flowing fluid or in a substantially static fluid. The embodiments herein could be applied to the detection and/or determination of properties of magnetic nanoparticles and/or analytes in an ex vivo and/or in vitro flow cytometry experiment or process. One or more magnetometers configured to detect magnetic fields produced by magnetic nanoparticles could be disposed in a wearable, body-mountable, handheld, desktop, floor-, wall-, ceiling-, or otherwise-mounted, or otherwise configured device or system. Further, methods and systems described herein could be used with permanently magnetic and/or magnetized nanoparticles. The nanoparticles could be disposed in a flowing fluid or in a substantially static fluid according to an application. Other environments and applications are anticipated.

III. Example methods for detecting magnetic nanoparticles

[0082] Magnetometers of embodiments described herein could be configured to detect magnetic fields produced intrinsically by nanoparticles, e.g., produced by permanently and/or spontaneously magnetic elements of the nanoparticles. Additionally or alternatively, the nanoparticles could be induced to produce a magnetic field, e.g., by being temporarily or permanently magnetized, by being exposed to an oscillating or otherwise time-varying electromagnetic field, or by some other means. Additionally or alternatively, magnetometers could be configured to detect magnetic fields related to magnetic fields produced by magnetized magnetic nanoparticles. For example, precessing magnetic spins of atomic nuclei (e.g., hydrogen atoms in water) could precess at a frequency that is related to the magnetic field magnitude in the environment of the atomic nuclei, e.g., related to a magnetic field that is a combination of the Earth's magnetic field and a magnetic field produced by magnetic nanoparticles. Such magnetic spins of atomic nuclei could produce time-varying magnetic

fields related to the precession and the magnetometer could detect such produced magnetic fields (e.g., the magnetometer could be configured to indirectly detect magnetic fields produced by magnetic nanoparticles by using the techniques of nuclear magnetic resonance to detect the effects of such magnetic nanoparticles on proximate atomic nuclei).

[0083] A magnetometer could be configured to directly detect the magnetic field produced by one or more magnetic nanoparticles. The direction, magnitude, and/or other properties of the produced magnetic field at a particular location can be related to the location and/or orientation of the one or more magnetic nanoparticles relative to the particular location, the magnitude of the permanent and/or induced magnetic dipole moment of the magnetic nanoparticles, magnetic properties of materials proximate the particular location, or other factors. A magnetic field at the particular location (e.g., a direction and/or magnitude of a magnetic field detected by, e.g., a magnetometer) could be related to the magnetic field of the earth, magnetic fields produced by electronics or other devices proximate the particular location, magnetic and/or electromagnetic fields produced by atomic magnetic spins that are precessing in a magnetic field (e.g., a magnetic field produced by the Earth and/or by one or more magnetic nanoparticles), magnetized or otherwise magnetic materials proximate the particular location, or other factors in addition to the magnetic field produced by the one or more magnetic nanoparticles.

[0084] In such examples wherein the magnetometer is configured to directly detect magnetic fields produced by magnetic nanoparticles, the magnetometer could have a sensitivity below approximately 10 femtoteslas to, e.g., permit detection of magnetic fields produced by the magnetic nanoparticles that are within an environment of interest that is displaced from the magnetometer by some distance, e.g., magnetic nanoparticles that are disposed in a portion of subsurface vasculature that is approximately 1 centimeter from the magnetometer beneath a skin surface to which the magnetometer is mounted. Such a magnetometer could be an optical atomic magnetometer, i.e., a magnetometer configured to detect magnetic fields by optically pumping and/or optically detecting a state of atoms in a gas (e.g., atoms of a metal vapor comprising cesium, rubidium, potassium, or some other fermionic atoms) that is related to the magnitude, direction, magnitude in a specified direction, or some other property of the magnetic field within the gas. For example, the magnetometer could be a spin-exchange relaxation-free (SERF) magnetometer configured to detect low-frequency components of a magnetic field in one or more specified directions. Additionally or alternatively, the magnetometer could include a multipass scalar atomic magnetometer configured to detect the magnitude of the magnetic field.

[0085] In some examples, multiple magnetometers could be operated to detect magnetic fields produced by magnetic nanoparticles (e.g., by permanently magnetic nanoparticles, by magnetized nanoparticles) proximate the multiple magnetometers to provide applications described herein. Such multiple magnetometers could be configured and/or operated to detect a magnetic field gradient, to map a magnetic field across an area and/or volume, to determine a magnetic field produced by magnetic nanoparticles in an environment by detecting a magnetic field using a first magnetometer and subtracting a background magnetic field detected by a second magnetometer, or according to some other scheme to provide some other application(s).

[0086] Such multiple magnetometers could be configured to detect the same property of magnetic fields at respective locations (e.g., field magnitude, field magnitude in a specified direction, field direction) or different properties. The magnetometers could be similarly configured and/or the same type of magnetometer (e.g., the magnetometers could both be SERF magnetometers, inductive pickup coils, SQUIDs, multipass scalar atomic magnetometers, radio frequency atomic magnetometers) or differently configured. For example, a first magnetometer could be less sensitive than a second magnetometer and the output of the first magnetometer could be used to operate the second magnetometer (e.g., to set a bias, to set an offset, to apply a biasing magnetic field, or to otherwise improve the sensitivity or some other aspect of the operation of the second magnetometer based on information about the magnetic field expected to be detected by the second magnetometer determined from magnetic field information detected by the first magnetometer).

[0087] Figure 2A illustrates an example complex 265 that includes magnetic particles bound to an analyte of interest disposed in a blood vessel 250 (i.e., a portion of subsurface vasculature). The blood vessel 250 is located in an arm 290 and contains blood that is flowing (direction of flow indicated by the arrow 255). A body-mountable device 200 includes a housing 210 mounted outside of the blood vessel 250 by a mount 220 configured to encircle the arm 290. The body-mountable device 200 includes first 230a and second 230b magnetometers disposed in the housing 210 and configured to detect magnetic fields at respective locations proximate to (e.g., outside of) the arm 290 (e.g., at locations within the magnetometers 230a, 230b). The magnetic fields detected by the magnetometers 230a, 230b could include magnetic fields produced by magnetic nanoparticles of the complex 265 that are proximate the magnetometers 230a, 230b, a magnetic field produced by the Earth, a magnetic field produced by electronics and/or electrical wiring (e.g., a magnetic field produced by an electromagnet, by other electronics of the body-mountable device 200, a

magnetic field produced by a nearby automobile), a magnetic field produced and/or affected by a magnet or other magnetic material, and or some other magnetic fields and/or combinations of magnetic fields.

[0088] Figure 2B illustrates first 233a and second 233b example signals detected by the first 230a and second 230b magnetometers, respectively, over time. The signals 231a, 231b represent the magnitude of respective detected magnetic fields over time. As shown in Figure 2B, the signals 231a, 231b each include a respective pulse 233a, 233b related to respective increases in the magnetic fields detected by the magnetometers 230a, 230b. These pulses are related to the flow of blood 255 in the blood vessel 250 causing the complex 265 to become proximate to each of the magnetometers 230a, 230b (e.g., to become sufficiently proximate that the magnetic field produced by the magnetic nanoparticles of the complex 265 can be detected by the magnetometers 230a, 230b) and subsequently to move away from the magnetometers 230a, 230b.

[0089] The signals 231a, 231b include a background signal substantially in common that corresponds to a background magnetic field detected by both of the magnetometers 230a, 230b. The signals 231a, 231b additionally include pulses 233a, 233b corresponding to the motion of the complex 265 through the blood vessel 250 proximate the first 230a and second 230b magnetometers, respectively. The body-mountable device 200 could determine the background magnetic field and/or determine the magnetic field produced by magnetic nanoparticles in the blood vessel 250 (e.g., 275) at the location of each of the magnetometers 230a, 230b based on the first 231a and second 231b signals. This could include performing a linear operation (e.g., averaging, subtraction, correlation, filtering), a nonlinear operation (e.g., nonlinear filtering, application of some probabilistic or clustering algorithm), or some other operation on one or both of the signals 231a, 231b. For example, Figure 2C shows an example difference signal 241 determined as the difference between the first 231a and second 231b detected magnetic field signals. The difference signal 241 includes first 243a and second 243b pulses corresponding to the motion of the complex 265 through the blood vessel 250 proximate the first 230a and second 230b magnetometers, respectively.

[0090] The body-mountable device 200 could determine and/or detect the presence or other properties of the complex 265 and/or of an analyte and/or magnetic nanoparticles in the blood vessel 250 based on the width, amplitude, timing, or other properties of the detected pulses 233a, 233b. For example, a number of magnetic nanoparticles proximate a particular magnetometer (e.g., 230a, 230b) at a particular time corresponding to a particular pulse detected in the difference signal 241 could be determined based on the amplitude and/or sign

of the particular pulse. For example, it could be determined that an aggregate of magnetic nanoparticles (e.g., 265) is proximate to the first magnetometer 230a at a point in time corresponding to the first, positive-sign pulse 243a. Further, a velocity of the complex 265 (or of some other magnetic element(s) producing magnetic fields detected by the magnetometers 230a, 230b) could be determined based on a difference in timing of detected pulses or other features of detected magnetic field signals produced by two or more magnetometers (e.g., 230a, 230b).

[0091] The magnetometers 230a, 230b could be configured to detect the same property of magnetic fields at respective locations (e.g., field magnitude, field magnitude in a specified direction, field direction) or different properties. The magnetometers could be similarly configured and/or the same type of magnetometer (e.g., the magnetometers 230a, 230b could both be SERF magnetometers, inductive pickup coils, SQUIDS) or differently configured. For example, the first magnetometer 230a could be less sensitive than the second magnetometer 230b and the output of the first magnetometer 230a could be used to operate the second magnetometer 230b (e.g., to set a bias, to set an offset, to apply a biasing magnetic field, or to otherwise improve the sensitivity or some other aspect of the operation of the second magnetometer 230b based on information about the magnetic field expected to be detected by the second magnetometer 230b determined from magnetic field information detected by the first magnetometer 230a).

[0092] Note that the background magnetic field detected by both magnetometers 230a, 230b and present substantially in common in both detected magnetic field signals 231a, 231b could be produced by and/or related to a variety of factors and/or objects. The background magnetic fields detected by the magnetometers 230a, 230b could include magnetic fields produced by magnetic elements and/or currents in the arm 290 that are substantially equally proximate to both magnetometers 230a, 230b, a magnetic field produced by the Earth, a magnetic field produced by electronics and/or electrical wiring (e.g., a magnetic field produced by an electromagnet, by other electronics of the body-mountable device 200, a magnetic field produced by a nearby automobile), a magnetic field produced and/or affected by a magnet or other magnetic material, and or some other magnetic fields and/or combinations of magnetic fields. As described herein, such a detected background magnetic field could be used to determine and/or detect the magnetic field produced by magnetic nanoparticles in a portion of subsurface vasculature (or other environment of interest), to operate one or more magnetometers (e.g., to set a bias, to apply a biasing magnetic field), or to provide some other operation related to the detection of magnetic fields

produced by magnetic nanoparticles. Additionally or alternatively, such a detected background magnetic field could be used for some other application, e.g., to determine a local environmental magnetic field (e.g., related to magnetic north), to detect the location and/or orientation or changes of the body-mountable device 200 and/or changes thereof (e.g., motion, rotation), or to provide some other application.

[0093] In some examples, a detected and/or determined background field at a particular location could be reduced to improve the operation of a magnetometer to detect a magnetic field of interest (e.g., a magnetic field produced by magnetic nanoparticles proximate the location) at the particular location. This could be performed to reduce a dynamic range required to detect a magnetic field of interest, because a magnetometer is configured to operate in low-field conditions (e.g., the magnetometer is a SERF magnetometer configured to operate in magnetic fields less than some maximum value), or according to some other consideration. In some examples, this could include disposing magnetic shielding and/or shimming materials or components (e.g., components composed of mu-metal, ferrites, conductors, or other magnetic materials) to reduce the effect and/or presence of the background magnetic field at the particular location. In some examples, a biasing magnetic field could be applied to the particular location to cancel the background field. This could include magnets and/or electromagnets configured to provide the cancelling field. In some examples, the cancelling field could be controlled to match the background magnetic field, e.g., by controlling a location and/or orientation of a magnet and/or magnetic material (e.g., shim), by controlling a current applied to an electromagnetic coil, or by some other means.

[0094] Figure 3A illustrates an example complex 365 that includes magnetic particles bound to an analyte of interest disposed in a blood vessel 350 (i.e., a portion of subsurface vasculature). The blood vessel 350 is located in an arm 390 and contains blood that is flowing (direction of flow indicated by the arrow 355). A body-mountable device 300 includes a housing 310 mounted outside of the blood vessel 350 by a mount 320 configured to encircle the arm 390. The body-mountable device 300 includes a magnetometer 330 disposed in the housing 310 and configured to detect magnetic fields at a location proximate to (e.g., outside of) the arm 390 (e.g., at a location within the magnetometer 330). The body-mountable device 300 additionally includes a bias coil 335 disposed proximate to the magnetometer 330 and configured to produce a bias magnetic field such that the magnetic field detected by the magnetometer 330 (e.g., the magnetic field at the location outside of the arm 390) is reduced by an amount related to the bias magnetic field (e.g., the detected

magnetic field is substantially equal to the vector sum of the bias magnetic field and any other magnetic fields present at the location outside the arm, e.g., a magnetic field produced by the complex 365). The magnetic fields detected by the magnetometer 330 could additionally include a magnetic field produced by the Earth, a magnetic field produced by electronics and/or electrical wiring (e.g., a magnetic field produced by an electromagnet, by other electronics of the body-mountable device 300, a magnetic field produced by a nearby automobile), a magnetic field produced and/or affected by a magnet or other magnetic material, and or some other magnetic fields and/or combinations of magnetic fields.

[0095] Figure 3B illustrates an unbiased magnetic field 331a that could be present at the location at which the magnetometer detects a magnetic field over time. The unbiased magnetic field 331a includes a pulse 333a related to an increases in the magnetic field detected by the magnetometer 330 related to the flow of blood 355 in the blood vessel 350 causing the complex 365 to become proximate to the magnetometer 330 and subsequently to move away from the magnetometer 330. Figure 3B additionally illustrates a bias field magnitude 336 that shows the magnitude of the bias field generated by the bias coil 335 over time, as measured at the location at which the magnetometer detects a magnetic field. The bias magnetic field (i.e., the magnetic field generated by the bias coil 335 according to the bias field magnitude 336) and the unbiased magnetic field (i.e., the magnetic fields present at the location at which the magnetometer detects a magnetic field that are not produced by the bias coil 335) have opposite directions at the location at which the magnetometer detects a magnetic field; that is, the bias magnetic field at least partially cancels the unbiased magnetic field. The bias field magnitude 336 could be determined in a number of ways, e.g., based on magnetic field values detected by the magnetometer 330 at previous points in time, on a magnetic field detected by another magnetometer (not shown), on the output of some other sensor (not shown), or based on some other consideration. Figure 3B further illustrates an example detected signal 331b detected by the magnetometer 330 over time. The detected signal 331b represents the magnitude of the combination of the bias magnetic field and the unbiased magnetic field over time. As a result, the detected signal 331b includes a pulse 333b related to the magnetic fields produced by magnetic nanoparticles of the complex 365 as the complex moves past the magnetometer 330.

[0096] The bias field magnitude 336 could be determined and/or generated by a variety of methods and related to a variety of signals and/or factors such that a background magnetic field and/or some other unwanted signal or field is not detected by the magnetometer 330. In some examples, this could include performing a linear operation (e.g.,

averaging, subtraction, correlation, filtering), a nonlinear operation (e.g., nonlinear filtering, application of some probabilistic or clustering algorithm), or some other operation on the signals detected by the magnetometer 330, e.g., operating the bias coil 335 such that the generated bias magnetic field operates to reduce the signal detected by the magnetometer 330 using negative feedback. In another example, a second magnetometer (not shown) could be included (e.g., a magnetometer that is less-sensitive than, that has a greater dynamic range than, that detects magnetic fields at a different location than, or that is otherwise differently configured from the magnetometer 330) and the output of the second magnetometer could be used to determine the bias field magnitude.

[0097] A body-mountable device (e.g., 300) could include additional or alternative means for creating a bias magnetic field. For example, the body-mountable device 300 could include three or more coils configured to generate a bias magnetic field having a specified direction, magnitude, and/or other specified properties. In some examples, a permanent magnet or other magnetic materials (e.g., shims composed of mu-metal, ferrite, or some other magnetic material) could be configured to at least partially cancel an unwanted magnetic present at a magnetometer. In some examples, such magnetic elements could be actuated (e.g., motorized, have a modulatable magnetic property) such that the bias magnetic field produced can be controlled, e.g., based on a bias field magnitude determined based on an estimate of the unwanted magnetic field.

[0098] Magnetometers of embodiments described herein could be configured to detect magnetic fields produced intrinsically by magnetic nanoparticles, e.g., produced by permanently and/or spontaneously magnetic elements of the magnetic nanoparticles. Additionally or alternatively, the magnetic nanoparticles could be induced to produce a magnetic field, e.g., by being temporarily or permanently magnetized, by being exposed to an oscillating or otherwise time-varying electromagnetic field, or by some other means.

[0099] In some examples, a magnetometer could detect the response of magnetic nanoparticles to a provided external energy, e.g., to an oscillating or otherwise time-varying magnetic field produced in an environment of interest (e.g., produced by one or more pulse emitters and/or excitation coils). This could include detecting magnetic fields produced by the magnetic nanoparticles in response to such provided external energy, e.g., detecting a time-varying magnetic field produced by magnetic nanoparticles in response to being exposed to an oscillating magnetic field. For example, a difference between a phase, frequency, magnitude, or other properties of the provided and a responsively produced oscillating magnetic fields could be used to determine a susceptibility, coercivity, degree of

magnetization, degree of aggregation, or other magnetic properties of magnetic nanoparticles in an environment.

[00100] In some examples, a system could include an excitation coil (or some other antenna or other type of electromagnetic-field-producing element(s)) configured to produce an oscillating magnetic field in an environment of interest (e.g., in a portion of subsurface vasculature). The produced oscillating magnetic field could cause magnetic nanoparticles and/or other magnetic objects or materials in the environment of interest to produce a magnetic field that could be detected by a magnetometer positioned proximate to the environment of interest. One or more properties of the magnetic nanoparticles, analytes with which the magnetic nanoparticles are configured to selectively interact, and/or some other contents of the environment could be detected and/or determined based on the detected magnetic field. The magnetic field produced by the magnetic nanoparticles could include a reflected, phase-shifted, frequency-shifted, frequency-multiplied, or otherwise modified version of the field produced by the excitation coil.

[00101] For example, the magnetic field produced by the magnetic nanoparticles could include a fundamental frequency at the frequency of the oscillating field produced by the excitation coil and a number of harmonics at frequencies that are multiples of the frequency of the oscillating field. In some examples, the magnetization of the magnetic nanoparticles (e.g., the degree to which a magnetic flux source is configured and/or operated to magnetize the nanoparticles) could be specified to maximize the magnitude of such a responsively produced oscillating (or otherwise time-varying) signal. For example, the magnitude of oscillating time-varying magnetic fields that are harmonics of an exciting oscillating magnetic field and that are produced by a magnetized nanoparticle in response to exposure to the exciting field could be maximized by magnetizing the magnetized nanoparticles such that their degree of magnetization is near a particularly nonlinear aspect of a magnetization curve of the nanoparticles.

[00102] Figure 4 shows an example power spectrum 400 of a magnetic field produced by magnetic nanoparticles in such a scenario. The magnetic field produced by the magnetic nanoparticles in response to the oscillating magnetic field produced by the excitation coil includes an oscillating field at substantially the same frequency as the frequency of the oscillating field produced by the excitation coil (the fundamental peak 401 of the power spectrum 400) and oscillating fields at multiples of the frequency of the oscillating field produced by the excitation coil (the harmonic peaks 402, 403 of the power spectrum 400). The presence, location, number, or other properties of magnetic nanoparticles proximate the

magnetometer could be determined based on the amplitude, presence, phase shift, width, center frequency, or other properties of the harmonic peaks 402, 403, fundamental peak 401, and/or the aspects of the detected magnetic field corresponding to those peaks. In some examples, a filter or other means could be used to remove the fundamental peak 401 from the detected magnetic field to, e.g., increase a sensitivity of a detector to properties of the harmonic peaks 402, 403.

[00103] In some examples, an exciting, time-varying (e.g., oscillating) magnetic field could be produced to have a magnitude in a first direction, and magnetic fields responsively produced by magnetic nanoparticles could be detected in a second direction that is perpendicular to the first. For example, a magnetometer could be configured to detect the magnitude of a time-varying magnetic field in the second direction while being substantially insensitive to the magnitude of magnetic fields in the first direction. This could be performed, e.g., to reduce the interference of the exciting field on the nanoparticle-related fields detected by the magnetometer. Further, an easy axis, a direction of magnetization, or some other property of the magnetic nanoparticles could be controlled, relative to the first and second directions, to increase the magnitude of the signal detected by the magnetometer and/or to reduce an amount of the exciting magnetic field that is detected by the magnetometer. For example, a direction of the an easy axis of one or more nanoparticles and/or a direction of an induced magnetic moment of magnetic nanoparticles could be controlled (e.g., by a direction of a magnetic field produced by a magnetic flux source) to be in a direction between the first and second directions, e.g., a direction that is approximately 45 degrees from each of the first and second directions.

[00104] A magnetometer configured to detect such time-varying (e.g., oscillating) magnetic fields produced by magnetic nanoparticles could include a SERF magnetometer, a radio-frequency atomic magnetometer (e.g., a radio frequency atomic magnetometer that is configured to detect contents of a time-varying magnetic field at a frequency corresponding to a harmonic of a frequency of an exciting oscillating magnetic field), a SQUID, an inductive pickup (e.g., one or more coils of wire or otherwise-formed inductive antenna(s)), or some other time-varying magnetic field detecting means. Such a magnetometer could be sensitive to time-varying magnetic fields to a level of approximately 100 femtoteslas or less.

[00105] In some examples, magnetic fields produced by magnetic nanoparticles could be detected indirectly, e.g., the effects of the magnetic nanoparticles on elements of the environment proximate the magnetic nanoparticles could be detected. For example, a fluorophore or other element of the environment could have an optical property (e.g., a

fluorescence intensity, a fluorescence lifetime) that is related to the magnitude of the magnetic field to which the fluorophore is exposed (e.g., the magnitude of a magnetic field produced by a magnetic nanoparticle proximate the fluorophore) and the optical property of the fluorophore could be detected (e.g., by illuminating the fluorophore and detecting a responsively emitted light from the fluorophore). Such a fluorophore could include one or more magnetic moieties configured to change a shape of the fluorophore or to otherwise alter the fluorophore when exposed to a magnetic field such that the optical property of the fluorophore is related to the magnetic field (e.g., to a magnetic field produced by a proximate magnetic nanoparticle).

[00106] In some examples, indirectly detecting magnetic fields produced by magnetic nanoparticles could include using the techniques of nuclear magnetic resonance and/or magnetic resonance imaging to detect the effects of the magnetic nanoparticles on the magnetic spins of atomic nuclei (e.g., hydrogen atoms in water or in other compounds) that are proximate the magnetic nanoparticles. A magnetic spin of an atomic nucleus (e.g., a fermionic atomic nucleus having half-integer overall spin, e.g., a nucleus of a hydrogen atom) could, when perturbed from an equilibrium state (e.g., from alignment with a magnetic field in the environment of the atomic nucleus), precess for a period of time until it returns to the equilibrium state. Precession could occur at a frequency related to the magnitude of the background magnetic field. Thus, when a population of atomic nuclei are perturbed in a substantially homogeneous magnetic field (e.g., in the Earth's magnetic field, in the absence of a significant source of magnetic flux), the atomic nuclei will precess at substantially the same frequency. Conversely, when inhomogeneities are present in the magnetic field (e.g., inhomogeneities related to magnetic fields produced by one or more magnetic nanoparticles), the atomic nuclei will precess at a range of difference frequencies related to the range of magnetic field strengths throughout the inhomogeneous magnetic field.

[00107] Systems and devices as described herein (e.g., devices including magnetometers configured to detect magnetic fields related to magnetic nanoparticles and/or magnetic flux sources configured to magnetize such nanoparticles) could use such properties of atomic nuclei to detect properties of magnetic nanoparticles and/or of analyte to which such nanoparticles are configured to bind. That is, such systems and devices could use techniques from nuclear magnetic resonance and/or magnetic resonance imaging to detect the magnetic nanoparticles by detecting magnetic resonance time constants of the atomic nuclei (e.g., a T1 constant, a T2 constant, a T2* constant) or some other properties of the atomic nuclei. This could include polarizing the atomic nuclei (e.g., to increase a signal strength of a

magnetic field produced by precessing magnetic spins of the atomic nuclei that is detected by a magnetometer), rotating the polarized atomic nuclei (e.g., such that the polarized atomic nuclei begin to precess in the background magnetic field by, e.g., operating one or more pulse emitters to emit one or more magnetic spin rotating pulses), and detecting a time-varying magnetic and/or electromagnetic field generated by the precessing magnetic spins of the atomic nuclei.

[00108] Polarizing the magnetic spins of the atomic nuclei could include exposing the atomic nuclei to a strong magnetic field, e.g., a magnetic field having a strength on the order of one to several Tesla. In some examples, such a magnetic field could be provided by a magnetic flux source of a wearable device (e.g., a permanent magnet, electromagnet, or other element(s) of such a wearable device). In some examples, such a magnetic flux source could also be configured to magnetize nanoparticles as described elsewhere herein. In some examples, the magnetic flux source could polarize the magnetic spins of the atomic nuclei at a first location and the atomic nuclei could then flow downstream (e.g., in a blood flow) to a second location at which the magnetic spins could be rotated and/or a magnetometer could detect time-varying magnetic fields produced by such rotated, precessing magnetic spins. In some examples, the magnetic flux source could be configured such that the field produced by the magnetic flux source is substantially homogeneous proximate the magnetometer and/or pulse emitter(s) used to rotate the magnetic spins. This could include locating the magnetic flux source more than some minimum distance from the magnetometer and/or pulse emitters. Additionally or alternatively, the magnetic flux source could be operated to reduce the magnitude and/or inhomogeneity of the produced polarizing field (e.g., by reducing a current applied to an electromagnet of the magnetic flux source, by rotating or otherwise actuating a permanent magnet and/or magnetic shim of the magnetic flux source, by moving the magnetic flux source away from the magnetometer and/or pulse emitter(s)). In some examples, an electromagnet, permanent magnet, magnetic shims, or other elements could be configured and/or operated to reduce an inhomogeneity of the magnetic field proximate the magnetometer and/or pulse emitter(s).

[00109] Rotating the polarized atomic nuclei could include emitting a pulse of an oscillating magnetic field oriented in a particular direction using one or more coils or other pulse emitting components. The frequency of the emitted pulse(s) could be the Larmor frequency of the atomic nuclei in whatever background magnetic field is present. In some examples, a magnetometer (e.g., the magnetometer configured to detect time-varying magnetic fields produced by rotated magnetic spins of the atomic nuclei) could be operated to

detect the magnitude of the background magnetic field such that the Larmor frequency could be determined. The emitted pulses could include one or more π pulses, $\pi/2$ pulses, or other pulses of a magnetic and/or electromagnetic field to rotate or otherwise excite the polarized magnetic moments of the atomic nuclei such that the magnetic spins precess in a manner that can be detected by the magnetometer. For example, the emitted pulse(s) could result in the magnetic spins emitting a free induction decay pulse that decays at a rate related to T_2 or other magnetic resonance time constant of the atomic spins and that has a frequency related to the magnitude of the background magnetic field and any inhomogeneities thereof. An orientation of the emitted pulse (i.e., an orientation of the spin-rotating time-varying magnetic field) could be controlled (e.g., by controlling a relating amplitude and/or phase of current pulses applied to respective different pulse-emitting coils) according to a detected direction of the background magnetic field (e.g., such that the magnetic spins of the atomic nuclei are rotated approximately 90 degrees with respect to the direction of the background magnetic field).

[00110] The magnetometer could detect the direction, magnitude, magnitude in a particular direction, or other properties of the magnetic field emitted by the rotated magnetic spins of the atomic nuclei. For example, the magnetometer could be a spin-exchange relaxation-free (SERF) magnetometer configured to detect low-frequency components of a magnetic field in one or more specified directions. Additionally or alternatively, the magnetometer could include a multipass scalar atomic magnetometer configured to detect the magnitude of the magnetic field. Additionally or alternatively, the magnetometer could be tuned to detect specific components of the magnetic field (e.g., components within specified range(s) of frequencies) produced by the precessing magnetic spins. For example, the magnetometer could include a radio frequency atomic magnetometer tuned to the Larmor frequency of the magnetic spins of the atomic nuclei. In a particular example, wherein the background magnetic field is the Earth's magnetic field (e.g., between approximately 0.25 and approximately 0.65 Gauss at the Earth's surface), the radio frequency atomic magnetometer could be tuned to a corresponding Larmor frequency of several kilohertz (e.g., approximately 2 kilohertz). Additionally or alternatively, a multipass scalar atomic magnetometer could be configured to detect time-varying magnetic fields at such frequencies.

[00111] In some examples, multiple magnetometers could be operated to detect magnetic fields produced by and/or related to magnetic nanoparticles proximate the multiple magnetometers to provide applications described herein. Such multiple magnetometers could be configured and/or operated to detect a magnetic field gradient, to map a magnetic field

across an area and/or volume, to determine a magnetic field produced by magnetic nanoparticles in an environment by detecting a magnetic field using a first magnetometer and subtracting a background magnetic field detected by a second magnetometer, or according to some other scheme to provide some other application(s).

[00112] Magnetometers, devices containing magnetometers, magnetic nanoparticles, and other aspects and embodiments described herein (e.g., 100, 200, 300, 500, 600, 700, 800) could be configured and/or operated to provide a variety of applications. In some examples, magnetic nanoparticles could be configured to bind to an analyte of interest, and one or more magnetometers could detect a magnetic field produced by the magnetic nanoparticles to determine one or more properties (e.g., a presence, a location, a number, a concentration) of the analyte. In some examples, a device could be configured to collect, release, separate, modify, or otherwise manipulate the magnetic nanoparticles to enable the detection, extraction, modification, or other manipulation of the analyte. Additionally or alternatively, the system could include an energy emitter and the energy emitter could emit energy toward collected magnetic nanoparticles and/or when it is detected that the analyte is present to alter one or more properties of the analyte (e.g., to destroy, denature, heat, change a conformation state of, or otherwise modify the analyte). In some examples, detection of one or more properties of an analyte bound to magnetic nanoparticles could enable the determination of a course of medical treatment, the adjustment of a dosage of a drug, the generation of a medical alert, or some other action. Other configurations, operations, and applications of the embodiments described herein are anticipated.

[00113] The terms “binding”, “bound”, and related terms used herein are to be understood in their broadest sense to include any interaction between the receptor and the target or another functionalized particle such that the interaction allows the target to be modified or destroyed by energy emitted from a wearable device.

IV. Example use of magnetic flux sources with magnetic nanoparticles

[00114] In some examples, a system could include a permanent magnet, an electromagnet, or some other means (e.g., some other magnetic flux source) configured to produce a magnetic field in an environment of interest sufficient to at least temporarily magnetize magnetic nanoparticles (e.g., ferromagnetic, superparamagnetic, or otherwise magnetic nanoparticles) in the environment of interest. A magnetic field produced by the magnetized magnetic nanoparticles could then be detected by a magnetometer and used to determine one or more properties of the magnetic nanoparticles and/or of an analyte with

which the magnetic nanoparticles are configured to selectively interact.

[00115] Nanoparticles as described herein are configured to be magnetized by an externally applied magnetic field (e.g., a magnetic field produced by a magnetic flux source of a wearable device as described herein). Such nanoparticles could additionally be configured to become less magnetized over time, e.g., such that the nanoparticles do not remain magnetized and aggregate, forming aggregates that could have negative health effects (e.g., that could block blood vessels) and/or that could have negative effects on applications of the nanoparticles (e.g., that could reduce a degree of interaction of the nanoparticles with an analyte of interest and/or that could produce false positives in embodiments wherein the nanoparticles are configured to aggregate by binding to the analyte of interest). In such examples, the time-dependence of the magnetization of the nanoparticles could be related to a magnetic relaxation time of the nanoparticles. Such a magnetic relaxation time could be related to a time constant of an exponential or otherwise time-dependent function related to the decrease of the magnetization of a magnetized nanoparticle over time.

[00116] Additionally or alternatively, such a magnetic relaxation time could be related to a time-dependence of a statistical process of the magnetized nanoparticles. For example, the magnetic relaxation time could be related to an expected time during which a magnetic property of a magnetized nanoparticle changes (e.g., a mean time between the instances of the magnetic moment of a nanoparticle flipping direction, changing orientation, becoming demagnetized, or otherwise changing from a first state to a second state). For example, the nanoparticles could each include one or more particles of superparamagnetic material (e.g., superparamagnetic iron oxide) and the magnetic relaxation time of the nanoparticles could be related to the Néel relaxation time of the particles of superparamagnetic material of the nanoparticles.

[00117] To illustrate the operation of such systems and/or devices to magnetize nanoparticles and subsequently detect magnetic fields related to such magnetized nanoparticles, Figure 5 illustrates an example nanoparticle complex 565 that is disposed in a blood vessel 550 (i.e., a portion of subsurface vasculature). The complex 565 includes one or more nanoparticles that are bound to an analyte. The blood vessel 550 is located in an arm 590 and contains blood that is flowing (direction of flow indicated by the arrow 555). Figure 5 illustrates the motion of the complex 565 in the blood vessel 550 over time in the direction of the flow 555. Arrows in the illustrated complex 565 over time indicate the degree of magnetization of the complex 565 over time. A body-mountable device 500 includes a housing 510 mounted outside of the blood vessel 550 by a mount 520 configured to encircle

the arm 590. The body-mountable device 500 includes a magnetometer 530 disposed in the housing 510 and configured to detect magnetic fields at a location outside of the arm 590 (e.g., at a location within the magnetometer 530). The body-mountable device 500 additionally includes a magnetic flux source 535 (e.g., a permanent magnet, an electromagnet) disposed in the housing 510 and configured to produce a magnetic flux and/or field sufficient to at least partially magnetize and/or align a magnetic dipole of the one or more nanoparticles of the complex 565. For example, the magnetic flux source 535 could be configured to produce a magnetic field in the blood vessel 550 that has a strength greater than approximately 100 Gauss.

[00118] As shown in Figure 5, the complex 565 is moved by the blood flow 555 past the magnetic flux source 535. This can result in the nanoparticle(s) of the complex 565 becoming and/or being magnetized (illustrated by the increasing size of the arrows as the complex 565 passes over the magnetic flux source 535). The magnetometer 530 can then detect a magnetic field produced by the magnetized nanoparticle(s) of the complex 565 and/or a magnetic field related to such a produced magnetic field (e.g., a time-varying magnetic field produced by precessing magnetic spins of atomic nuclei in the blood vessel 550 that are precessing at a frequency related to the magnetic field produced by the magnetized complex 565). The detected magnetic field could be used to determine one or more properties of the magnetized complex 565 (e.g., properties of the one or more nanoparticles thereof), the analyte, and/or the environment (e.g., the blood in the blood vessel 550). For example, a rate of reduction of the magnetization of the magnetized nanoparticles, a rate of rotation of the magnetized nanoparticles (in examples wherein the nanoparticles are aligned by the magnetic field produced by the magnetic flux source 535), a degree of aggregation of the magnetized nanoparticles, or some other detected properties of the magnetized nanoparticles and/or the complex 565 could be detected and/or determined.

[00119] Note that, as illustrated in Figure 5, the degree of magnetization of the complex 565 (e.g., of a nanoparticle of the complex) is represented by a gradually increasing and gradually decreasing quantity. Such a continuously-valued magnetization could be related to an orientation of the magnetic moment of one or more particles of magnetic material and/or one or more magnetic domains thereof. Such a continuously-valued magnetization could additionally or alternatively be related to a degree of magnetization of a particle of magnetic material that includes more than one magnetic domain before being magnetized. Alternatively, the magnetization of the complex 565 could be a discrete-valued property. For example, the magnetization of a particular nanoparticle and/or complex of

nanoparticles transitions from a first state (e.g., an un-magnetized state, a random state of a discrete set of states, e.g., parallel and antiparallel spin states) to a second state (e.g., a magnetized state parallel to a field produced by the magnetic flux source 535) in response to exposure to a magnetic field generated by the magnetic flux source 535. The magnetization of the particular nanoparticle and/or complex of nanoparticles could further transition to a third state (e.g., a randomly selected state) subsequent to magnetization (e.g., subsequent to passing the magnetometer 530).

[00120] In some examples, magnetization of the particular nanoparticle and/or complex of nanoparticles could include changing a plurality of such discrete-valued or continuous-valued magnetic states of respective nanoparticles and/or magnetic elements thereof (e.g., particles of superparamagnetic iron oxide). For example, magnetization could include aligning the discrete-valued magnetizations of a plurality of nanoparticles and/or magnetic elements thereof such that the nanoparticle and/or complex 565 produces a greater external magnetic field (e.g., due to the magnetic fields produced by the individual nanoparticles and/or elements thereof being aligned such that they sum rather than partially cancel). Such a nanoparticle and/or complex of nanoparticles becoming less magnetized over time could include the magnetizations of the plurality of nanoparticles and/or magnetic elements thereof becoming less aligned such that the nanoparticle and/or complex 565 produces a lesser external magnetic field (e.g., due to the magnetic fields produced by the individual nanoparticles and/or elements thereof not being aligned).

[00121] A distance between the magnetic flux source 535 and the magnetometer 530 configured to detect magnetic fields produced by nanoparticles magnetized by the magnetic flux source 535, a length and strength of the magnetic flux source 535, and other properties of devices and systems as described herein could be related to the magnetic relaxation time of the nanoparticles, among other factors (e.g., the flow rate of a fluid, e.g., blood, carrying the magnetized nanoparticles from the magnetic flux source to the magnetometer). The magnetic relaxation time of the nanoparticles could be specified such that the nanoparticles substantially do not aggregate when not magnetized and/or not in the presence of an instance of an analyte to which the nanoparticles are configured to bind, e.g., the magnetic relaxation time of the nanoparticles could be less than some specified value (e.g., less than between approximately 1 second and approximately 2 seconds).

[00122] The distance between the magnetic flux source 535 and the magnetometer 530 could be greater than some minimum distance to reduce an interference in the operation of the magnetometer 530 by magnetic fields produced by the magnetic flux source 535 (e.g.,

fringe field produced by the magnetic flux source 535 that are detected by and/affect a magnetic field detected by the magnetometer 530). For example, the magnetic flux source 535 and magnetometer 530 could be separated by a distance on the order of a few centimeters (e.g., greater than approximately 1 centimeter). As a result, the magnetic relaxation time of the nanoparticles could be greater than some specified minimum time such that an amount of the nanoparticles magnetized by the magnetic flux source are still magnetized when they have travelled (e.g., been carried by blood flow in the blood vessel 550) downstream to a location proximate the magnetometer 530. Such a minimum relaxation time could be related to the distance between the magnetometer 530 and the magnetic flux source 535 and the flow velocity of blood in the blood vessel 550. For example, the magnetic relaxation time of the nanoparticles could be greater than between approximately 100 milliseconds and approximately 1 second.

[00123] In some examples, magnetic nanoparticles used in combination with systems, devices, and methods as described herein (e.g., systems including a magnetic flux source configured to magnetize such nanoparticles and magnetometers to detect magnetic fields related to such magnetized nanoparticles) could have magnetic relaxation times within a specified narrow range of relaxation times. Detection of one or more properties of such nanoparticles and/or of analytes to which such nanoparticles are configured to bind could be related to such a specified narrow range of magnetic relaxation times of the nanoparticles. For example, a system could include two or more magnetometers disposed at respective locations along a blood vessel. Such a system could be operated to detect magnetic fields at the respective different locations and to determine improved (e.g., higher accuracy, lower noise) estimates of properties of the nanoparticles and/or an analyte bound thereto based on magnetic field detected at the different locations by the magnetometers.

[00124] Figure 6 illustrates example nanoparticle complexes 665 that are disposed in a blood vessel 650 (i.e., a portion of subsurface vasculature). The complexes 665 each include one or more nanoparticles. The blood vessel 650 is located in an arm 690 and contains blood that is flowing (direction of flow indicated by the arrow 655). Figure 6 illustrates the motion of the complexes 665 in the blood vessel 650 over time in the direction of the flow 655. The fill color in the illustrated complexes 665 indicates the degree of magnetization of each complex 665; a black-filled complex is magnetized while a white-filled complex is substantially not magnetized. Note that magnetization of the complexes 665 is illustrated at a discrete, binary state for illustration purposes only; the magnetization of the complexes and/or nanoparticles thereof could be continuous-valued or discrete and having a number of

possible values greater than 2. A body-mountable device 600 includes a housing 610 mounted outside of the blood vessel 650 by a mount 620 configured to encircle the arm 690. The body-mountable device 600 includes a first 630a and second 630b magnetometers disposed in the housing 610 and configured to detect magnetic fields at respective first and second locations outside of the arm 690 (e.g., at locations within the magnetometers 630a, 630b). The body-mountable device 600 additionally includes a magnetic flux source 635 (e.g., a permanent magnet, an electromagnet) disposed in the housing 610 and configured to produce a magnetic flux and/or field sufficient to at least partially magnetize and/or align a magnetic dipole of the one or more nanoparticles of the complexes 665.

[00125] As shown in Figure 6, the complexes 665 are moved by the blood flow 655 past the magnetic flux source 635. This can result in the nanoparticle(s) of the complexes 665 becoming and/or being magnetized (illustrated by the complexes 665 being more likely to be black-filled, i.e., magnetized, as the complexes 665 pass over the magnetic flux source 635). The magnetometers 630a, 630b can then detect magnetic fields related to nanoparticle(s) of the complexes 665. As shown in Figure 6, the first magnetometer 630a is disposed proximate a first portion of subsurface vasculature wherein nanoparticles of the complexes 665 that were magnetized by the magnetic flux source 635 are substantially still magnetized (e.g., a location that is, based on a magnetic relaxation time of the nanoparticles and a flow rate of blood in the blood vessel 650, sufficiently close to the magnetic flux source). The second magnetometer 630b is disposed proximate a second portion of subsurface vasculature that is downstream from the first portion such that nanoparticles of the complexes 665 that were magnetized by the magnetic flux source 635 have become less magnetized and/or have become un-magnetized. A more accurate or otherwise improved estimate of a property of the complexes 665, nanoparticle(s) thereof, and/or an analyte bound thereto could be determined based on the signals generated by the first 630a and second 630b magnetometers. For example, a signal (e.g., a detected magnetic field, a determined magnetic resonance time constant) produced by the second magnetometer 630b could be used as a background signal (i.e., a signal corresponding to no nanoparticles and/or non-magnetized or un-magnetized nanoparticles) for comparison with a signal produced by the first magnetometer 630a (i.e., a signal corresponding to no nanoparticles and/or magnetized nanoparticles).

[00126] The distances of the magnetometers 630a, 630b and/or additional magnetometers (not shown) of the device 600 could be set based on a range of magnetic relaxation times of the nanoparticles in the complexes 665 and on an expected flow rate of

blood in the blood vessel 650. Additionally or alternatively, the system 600 could include additional magnetometers (not shown) disposed at further different distances from the magnetic flux source 635 and could use outputs generated by the additional magnetometers to perform such a determination of properties of the complexes 665, nanoparticles thereof, and/or an analyte bound thereto. In some examples, this could include detecting the flow velocity or rate of blood in the blood vessel 650 (e.g., using laser speckle velocimetry, ultrasonic velocimetry, or some other method) and using such information to determine the properties of the complexes 665, nanoparticles, and/or analyte, e.g., by determining respective sets of the magnetometers corresponding to regions of the blood vessel 650 wherein the complexes 665 are magnetized and regions wherein the complexes 665 are substantially non-magnetized.

[00127] In some examples, magnetic nanoparticles used in combination with systems, devices, and methods as described herein (e.g., systems including a magnetic flux source configured to magnetize such nanoparticles and magnetometers to detect magnetic fields related to such magnetized nanoparticles) could include multiple different sets of magnetic nanoparticles having magnetic relaxation times within respective different specified narrow ranges of relaxation times. In such examples, nanoparticles of each set could be configured to selectively interact with (e.g., bind to) respective different analytes. Detection of one or more properties of such sets of nanoparticles and/or of respective analytes to which such sets of nanoparticles are configured to bind could be related to such specified narrow ranges of magnetic relaxation times of the sets of nanoparticles.

[00128] Figure 7 illustrates example first 765a and second 765b nanoparticle complexes that are disposed in a blood vessel 750 (i.e., a portion of subsurface vasculature). The complexes 765a, 765b each include one or more nanoparticles. The blood vessel 750 is located in an arm 790 and contains blood that is flowing (direction of flow indicated by the arrow 755). Figure 7 illustrates the motion of the complexes 765a, 765b in the blood vessel 750 over time in the direction of the flow 755. The fill color in the illustrated complexes 765a, 765b indicate the degree of magnetization of each complex 765a, 765b; a black-filled complex is magnetized while a white-filled complex is substantially not magnetized. Note that magnetization of the complexes 765a, 765b is illustrated at a discrete, binary state for illustration purposes only; the magnetization of the complexes and/or nanoparticles thereof could be continuous-valued or discrete and having a number of possible values greater than 2. A body-mountable device 700 includes a housing 710 mounted outside of the blood vessel 750 by a mount 720 configured to encircle the arm 790. The body-mountable device 700

includes a first 730a and second 730b magnetometers disposed in the housing 710 and configured to detect magnetic fields at respective first and second locations outside of the arm 790 (e.g., at locations within the magnetometers 730a, 730b). The body-mountable device 700 additionally includes a magnetic flux source 735 (e.g., a permanent magnet, an electromagnet) disposed in the housing 710 and configured to produce a magnetic flux and/or field sufficient to at least partially magnetize and/or align a magnetic dipole of the one or more nanoparticles of the complexes 765a, 765b.

[00129] As shown in Figure 7, the complexes 765a, 765b are moved by the blood flow 755 past the magnetic flux source 735. This can result in the nanoparticle(s) of the complexes 765a, 765b becoming and/or being magnetized (illustrated by the complexes 765a, 765b being more likely to be black-filled, i.e., magnetized, as the complexes 765a, 765b pass over the magnetic flux source 735). The magnetometers 730a, 730b can then detect magnetic fields related to nanoparticle(s) of the complexes 765a, 765b that are magnetized when such magnetized complexes move proximate to the magnetometers 730a, 730b. The first 765a and second 765b complexes have respective different magnetic relaxation times (e.g., nanoparticles of the complexes have magnetic relaxation times within respective different ranges of relaxation times). Specifically, the first set of complexes 765a has a shorter magnetic relaxation time than the second set of complexes 765b.

[00130] This is shown in Figure 7, wherein the first magnetometer 730a is disposed proximate a first portion of subsurface vasculature wherein nanoparticles of both sets of complexes 765a, 765b that were magnetized by the magnetic flux source 735 are substantially still magnetized. The second magnetometer 730b is disposed proximate a second portion of subsurface vasculature that is downstream from the first portion such that nanoparticles of the first set of complexes 765a that were magnetized by the magnetic flux source 735 have become less magnetized and/or have become un-magnetized. Conversely, the second portion of subsurface vasculature is located such that nanoparticles of the second set of complexes 765b that were magnetized by the magnetic flux source 735 are substantially still magnetized. An estimate of a property of both sets of complexes 765a, 765b, nanoparticle(s) thereof, and/or the respective analytes bound thereto could be determined based on the signals generated by the first 730a and second 730b magnetometers.

[00131] In some examples, magnetic nanoparticles and/or analytes bound to such magnetic nanoparticles in an environment could be collected such that a magnitude of the magnetic field produced by the magnetic particles and detected by a magnetometer is increased, e.g., to improve a determination of a property of the analyte by, e.g., increasing a

magnitude of the detected magnetic field.

[00132] Figures 8A and 8B illustrate, during respective first and second periods of time, example magnetic nanoparticles 860 and an analyte of interest 870 with which the nanoparticles 870 are configured to selectively interact disposed in a blood vessel 850 (i.e., a portion of subsurface vasculature). The blood vessel 850 is located in an arm 890 and contains blood that is flowing (direction of flow indicated by the arrow 855). A body-mountable device 800 includes a housing 810 mounted outside of the blood vessel 850 by a mount 820 configured to encircle the arm 890. The body-mountable device 800 includes a magnetometer 830 disposed in the housing 810 and configured to detect a magnetic field at a location outside of the arm 890 (e.g., at a location within the magnetometer 830).

[00133] The body-mountable device 800 additionally includes a magnetic flux source 835 (e.g., a permanent magnet, an electromagnet) configured to exert an attractive magnetic force on the magnetic nanoparticles 860 and/or to magnetize the nanoparticles 860 such that at least some of the magnetic nanoparticles 870 in the blood vessel 850 are collected proximate the magnetic flux source 835. Such a magnetic flux source could be considered a collection magnet. In the example shown in Figures 8A and 8B, this includes collecting magnetic nanoparticles 860 that are bound to instances of the analyte 870 into a bolus 875 located proximate the magnetic flux source 835. Note that, in some examples, separate components (e.g., separate permanent magnets) of the device 800 could be configured to, respectively, magnetize the nanoparticles and to collect the magnetic nanoparticles.

[00134] Figure 8A shows the body-mountable device 800 during a first period of time during which the magnetic flux source 835 is exerting an attractive magnetic force to attract magnetic nanoparticles 860 and instances of the analyte 870 bound thereto to form a bolus 875 of collected magnetic nanoparticles 860. Figure 8B shows the body-mountable device 800 during a second period of time. The magnetic flux source 835 is configured and/or operated during the second period of time to exert a lesser magnetic force (e.g., to exert substantially no magnetic force) on the magnetic nanoparticles 860 such that the bolus 875 is released from the proximity of the magnetic flux source 835 and flows within the blood vessel 850 to a downstream location, past the magnetometer 830. The magnetometer 830 operates to detect a magnetic field produced by the magnetic nanoparticles 860 and/or a magnetic field related to such a produced magnetic field (e.g., by magnetic nanoparticles of the bolus 875) to determine a property of the magnetic nanoparticles 860, the analyte 870, and/or the bolus 875. For example, a number of instances of the analyte 870 in the bolus 875 (and/or a concentration or number of the analyte 870 in the blood overall) could be

determined based on a magnitude, nuclear magnetic time constant, or other properties of and/or determined from the detected magnetic field.

[00135] Note that the configuration and operation shown in Figures 8A and 8B are non-limiting examples. In some embodiments, a magnetic flux source could be co-located with a magnetometer (e.g., could act to collect and/or magnetize nanoparticles proximate the magnetometer). In some examples, the magnetometer could operate to detect the magnetic field produced by the magnetic nanoparticles while the magnetic flux source is exerting an attractive magnetic force to collect the magnetic nanoparticles (e.g., by introducing a bias magnetic field using a coil or other magnetic materials to cancel the magnetic field generated by the magnetic flux source that is detected by the magnetometer, by configuring the magnetometer to detect magnetic fields in a direction perpendicular to a field produced by a magnetic flux source, by detecting oscillating magnetic fields produced by the magnetic nanoparticles, e.g., in response to exposure to an oscillating magnetic field produced by an excitation coil).

V. Example separation of nanoparticles

[00136] Systems, devices, and methods described herein for detecting properties of magnetic nanoparticles and/or properties of analytes bound thereto can include such nanoparticles having magnetic relaxation times within specified ranges of relaxation times. For example, a system could include a magnetic flux source configured to magnetize such nanoparticles at a first location and a magnetometer to detect magnetic fields related to the magnetized nanoparticles at a second location that is downstream relative to a fluid flow (e.g., a blood flow) that transports the magnetized nanoparticles from the magnetic flux source to the magnetometer. A distance between such a magnetometer and magnetic flux source, a sensitivity of the magnetometer, a strength of the field produced by the magnetic flux source, or some other properties of the system could be specified based on the range of magnetic relaxation times of the nanoparticles, among other factors (e.g., a flow velocity of blood in a portion of subsurface vasculature). Additionally or alternatively, the nanoparticles could include multiple subsets of nanoparticles having magnetic relaxation times within respective ranges of relaxation times to provide some functionality according to an application (e.g., simultaneous detection of multiple respective different analytes).

[00137] In such examples, a supply of nanoparticles having relaxation times within such a specified range of relaxation times could be produced according to the specified range of relaxation times. For example, such nanoparticles could be fabricated using self-assembly

to have substantially uniform size, geometry, composition, or other properties such that the magnetic relaxation times of the formed nanoparticles are within the specified range of relaxation times. Additionally or alternatively, a source of nanoparticles having magnetic relaxation times spanning a range that exceeds in one or both directions the specified range of relaxation times could be sieved, filtered, or otherwise separated to produce a subset of the provided nanoparticles that have magnetic relaxation times within the specified range of relaxation times.

[00138] In some examples, the magnetic relaxation time of a nanoparticle could be related to a size of the particle. For example, a nanoparticle could include a particle of superparamagnetic iron oxide and the magnetic relaxation time of the nanoparticle could be related to the Néel relaxation time of the particle of superparamagnetic iron oxide of the nanoparticles. The Néel relaxation time of a particle of superparamagnetic material can be related to the size of the particle of superparamagnetic material. Thus, the magnetic relaxation time of such nanoparticles could be controlled by controlling a size of the nanoparticles, e.g., by using one or more filters or other size-dependent methods to separate nanoparticles having sizes within a specified range of sizes related to the specified range of magnetic relaxation times. For example, superparamagnetic material particle sizes between approximately 10 nanometers and approximately 20 nanometers could correspond to magnetic relaxation times between approximately 1 second and approximately 1 nanosecond.

[00139] Additionally or alternatively, magnetic fields could be applied to a plurality of nanoparticles to separate nanoparticles of the plurality that have magnetic relaxation times within a specified range of relaxation times. In such examples, the nanoparticles could be separated based directly on the magnetic relaxation time of the nanoparticles. That is, the nanoparticles could be magnetized and then a separating magnetic force could be applied during a specified period of time relative to the timing of the magnetization such that the nanoparticles are separated according to their magnetic relaxation times. In some examples, the nanoparticles could be disposed within a region of flow (e.g., a tube or other vessel containing a flowing carrier fluid in which the nanoparticles are disposed) and a first magnetic flux source disposed at a first location could be configured to magnetize the nanoparticles in the region of flow proximate the first location. A second magnetic flux source could be disposed at a second location and configured to apply a separating magnetic force to nanoparticles that were magnetized by the magnetic flux source at the first location, that traveled to the second location, and that are still magnetized when they arrive at the second location. As a result, the separating magnetic force is applied to nanoparticles having

relaxation times greater than a specified relaxation time, where the specified relaxation time is related to a distance between the first and second locations and a flow velocity of the carrier fluid within the region of flow.

[00140] To illustrate such a method of nanoparticle separation, Figure 9 illustrates an example separation system 900. Example nanoparticles 930a, 930b are disposed in a region of flow 940 (i.e., a cylinder of the system 900 configured to carry a carrier fluid within which the nanoparticles 930a, 930b are disposed). The nanoparticles 930a, 930b include first 930a and second 930b sets of nanoparticles having magnetic relaxation times within respective different ranges of relaxation times. The first nanoparticles 930a have magnetic relaxation times that are longer than the magnetic relaxation times of the second nanoparticles 930b. The region of flow 940 contains a carrier fluid that is flowing (direction of flow indicated by the arrow 945). The carrier fluid could be an aqueous solution, a solution configured to mimic the properties of blood (e.g., a phosphate-buffered saline solution), blood stabilized by an anti-coagulating agent, or some other carrier fluid according to an application. The region of flow 940 is separated into first 950a and second 950b output regions of flow.

[00141] The system 900 includes a first magnetic flux source 910 disposed at a first location relative to the region of flow 940 and a second magnetic flux source 920 disposed at a second location relative to the region of flow 940, where the second location is downstream, relative to a direction of flow 945 within the region of flow 940. The first magnetic flux source 910 is configured to produce a magnetic flux and/or field sufficient to at least partially magnetize and/or align a magnetic dipole of proximate nanoparticles 930a, 930b in the region of flow 940 (e.g., by providing a high magnitude magnetic field region of flow 940). The second magnetic flux source 920 is configured to provide a separating magnetic force to proximate magnetized nanoparticles 930a, 930b in the region of flow 940 (e.g., by providing a magnetic field in the region of flow 940 that has a high gradient magnitude).

[00142] The fill color in the illustrated nanoparticles 930a, 930b indicates the degree of magnetization of each nanoparticle; a black-filled complex is magnetized while a white-filled complex is substantially not magnetized. Note that magnetization of the nanoparticles 930a, 930b is illustrated at a discrete, binary state for illustration purposes only; the magnetization of the complexes and/or nanoparticles thereof could be continuous-valued or discrete and having a number of possible values greater than 2. Further, a plurality of nanoparticles to be separated could include a population of nanoparticles having magnetic relaxation times across a continuous range of relaxation times. The two sets of nanoparticles 930a, 930b

shown in Figure 9, having magnetic relaxation times within respective ranges of relaxation times, are provided as non-limiting illustrative examples of methods and systems for separating such nanoparticles according to magnetic relaxation time.

[00143] As shown in Figure 9, the nanoparticles 930a, 930b are moved by carrier fluid flow 945 past the first magnetic flux source 910. This can result in the nanoparticle 930a, 930b becoming and/or being magnetized (illustrated by the nanoparticles being more likely to be black-filled, i.e., magnetized, as they pass over the first magnetic flux source 910). Over time, the nanoparticles 930a, 930b become less magnetic (e.g., become non-magnetic, as shown in Figure 9) according to processes related to their magnetic relaxation times. Due to the carrier fluid flow 945, these times are related to distances, within the region of flow 940, from the first magnetic flux source 910. As a result, most of the first nanoparticles 930a remain magnetized at a second location at which the second magnetic flux source 920 is located. Conversely, most of the second nanoparticles 930b are not magnetized at the second location. As a result, substantially only the first nanoparticles 930a experience the separating magnetic force (illustrated by the arrows) exerted by the second magnetic flux source 920.

[00144] The separating magnetic force acts to move the first nanoparticles 930a upward, such that substantially only carrier fluid in the first output region of flow 950a contains the first nanoparticles 930a. Further, the second output region of flow contains substantially only the second nanoparticles 930b. Thus, carrier fluid from the first output region of flow 950a could be used as a source of nanoparticles that is enriched in nanoparticles having magnetic relaxation times above a specified value, where the specified value is related to the distance between the first and second locations of respective first 910 and second 920 magnetic flux sources and the flow velocity of carrier fluid in the region of flow 940. Further, carrier fluid from the second output region of flow 950b could be used as a source of nanoparticles that is enriched in nanoparticles having magnetic relaxation times below such a specified value.

[00145] Note that the production, by the second magnetic flux source 920, of a separating magnetic force that is directed in a single direction relative the carrier fluid flow 945 (i.e., upward) is intended as a non-limiting example. The second magnetic flux source 920 could apply a separating magnetic force in a different direction or in more than one direction. Related to this, the illustration of the region of flow 940 separating into oppositely-angled output regions of flow 950a, 950b is intended as a non-limiting example, and is related to whatever separating force is applied by the second magnetic flux source 920. For example, the second magnetic flux source 920 could be configured to apply a separating

magnetic force from the center of the region of flow 940 toward the walls of the region of flow 940 (e.g., a cylindrically symmetric magnetic separating force). In such examples, the output regions of flow could include concentric pipes, the inner pipe carrying carrier fluid that is enriched nanoparticles that were not substantially affected by the separating magnetic force (e.g., nanoparticles having magnetic relaxation times below some specified value) and the outer output pipe carrying carrier fluid that is enriched nanoparticles that were substantially affected by the separating magnetic force (e.g., nanoparticles having magnetic relaxation times above the specified value).

[00146] Further, the second magnetic flux source 920 could be configured to collect proximate magnetized nanoparticles. In such examples, the system 900 could be operated in a non-continuous manner. For example, during a first period of time, carrier fluid containing a plurality of nanoparticles having a range of magnetic relaxation times could be passed through the region of flow 940 and the second magnetic flux source 920 could act to collect, against the walls of the region of flow 940, nanoparticles having magnetic relaxation times greater than some specified value. During a second period of time, carrier fluid containing no nanoparticles could be passed through the region of flow 940 and the second magnetic flux source 920 could be operated to release the collected nanoparticles such that carrier fluid output from the system 900 during the second period of time contains substantially only nanoparticles having magnetic relaxation times greater than the specified value.

[00147] A set of nanoparticles having magnetic relaxation times within a specified range of relaxation times could be generated using the methods described herein (e.g., using the system 900) in a variety of ways. In some examples, a first set of nanoparticles having magnetic relaxation times less than a maximum relaxation time of the range of relaxation times could be separated from a source of nanoparticles. A second set of nanoparticles having magnetic relaxation times greater than a minimum relaxation time of the range of relaxation times could then be separated from the first set of nanoparticles. In some examples, such separation could be implemented in a single system, e.g., a system including multiple magnetic flux sources configured to magnetize nanoparticles and multiple magnetic flux sources configured to exert a magnetic force to collect or otherwise separate such magnetized nanoparticles according to magnetic relaxation time.

[00148] Further, systems and methods described herein to separate nanoparticles according to magnetic relaxation time could be used multiple times on a carrier fluid containing such nanoparticles to improve a degree and/or specificity of the separation or according to some other application. For example, the carrier fluid of the first output region

of flow 950a could be applied to the system 900 one or more further times to reduce the amount of the second nanoparticles 930b in the carrier fluid relative to the amount of the first nanoparticles 930a. This could include connecting the first output region of flow 950a to the input of the region of flow 940 in a loop (e.g., via a pump) such that the separation process is continuous.

[00149] Note that, while the system 900 and methods related thereto described herein reference separating nanoparticles that are able to be magnetized and that could be configured to selectively interact with (e.g., bind to) an analyte of interest, these systems and methods could be additionally or alternatively be used to separate elements used to fabricate such nanoparticles. For example, these methods could be used to separate a population of particles of superparamagnetic iron oxide according to magnetic relaxation time. Further, such separation could provide separation of such components according to size or some other property of the components that is related to magnetic relaxation time. Such separated elements could then be used to construct the nanoparticles (e.g., by self-assembly). Such constructed nanoparticles could also be separated according to magnetic relaxation time using the method.

[00150] In some examples, magnetic properties of the nanoparticles 930a, 930b (e.g., magnetic relaxation times) can be related to properties (e.g., a pH, an osmolality, a viscosity, a proton content, a Debye length, a degree of adsorption of proteins and other contents of the carrier fluid to the nanoparticles) of a fluid in which the nanoparticles 930a are disposed 930b. In such examples, the region of flow 940 could include a carrier fluid designed to mimic the relevant properties (e.g., in examples wherein the nanoparticles will be used in blood of a person, the region of flow 940 could include blood or blood products from a blood bank).

[00151] Note that, while separation of nanoparticles according to magnetic relaxation time is provided in the context of using such nanoparticles to detect analytes in or other properties of a human body, such separation could be applied to other applications. For example, such methods could be used to separate nanoparticles within a specified narrow range of sizes by using these methods to separate nanoparticles having magnetic relaxation times within a range of relaxation times that corresponds to the range of sizes. This could provide for separation of nanoparticles according to size that is improved in some way relative to using a sieve or filter or otherwise separating the nanoparticles by size. For example, nanoparticles separated according to magnetic relaxation time could be more specifically selected, could be separated according to narrower ranges of sizes, or could be

improved in some other way.

VI. Example Wearable Devices

[00152] Wearable devices as described herein can be configured to be mounted to an external body surface of a wearer and to enable a variety of applications and functions including the detection of magnetic fields produced by magnetic nanoparticles disposed in the body of the wearer (e.g., disposed in a portion of subsurface vasculature of the wearer). Such devices could include one or more magnetic flux sources configured to magnetize such nanoparticles and/or to provide some other functionality (e.g., to polarize the magnetic spins of atomic nuclei in a body). One or more magnetometers of the wearable device could be configured to detect (directly or indirectly) the magnetic fields produced by magnetic nanoparticles disposed proximate the one or more magnetometers (e.g., in portions of subsurface vasculature that are downstream, relative to a direction of blood flow, from a location at which the one or more magnetic flux sources magnetize the nanoparticles). Such wearable devices could enable a variety of applications, including measuring properties of the magnetic nanoparticles and/or an analyte with which the magnetic nanoparticles are configured to selectively interact (e.g., bind to), to detect other physiological information about a wearer (e.g., heart rate), indicating such measured information or other information to the wearer (e.g., using a vibrator, a screen, a beeper), or other functions.

[00153] A wearable device 1000 (illustrated in Figure 10) can be configured to magnetize magnetic nanoparticles disposed in a wearer's body (e.g., disposed in portions of subsurface vasculature proximate the device 1000) and/or to detect magnetic fields produced by such magnetic nanoparticles disposed in the wearer's body or other physiological parameters of a person wearing the device. The term "wearable device," as used in this disclosure, refers to any device that is capable of being worn at, on or in proximity to a body surface, such as a wrist, ankle, waist, chest, or other body part. In order to take in vivo measurements in a non-invasive manner from outside of the body, the wearable device may be positioned on a portion of the body where subsurface vasculature or other targets or elements of the body of the wearer are easily observable, the qualification of which will depend on the type of detection system used. The device may be placed in close proximity to the skin or tissue. A mount 1010, such as a belt, wristband, ankle band, etc. can be provided to mount the device at, on or in proximity to the body surface. The mount 1010 may prevent the wearable device from moving relative to the body to reduce measurement error and noise.

In one example, shown in Figure 10, the mount 1010, may take the form of a strap or band 1020 that can be worn around a part of the body. Further, the mount 1010 may be an adhesive substrate for adhering the wearable device 1000 to the body of a wearer.

[00154] A housing 1030 is disposed on the mount 1010 such that it can be positioned on the body. A contact surface 1040 of the housing 1030 is intended to be mounted facing to the external body surface. The housing 1030 may include a magnetic flux source 1055 for producing a magnetic field sufficient to magnetize magnetic nanoparticles disposed in the body of the wearer (e.g., magnetic nanoparticles disposed in portions of subsurface vasculature) or to provide some other functionality (e.g., to polarize atomic magnetic spins of atoms in a portion of subsurface vasculature). The housing 1030 may additionally include a magnetometer 1050 for detecting magnetic fields produced by magnetic nanoparticles disposed in the body of the wearer (e.g., produced by magnetic nanoparticles magnetized by the magnetic flux source 1055). The housing 1030 could be configured to be water-resistant and/or water-proof. That is, the housing 1030 could be configured to include sealants, adhesives, gaskets, welds, transparent windows, apertures, press-fitted seams, and/or other joints such that the housing 1030 was resistant to water entering an internal volume or volumes of the housing 1030 when the housing 1030 is exposed to water. The housing 1030 could further be water-proof, i.e., resistant to water entering an internal volume or volumes of the housing 1030 when the housing 1030 is submerged in water. For example, the housing 1030 could be water-proof to a depth of 1 meter, i.e., configured to resist water entering an internal volume or volumes of the housing 1030 when the housing 1030 is submerged to a depth of 1 meter.

[00155] The magnetic flux source 1055 is configured to produce a magnetic field sufficient to magnetize nanoparticles disposed proximate to the magnetic flux source 1055 in an environment of interest, e.g., a portion of subsurface vasculature of a wearer. For example, the magnetic flux source 1055 could be configured to produce a magnetic field having a magnitude of several hundred Gauss (e.g., greater than approximately 100 Gauss) at a distance of approximately 1 centimeter from the contact surface 1040 (e.g., a distance within which a portion of subsurface vasculature containing the nanoparticles may be located when the device 1000 is mounted to a body). The magnitude of the magnetic field produced by the magnetic flux source 1055 and the dimensions of the magnetic flux source 1055 (e.g., the length of the magnetic flux source 1055 in a direction aligned with a direction of the portion of subsurface vasculature) could be specified such that nanoparticles flowing in the body proximate to the magnetic flux source 1055 are magnetized. In an illustrative example,

the nanoparticles could have a magnetic relaxation time of approximately 1 second and could be disposed in a blood flow having a flow velocity of several centimeters per second. In such an example, a magnetic flux source as described herein could have a length, in the direction of the blood flow, of several centimeters such that the nanoparticles are maintained proximate to the magnetic flux source for a sufficient period of time to be magnetized by the magnetic flux source.

[00156] Note that the magnetic flux source 1055 could be configured to provide some other functionality, e.g., to polarize the magnetic spins of atomic nuclei such that the magnetic field in the environment of such atomic nuclei (e.g., a magnetic field produced by a magnetic nanoparticle proximate such atomic nuclei) could be detected (e.g., by the magnetometer 1050 detecting time-varying magnetic and/or electromagnetic fields produced by such atomic nuclei through nuclear magnetic resonance). In another example, the magnetic flux source 1055 could be configured to collect magnetic nanoparticles and/or to release such collected magnetic nanoparticles, e.g., to facilitate extraction of the collected nanoparticles from the body, to provide a higher-magnitude signal for the magnetometer 1050 to detect, or according to some other application. The magnetic flux source 1055 could include one or more electromagnets, permanent magnets, or other magnetic producing elements. Further, the magnetic flux source 1055 could be configured and/or operated to change a magnetic field produced by the magnetic flux source 1055, e.g., to reduce a magnitude of a produced magnetic field that is detected by the magnetometer 1050, to reduce an inhomogeneity of the magnetic field proximate the magnetometer 1050 that is caused by the magnetic flux source 1055, or according to some other application. This could include changing a current applied to an electromagnet of the magnetic flux source 1055, mechanically actuating an electromagnet, permanent magnet, or other flux producing element of the magnetic flux source 1055, or performing some other operation(s).

[00157] The magnetometer 1050 is configured to detect a magnetic field produced by magnetic nanoparticles, precessing magnetic spins of atomic nuclei, or other magnetic-field-producing elements disposed proximate the magnetometer (e.g., within from approximately 1 millimeter to approximately 1 centimeter) in an environment of interest, e.g., a portion of subsurface vasculature of a wearer. The magnetometer could be configured to have a sensitivity such that the magnetometer can detect changes in a measured magnetic field of less than approximately 10 femtoteslas. The magnetometer could be configured to detect a direction, magnitude, property of change over time, or some other property of the magnetic fields produced by the magnetic nanoparticles. The magnetometer 1050 could be configured

to detect time-varying magnetic fields across a specified range of frequencies, e.g., less than several kilohertz (e.g., a spin-exchange relaxation-free atomic magnetometer, a multi-pass scalar atomic magnetometer), at a particular frequency (e.g., a radio-frequency atomic magnetometer tuned to a frequency of interest, e.g., an expected frequency of precession of magnetic spins of atomic nuclei in a magnetic field).

[00158] The wearable device 1000 could include one or more bias coils, magnets, shims, magnetic shielding elements, or other components to reduce a background magnetic field to which the magnetometer 1050 is exposed (e.g., to cancel the effects of the Earth's magnetic field on the magnetometer 1050, to cancel the effects of the magnetic flux source 1055 on the magnetometer), to reduce an inhomogeneity of the magnetic field in an environment of interest (e.g., to reduce an inhomogeneity in the earth's magnetic field in a portion of subsurface vasculature proximate the magnetometer 1050), and/or to provide some other functionality. Additionally or alternatively, in examples wherein a magnetic field produced by the magnetic flux source 1055 interferes with the operation of the magnetometer 1050 to detect properties of the magnetic nanoparticles and/or an analyte bound thereto (e.g., wherein the magnetic flux source 1055 creates an inhomogeneity in the Earth's magnetic field proximate the magnetometer 1050, wherein the flux source 1055 creates a magnetic field at the location of the magnetometer 1050 that interferes with measurement of a magnetic field produced by and/or affected by the magnetic nanoparticles), the magnetic flux source 1055 could be intermittently operated to produce such a magnetic field (e.g., a current applied to an electromagnet of the magnetic flux source 1055 could be reduced or zeros during certain periods of time wherein the magnetometer 1050 could operate to detect magnetic fields).

[00159] The magnetometer 1050 could be configured to detect an oscillating or otherwise time-varying magnetic field produced by the magnetic nanoparticles in response to exposure to an oscillating magnetic field produced by an excitation coil or other component (e.g., antenna) of the wearable device 1000. In some examples, this could include the magnetometer including one or more inductive pickup coils configured to detect the produced oscillating or otherwise time-varying magnetic fields and/or to emit the oscillating magnetic field produced by the wearable device 1000 (i.e., the excitation coil used to produce the oscillating magnetic field in the environment of interest is also part of the magnetometer and used to detect the oscillating or otherwise time-varying magnetic fields responsively produced by the magnetic nanoparticles). Additionally or alternatively, such a responsively produced magnetic field could be detected by an optical atomic magnetometer (e.g., a SERF,

a multipass scalar atomic magnetometer, a radio-frequency atomic magnetometer). For example, a magnitude of a responsively produced time-varying magnetic field could be detected by a radio-frequency atomic magnetometer tuned to the frequency of the responsively produced time-varying magnetic field, e.g., to a frequency of a harmonic of the oscillating magnetic field produced by the device 1000.

[00160] The magnetometer 1050 could be configured to detect an oscillating or otherwise time-varying magnetic and/or electromagnetic field produced by magnetic spins of atomic nuclei that are precessing proximate the magnetometer 1050. That is, the magnetometer 1050 could be configured to detect, using the techniques of nuclear magnetic resonance, the magnetic field strength in the environment of the atomic nuclei, e.g., of hydrogen atoms in water or other chemicals in a portion of subsurface vasculature. For example, the magnetometer 1050 could include one or more pulse emitters (e.g., electromagnetic coils) configured to emit time-varying magnetic fields (e.g., π pulses, $\pi/2$ pulses, other waveforms used in nuclear magnetic resonance and/or magnetic resonance imaging) to rotate the magnetic spins of the atomic nuclei. The background magnetic field proximate the magnetometer 1050 could be substantially homogeneous (e.g., could be the Earth's magnetic field) such that the rotated magnetic spins of the atomic nuclei precess at approximately the same frequency (e.g., at a frequency related to strength of the magnetic field proximate each of the atomic nuclei). The magnetic field produced by a magnetized nanoparticle could alter the precession frequency of atomic nuclei proximate the magnetized nanoparticle. The magnetometer could detect a time-varying magnetic field produced by the precessing magnetic spins of the atomic nuclei and such detected information could be used to determine a property of the magnetized nanoparticles and/or of an analyte bound thereto.

[00161] The magnetometer could include a variety of components configured in a variety of ways to detect one or more properties of a magnetic field produced by and/or related to magnetic nanoparticles. The magnetometer could include a superconducting quantum interference device (SQUID), spin-exchange relaxation-free (SERF) magnetometer, a multipass scalar atomic magnetometer, a radio-frequency atomic magnetometer, one or more inductive loops or coils or other antenna structures, a spin precession magnetometer, or some other magnetic-field-detecting components or devices. In examples wherein the magnetometer 1050 includes elements having a very high temperature (e.g., an alkali vapor cell of a SERF, multipass scalar atomic magnetometer, and/or radio-frequency atomic magnetometer) or a very low temperature (e.g., the Josephson junction(s) of a SQUID), the magnetometer 1050 and/or the housing 1010 could include means for insulating the high- or

low-temperature elements or for otherwise controlling the temperature of such elements and/or preventing injury to a user due to exposure to extreme temperatures of such elements. For example, an alkali vapor cell and/or other elements of a SERF magnetometer could be wholly or partially contained in an evacuated volume (e.g., a dewar), insulated with an aerogel, or otherwise insulated.

[00162] The wearable device 1000 may also include a user interface 1090 via which the wearer of the device may receive one or more recommendations or alerts generated either from a remote server or other remote computing device, or from a processor within the device. The alerts could be any indication that can be noticed by the person wearing the wearable device. For example, the alert could include a visual component (e.g., textual or graphical information on a display), an auditory component (e.g., an alarm sound), and/or tactile component (e.g., a vibration). Further, the user interface 1090 may include a display 1092 where a visual indication of the alert or recommendation may be displayed. The display 1092 may further be configured to provide an indication of the measured magnetic field and/or one or more determined properties of the magnetic nanoparticles and/or an analyte in the body of the wearer.

[00163] Note that example devices herein are configured to be mounted to a wrist of a wearer. However, the embodiments described herein could be applied to other body parts (e.g., an ankle, a thigh, a chest, a forehead, a thigh, a finger), or to detect magnetic fields produced by magnetic nanoparticles in other environments. For example, embodiments described herein could be applied to detect one or more properties in a target environment (e.g., a natural environment, an environment of an industrial, pharmaceutical, or water treatment process).

[00164] Wearable devices and other embodiments as described herein can include a variety of components configured in a variety of ways. Devices described herein could include electronics including a variety of different components configured in a variety of ways to enable applications of the wearable device. The electronics could include controllers, amplifiers, switches, display drivers, touch sensors, wireless communications chipsets (e.g., Bluetooth radios or other radio transceivers and associated baseband circuitry to enable wireless communications between the wearable device and some other system(s)), or other components. The electronics could include a controller configured to operate one or more magnetic flux sources, magnetometers and/or other sensors to detect a magnetic field and/or to detect some other properties of a wearer or to perform some other functions. The controller could include a processor configured to execute computer-readable instructions

(e.g., program instructions stored in data storage of the wearable device) to enable applications of the wearable device. The electronics can include additional or alternative components according to an application of the wearable device.

[00165] Wearable devices as described herein could include one or more user interfaces. A user interface could include a display configured to present an image to a wearer and to detect one or more finger presses of a wearer on the interface. The controller or some other component(s) of the electronics could operate the user interface to provide information to a wearer or other user of the device and to enable the wearer or other user to affect the operation of the wearable device, to determine some property of the wearable device and/or of the wearer of the wearable device (e.g., a concentration of an analyte in the blood of the wearer determined based on a detected magnetic field and/or a health state of a wearer of the wearable device), or to provide some other functionality or application to the wearer and/or user. As one example, the wearer could press an indicated region of the user interface to indicate that the wearable device should begin logging detected medical information about the wearer. Other indicated information, changes in operation of the wearable device, or other functions and applications of the user interface are anticipated.

[00166] Note that the embodiments illustrated in the Figures are illustrative examples and not meant to be limiting. Alternative embodiments, including more or fewer components in alternative configurations are anticipated. A wearable device could include multiple housings or other such assemblies each containing some set of components to enable applications of such a wearable device. For example, a wearable device could include a first housing within which are disposed one or more magnetic flux sources configured to magnetize nanoparticles disposed in the wearer's body (e.g., within portions of subsurface vasculature of the wearer) and one or more magnetometers configured to detect magnetic fields produced by magnetic nanoparticles (e.g., by magnetic nanoparticles magnetized by the flux source(s)). The wearable device could additionally include a second housing containing a user interface and electronics configured to operate the magnetic flux source(s) and magnetometer(s) and to present information to and receive commands from a user of the wearable device. A wearable device could be configured to perform a variety of functions and to enable a variety of applications. Wearable devices could be configured to operate in concert with other devices or systems; for example, wearable devices could include a wireless communication interface configured to transmit data indicative of one or more properties of the body of a wearer of the wearable device. Other embodiments, operations, configurations, and applications of a wearable device as described herein are anticipated.

[00167] Figure 11 is a simplified schematic of a system including one or more wearable devices 1100. The one or more wearable devices 1100 may be configured to transmit data via a communication interface 1110 over one or more communication networks 1120 to a remote server 1130. In one embodiment, the communication interface 1110 includes a wireless transceiver for sending and receiving communications to and from the server 1130. In further embodiments, the communication interface 1110 may include any means for the transfer of data, including both wired and wireless communications. For example, the communication interface may include a universal serial bus (USB) interface or a secure digital (SD) card interface. Communication networks 620 may be any one of may be one of: a plain old telephone service (POTS) network, a cellular network, a fiber network and a data network. The server 1130 may include any type of remote computing device or remote cloud computing network. Further, communication network 1120 may include one or more intermediaries, including, for example wherein the wearable device 1100 transmits data to a mobile phone or other personal computing device, which in turn transmits the data to the server 1130.

[00168] In addition to receiving communications from the wearable device 1100, such as detected magnetic fields produced by magnetic nanoparticles disposed in a body of a wearer (e.g., disposed in portion(s) of subsurface vasculature of a wearer) and/or information determined therefrom (e.g., information about an analyte with which the magnetic nanoparticles are configured to selectively interact) or other collected physiological properties and data, the server may also be configured to gather and/or receive either from the wearable device 1100 or from some other source, information regarding a wearer's overall medical history, environmental factors and geographical data. For example, a user account may be established on the server for every wearer that contains the wearer's medical history. Moreover, in some examples, the server 1130 may be configured to regularly receive information from sources of environmental data, such as viral illness or food poisoning outbreak data from the Centers for Disease Control (CDC) and weather, pollution and allergen data from the National Weather Service. Further, the server may be configured to receive data regarding a wearer's health state from a hospital or physician. Such information may be used in the server's decision-making process, such as recognizing correlations and in generating clinical protocols.

[00169] Additionally, the server may be configured to gather and/or receive the date, time of day and geographical location of each wearer of the device during each measurement period. Such information may be used to detect and monitor spatial and temporal spreading

of diseases. As such, the wearable device may be configured to determine and/or provide an indication of its own location. For example, a wearable device may include a GPS system so that it can include GPS location information (e.g., GPS coordinates) in a communication to the server. As another example, a wearable device may use a technique that involves triangulation (e.g., between base stations in a cellular network) to determine its location. Other location-determination techniques are also possible.

[00170] The server may also be configured to make determinations regarding the efficacy of a drug or other treatment based on information regarding the drugs or other treatments received by a wearer of the device and, at least in part, the detected magnetic field data and the indicated health state of the user. From this information, the server may be configured to derive an indication of the effectiveness of the drug or treatment. For example, if a drug is intended to treat nausea and the wearer of the device does not indicate that they are experiencing nausea after beginning a course of treatment with the drug, the server may be configured to derive an indication that the drug is effective for that wearer. In another example, a wearable device may be configured to detect cancer cells by detecting properties of magnetic nanoparticles that are configured to selectively interact with cancer cells. If a wearer is prescribed a drug intended to destroy cancer cells, but the server receives data from the wearable device indicating that the number of cancer cells in the wearer's blood has been increasing over a certain number of measurement periods, the server may be configured to derive an indication that the drug is not effective for its intended purpose for this wearer.

[00171] Further, some embodiments of the system may include privacy controls which may be automatically implemented or controlled by the wearer of the device. For example, where a wearer's collected magnetic field data and health state data are uploaded to a cloud computing network for trend analysis by a clinician, the data may be treated in one or more ways before it is stored or used, so that personally identifiable information is removed. For example, a user's identity may be treated so that no personally identifiable information can be determined for the user, or a user's geographic location may be generalized where location information is obtained (such as to a city, ZIP code, or state level), so that a particular location of a user cannot be determined.

[00172] Additionally or alternatively, wearers of a device may be provided with an opportunity to control whether or how the device collects information about the wearer (e.g., information about a user's medical history, social actions or activities, profession, a user's preferences, or a user's current location), or to control how such information may be used. Thus, the wearer may have control over how information is collected about him or her and

used by a clinician or physician or other user of the data. For example, a wearer may elect that data, such as health state and detected magnetic field data, collected from his or her device may only be used for generating an individual baseline and recommendations in response to collection and comparison of his or her own data and may not be used in generating a population baseline or for use in population correlation studies.

VII. Example Electronics Platform for a Device

[00173] Figure 12 is a simplified block diagram illustrating the components of a device 1200, according to an example embodiment. Device 1200 may take the form of or be similar to one of the wearable devices 100, 200, 300, 400, 500, 600, 700, 800, or 1000 shown in Figures 1, 2, 3, 4, 5, 6, 7, 8A-B, and 10. However, device 1200 may also take other forms, such as an ankle, waist, or chest-mounted device. Device 1200 could also take the form of a device that is not configured to be mounted to a body. For example, device 1200 could take the form of a handheld device configured to be maintained in proximity to an environment of interest (e.g., a body part, a biological sample container, a volume of a water treatment system) by a user or operator of the device 1200 or by a frame or other supporting structure. In some examples, device 1200 could be or could form part of device configured to detect properties of an ex vivo and/or in vitro environment (e.g., the device 1200 could be configured to be operated as part of a flow cytometry experiment). Device 1200 also could take other forms.

[00174] In particular, Figure 12 shows an example of a device 1200 having a data collection system 1210 that includes a magnetometer 1212, a bias coil 1214, and an excitation coil 1216, a magnetic flux source 1218, a user interface 1220, communication interface 1230 for transmitting data to a remote system, and a controller 1250. The components of the device 1200 may be disposed on a mount or on some other structure for mounting the device to enable stable detection of one or more properties (e.g., magnetic fields produced by magnetic nanoparticles) of an environment of interest (e.g., of a body of a wearer of the device 1200), for example, mounting to an external body surface where one or more portions of subsurface vasculature or other anatomical elements are readily observable.

[00175] Controller 1250 may be provided as a computing device that includes one or more processors 1240. The one or more processors 1240 can be configured to execute computer-readable program instructions 1270 that are stored in the computer readable data storage 1260 and that are executable to provide the functionality of a device 1200 described herein.

[00176] The computer readable medium 1260 may include or take the form of one or more non-transitory, computer-readable storage media that can be read or accessed by at least one processor 1240. The one or more computer-readable storage media can include volatile and/or non-volatile storage components, such as optical, magnetic, organic or other memory or disc storage, which can be integrated in whole or in part with at least one of the one or more processors 1240. In some embodiments, the computer readable medium 1260 can be implemented using a single physical device (e.g., one optical, magnetic, organic or other memory or disc storage unit), while in other embodiments, the computer readable medium 1260 can be implemented using two or more physical devices.

[00177] The magnetometer 1212 is configured to detect a magnetic field produced by and/or related to magnetic nanoparticles disposed proximate the magnetometer (e.g., within from approximately 1 millimeter to approximately 1 centimeter) in an environment of interest, e.g., a portion of subsurface vasculature of a wearer. The magnetometer could be configured to have a sensitivity such that the magnetometer can detect changes in a measured magnetic field of less than approximately 10 femtoteslas. The magnetometer could include one or more inductive pickup coils configured to detect an oscillating or otherwise time-varying magnetic field produced by the magnetic nanoparticles in response to exposure to an oscillating magnetic field produced by the excitation coil 1216 or some other component (e.g., antenna) of the device 1200.

[00178] The magnetometer 1212 could include more or more pulse emitters (e.g., electromagnetic coils) configured to emit pulses or other patterns of magnetic field into the environment of interest (e.g., pi pulse, pi/2 pulses) to rotate magnetic spins of atomic nuclei in the environment of interest. The magnetometer 1212 could then detect time-varying magnetic and/or electromagnetic fields generated by the rotated magnetic moments of the atomic nuclei as the magnetic moments precess in response to the rotation. A frequency, frequency spectrum, or other properties of the detected time-varying field could be related to the presence, location, orientation, amount, degree of aggregation, or other properties of magnetized nanoparticles in the environment of interest.

[00179] The magnetometer could include amplifiers, oscillators, ADCs, switches, filters, light emitter, light detectors, or other components configured to detect a magnetic field using one or more magnetic-field-sensitive elements of the magnetometer 1212. For example, the magnetometer 1212 could be a SERF magnetometer, a multipass scalar atomic magnetometer, a radio-frequency atomic magnetometer, or some other variety of atomic magnetometer that includes an alkali vapor cell (i.e., an enclosed volume containing a high-

pressure, high-temperature vapor that includes alkali metal atoms) and the electronics could include a heater configured to vaporize the alkali metal in the vapor cell, a pump laser configured to emit circularly polarized light into the vapor cell to align the alkali metal atoms, a probe laser configured to probe the aligned alkali atoms with linearly polarized light, and a light detector configured to detect the change in orientation of the linearly polarized light that is related to the detected magnetic field. Other examples of magnetometers and electronics thereof are anticipated.

[00180] The bias coil 1214 is configured to produce a bias magnetic field to reduce a background magnetic field to which the magnetometer 1212 is exposed and/or to reduce an inhomogeneity of the magnetic field in the environment of interest (e.g., to cancel the effects of the Earth's magnetic field on the magnetometer 1212, to cancel the effects of the magnetic flux source 1218 on the magnetometer 1212) and/or to provide some other functionality. The bias coil 1214 could be driven according to a bias field magnitude determined based on an output of the magnetometer 1212, an output of some other magnetometer (not shown), an output of an accelerometer, gyroscope, or some other sensor, or based on some other consideration.

[00181] The magnetic flux source 1218 is configured to produce magnetic field sufficient to provide some application or function of the device. This could include magnetizing magnetic nanoparticles proximate the device 1200 (e.g., proximate the magnetic flux source 1218) that are upstream, relative to a direction of flow in the environment of interest (e.g., a direction of a blood flow in a portion of subsurface vasculature), from the location of the magnetometer 1212. Such magnetized nanoparticles can flow downstream to be detected by the magnetometer 1212 (e.g., by detecting a magnetic field produced by and/or affected by the magnetized nanoparticles). The magnetic flux source 1218 could be a permanent magnet and/or an electromagnet. In some examples, the magnetic flux source 1218 could be operated to collect nanoparticles (e.g., by exerting an attractive magnetic force) during a first period of time and subsequently to release the collected nanoparticles (e.g., to allow detection, by the magnetometer 1212, of a magnetic field produced by and/or affected by the collected nanoparticles). In some examples, the magnetic flux source 1218 and/or some other source of magnetic flux could be configured to polarize magnetic spins of atomic nuclei in the environment of interest such that the magnetometer 1212 can detect the presence or other properties of the magnetic nanoparticles by rotating the polarized magnetic spins of the atomic nuclei and detecting a time-varying magnetic field produced by precession of the rotated magnetic spins of the atomic nuclei.

[00182] Note that a device could include a subset of the elements described here, e.g., a device could lack a bias coil, excitation coil, magnetic flux source, and/or some other combination of elements. Further, a device could include multiple of one or more illustrated elements. For example, a device could include multiple magnetometers configured to detect a magnetic field at respective multiple different locations and/or in multiple different directions. In another example, a device could include multiple bias coils to cancel magnetic fields in multiple different directions and/or for multiple different magnetometers. In some examples, multiple illustrated elements of the device 1200 could be implemented as the same component and/or share some component(s) in common. For example, the excitation coil 1216 could form part of the magnetometer 1212 and could be used to detect an oscillating or otherwise time-varying magnetic field produced by the magnetic nanoparticles in response to exposure to an oscillating magnetic field produced by the excitation coil 1216.

[00183] The program instructions 1270 stored on the computer readable medium 1260 may include instructions to perform any of the methods described herein. For instance, in the illustrated embodiment, program instructions 1270 include a controller module 1272, calculation and decision module 1274 and an alert module 1276.

[00184] Calculation and decision module 1274 may include instructions for operating the magnetometer 1212, bias coil 1214, and/or excitation coil 1216 to detect magnetic fields produced by and/or affected by magnetic nanoparticles proximate the magnetometer 1212 and analyzing data generated by the magnetometer 1212 to determine information about magnetic nanoparticles and/or analytes in a body (e.g., by detecting pulses or other features in a detected magnetic field, a detected $T2^*$ of atomic nuclei, or other detected parameters related to aggregates of magnetic nanoparticles in the change of a detected magnetic field over time) or other information (e.g., health states) of a body of a wearer of the device 1200, such as a concentration of an analyte in blood of the body at a plurality of points in time. Calculation and decision module 1274 can additionally include instructions for analyzing the data to determine if a medical condition or other specified condition is indicated, or other analytical processes relating to the environment proximate to the device 1200. In particular, the calculation and decision module 1274 may include instructions for operating the bias coil 1214 to reduce a magnetic field detected by the magnetometer 1212 and/or instructions for operating the excitation coil 1216 to produce an oscillating or otherwise time-varying magnetic field in an environment containing magnetic nanoparticles, for operating a pulse emitter to rotate magnetic spins of atomic nuclei, or for performing some other operations. These instructions could be executed at each of a set of preset measurement times.

[00185] The controller module 1272 can also include instructions for operating a user interface 1220. For example, controller module 1272 may include instructions for displaying data collected by the data collection system 1210 and analyzed by the calculation and decision module 1274, or for displaying one or more alerts generated by the alert module 1276. Controller module 1272 may include instructions for displaying data related to a detected magnetic field produced by and/or affected by magnetic nanoparticles in one or more portions of subsurface vasculature or some other detected and/or determined health state of a wearer. Further, controller module 1272 may include instructions to execute certain functions based on inputs accepted by the user interface 1220, such as inputs accepted by one or more buttons disposed on the user interface.

[00186] Communication interface 1230 may also be operated by instructions within the controller module 1272, such as instructions for sending and/or receiving information via a wireless antenna, which may be disposed on or in the device 1200. The communication interface 1230 can optionally include one or more oscillators, mixers, frequency injectors, etc. to modulate and/or demodulate information on a carrier frequency to be transmitted and/or received by the antenna. In some examples, the device 1200 is configured to indicate an output from the processor by modulating an impedance of the antenna in a manner that is perceivable by a remote server or other remote computing device.

[00187] The program instructions of the calculation and decision module 1274 may, in some examples, be stored in a computer-readable medium and executed by a processor located external to the device 1200. For example, the device 1200 could be configured to collect certain data regarding magnetic fields produced by and/or affected by magnetic nanoparticles disposed in the body of the user and then transmit the data to a remote server, which may include a mobile device, a personal computer, the cloud, or any other remote system, for further processing.

[00188] The computer readable medium 1260 may further contain other data or information, such as medical and health history of a user of the device 1200, that may be useful in determining whether a medical condition or some other specified condition is indicated. Further, the computer readable medium 1260 may contain data corresponding to certain physiological parameter baselines, above or below which a medical condition is indicated. The baselines may be pre-stored on the computer readable medium 1260, may be transmitted from a remote source, such as a remote server, or may be generated by the calculation and decision module 1274 itself. The calculation and decision module 1274 may include instructions for generating individual baselines for the user of the device 1200 based

on data collected over a certain number of measurement periods. Baselines may also be generated by a remote server and transmitted to the device 1200 via communication interface 1230. The calculation and decision module 1274 may also, upon determining that a medical or other emergency condition is indicated, generate one or more recommendations for the user of the device 1200 based, at least in part, on consultation of a clinical protocol. Such recommendations may alternatively be generated by the remote server and transmitted to the device 1200.

[00189] In some examples, the collected magnetic field data, baseline profiles, health state information input by device users and generated recommendations and clinical protocols may additionally be input to a cloud network and be made available for download by a user's physician. Trend and other analyses may also be performed on the collected data, such as analyte and/or magnetic nanoparticle data and health state information, in the cloud computing network and be made available for download by physicians or clinicians.

[00190] Further, detected magnetic field data and determined magnetic nanoparticle, analyte, and health state data from individuals or populations of device users may be used by physicians or clinicians in monitoring efficacy of a drug or other treatment. For example, high-density, real-time data may be collected from a population of device users who are participating in a clinical study to assess the safety and efficacy of a developmental drug or therapy. Such data may also be used on an individual level to assess a particular wearer's response to a drug or therapy. Based on this data, a physician or clinician may be able to tailor a drug treatment to suit an individual's needs.

[00191] In response to a determination by the calculation and decision module 1274 that a medical or other specified condition is indicated, the alert module 1276 may generate an alert via the user interface 1220. The alert may include a visual component, such as textual or graphical information displayed on a display, an auditory component (e.g., an alarm sound), and/or tactile component (e.g., a vibration). The textual information may include one or more recommendations, such as a recommendation that the user of the device contact a medical professional, seek immediate medical attention, or administer a medication.

VIII. Example Methods

[00192] Figure 13 is a flowchart of an example method 1300 for detecting properties of magnetic nanoparticles in a biological environment by detecting a magnetic field produced by the magnetic nanoparticles. The method 1300 includes detecting, using a magnetometer, a

magnetic field produced by magnetic particles in a biological environment that are proximate the magnetometer (1310). This could include detecting a magnitude, direction, magnitude in a particular direction, a pattern or property of change over time of a property of the produced magnetic field, or some other property of the produced magnetic field. In some examples, detecting the magnetic field produced by the magnetic nanoparticles (1310) could include detecting the produced field at more than one location proximate to more than one magnetometer. Detecting the magnetic field produced by the magnetic nanoparticles (1310) could include producing an oscillating magnetic field in the biological environment and detecting a time-varying magnetic field responsively reflected, phase-shifted, frequency-shifter, frequency-multiplied, or otherwise produced by the magnetic nanoparticles. Detecting the magnetic field produced by the magnetic nanoparticles (1310) could include applying a bias magnetic field (e.g., by operating a bias coil disposed proximate the magnetometer) to cancel a background magnetic field (e.g., a magnetic field produced by the Earth) to which the magnetometer is exposed.

[00193] The method 1300 additionally includes determining a property of the magnetic nanoparticles based on the detected magnetic field (1320). This could include determining the orientation and/or location of one or more of the magnetic nanoparticles, a degree of aggregation of the magnetic nanoparticles, or the detection of some other property of the magnetic nanoparticles. Determining a property of the magnetic nanoparticles (1320) could include determining and/or detecting features of the detected magnetic field, e.g., detecting the amplitude, width, timing, or other properties of pulses in the detected magnetic field produced by the magnetic nanoparticles over time. Further, such determined properties of the magnetic nanoparticles could be related to properties of an analytes of interest with which the magnetic nanoparticles are configured to selectively interact (e.g., to bind to). For example, multiple magnetic nanoparticles could bind to a single instance of an analyte (e.g., to a single cancer cell) such that detection of an aggregate of magnetic nanoparticles (e.g., detection of a large amplitude magnetic field produced by such aggregated magnetic nanoparticles) allows for the determination that the single instance of the analyte is present (e.g., that a cancer cell is present in a portion of subsurface vasculature). Other properties of a detected magnetic field produced by magnetic nanoparticles could be used in similar or different ways to determine properties of one or more analytes in an environment of interest.

[00194] The method 1300 could include additional steps or elements. For example, the method 1300 could include introducing the magnetic particles into the biological environment (e.g., into a portion of subsurface vasculature by injecting, ingesting,

transdermally transferring, or otherwise introducing the engineered particles into a lumen of vasculature of a human). In some examples, the method 1300 could include collecting the magnetic particles in a portion of subsurface vasculature, e.g., to extract the magnetic nanoparticles and/or to increase a magnitude of the magnetic field produced by the magnetic nanoparticles as detected by the magnetometer. The method 1300 could include additional or alternative steps.

[00195] Figure 14 is a flowchart of an example method 1400 for detecting properties of nanoparticles and/or an analyte bound thereto in a biological environment by detecting a magnetic field produced by and/or affected by the nanoparticles. The method 1400 includes magnetizing, using a magnetic flux source, nanoparticles in a first location of subsurface vasculature (1410). This could include the magnetic flux source producing a magnetic field in the first location of a portion of subsurface vasculature having a sufficient magnetic field magnitude (e.g., greater than approximately 100 Gauss) to at least partially magnetize, to align one or more magnetic moments of (e.g., magnetic moments of one or more nanoparticles of superparamagnetic iron oxide of), to rotate, or to otherwise magnetize the nanoparticles. Magnetizing the nanoparticles (1410) could include applying current to an electromagnet of the magnetic flux source, rotating, translation, or otherwise actuating a permanent magnet, magnetic shim, or other element of the magnetic flux source, moving the magnetic flux source proximate to the portion of subsurface vasculature, or performing some other steps to produce a magnetic field sufficient to magnetize the nanoparticles.

[00196] The method 1400 includes detecting, using a magnetometer, a magnetic field at a second location of the subsurface vasculature, wherein the second location is located downstream from the first location relative to a direction of blood flow in the subsurface vasculature (1420). This could include detecting a magnitude, direction, magnitude in a particular direction, a pattern or property of change over time of a property of the magnetic field, or some other property of the produced magnetic field. The detected magnetic field could be directly related to the magnetic field produced by the magnetized nanoparticles (e.g., could be a field generated by a magnetic moment of the magnetized nanoparticles, could be produced by the nanoparticles in response to an applied external energy, e.g., an applied oscillating magnetic field). The detected magnetic field could be indirectly related to the magnetic field produced by the magnetized nanoparticles (e.g., could be a magnetic field produced by rotated, precessing magnetic spins of atomic nuclei proximate the magnetized nanoparticles, where a frequency, coherence, or other properties of the precession is related to the magnetic field produced by the magnetized nanoparticles). Detecting the magnetic field

(1420) could include producing an oscillating magnetic field in the second location of subsurface vasculature and detecting a time-varying magnetic field responsively reflected, phase-shifted, frequency-shifted, frequency-multiplied, or otherwise produced by the magnetized nanoparticles. Detecting the magnetic field (1420) could include applying a bias magnetic field (e.g., by operating a bias coil disposed proximate the magnetometer) to cancel a background magnetic field (e.g., a magnetic field produced by the Earth) to which the magnetometer is exposed. Detecting the magnetic field (1420) could include rotating magnetic spins of atomic nuclei in the second location of subsurface vasculature (e.g., by emitting a magnetic or electromagnetic pulse at the Larmor frequency of the magnetic spins of the atomic nuclei, e.g., a π pulse, a $\pi/2$ pulse) and detecting magnetic fields produced by the responsively precessing rotated magnetic spins.

[00197] The method 1400 additionally includes determining a property of the magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the first location and that traveled to the second location (1430). This could include determining the orientation and/or location of one or more of the magnetized nanoparticles, a degree of aggregation of the magnetized nanoparticles, or the detection of some other property of the magnetized nanoparticles. Determining a property of the magnetized nanoparticles (1430) could include determining and/or detecting features of the detected magnetic field, e.g., detecting the amplitude, width, timing, decay rate or decay time constant, frequency spectrum or Fourier transform, or other properties of the detected magnetic field over time. Further, such determined properties of the magnetized nanoparticles could be related to properties of an analytes of interest with which the magnetized nanoparticles are configured to selectively interact (e.g., to bind to). For example, multiple magnetized nanoparticles could bind to a single instance of an analyte (e.g., to a single cancer cell) such that detection of an aggregate of magnetized nanoparticles (e.g., detection of a large amplitude magnetic field produced by such aggregated magnetized nanoparticles, detection of a shortened decoherence time, T2 time constant, or other properties of magnetic spins of atomic nuclei) allows for the determination that the single instance of the analyte is present (e.g., that a cancer cell is present in a portion of subsurface vasculature). Other properties of a detected magnetic field produced by and/or affected by magnetized nanoparticles could be used in similar or different ways to determine properties of one or more analytes in an environment of interest.

[00198] The method 1400 could include additional steps or elements. For example, the method 1400 could include introducing the nanoparticles into the biological environment

(e.g., into a portion of subsurface vasculature by injecting, ingesting, transdermally transferring, or otherwise introducing the engineered nanoparticles into a lumen of vasculature of a human). In some examples, the method 1400 could include collecting the magnetized nanoparticles in a portion of subsurface vasculature, e.g., to extract the nanoparticles and/or to increase a magnitude of the magnetic field produced by the magnetized nanoparticles as detected by the magnetometer. The method 1400 could include additional or alternative steps.

IX. Conclusion

[00199] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims.

[00200] While various aspects and embodiments herein are described in connection with detecting magnetic and/or electromagnetic fields produced and/or influenced by magnetic nanoparticles (e.g., nanoparticles that are intrinsically magnetic and/or that have been magnetized) disposed in particular example biological environments (e.g., a portion of subsurface vasculature) to detect and/or determine properties (e.g., a presence, a concentration, a number, a degree of aggregation, a binding state) of the magnetic nanoparticles, other applications and environments are possible.

[00201] Aspects and embodiments herein could be applied to detect properties of magnetic nanoparticles in *in vivo* or *in vitro* human or animal tissues, a fluid in a scientific, medical, or industrial testing process, or some other environment. Properties of magnetic nanoparticles disposed in a natural environment, e.g., a lake, river, stream, marsh, or other natural locale could be detected. Properties of magnetic nanoparticles disposed in a fluid environment of an industrial process or other artificial environment, e.g., a water treatment process, a food preparation process, a pharmaceutical synthesis process, a chemical synthesis process, a brewing and/or distilling process, or other artificial locale could be detected. Properties of magnetic nanoparticles disposed in an environment that includes a flowing fluid (e.g., fluid flowing in a blood vessel, a pipe, a culvert) and/or a substantially static fluid could be detected. Other environments and applications of aspects and embodiments described herein are anticipated.

[00202] Where example embodiments involve information related to a person or a

device of a person, such embodiments may include privacy controls. Such privacy controls may include, at least, anonymization of device identifiers, transparency and user controls, including functionality that would enable users to modify or delete information relating to the user's use of a product.

[00203] Further, in situations wherein embodiments discussed herein collect personal information about users, or make use of personal information, the users may be provided with an opportunity to control whether programs or features collect user information (e.g., information about a user's medical history, social network, social actions or activities, profession, a user's preferences, or a user's current location), or to control whether and/or how to receive content from the content server that may be more relevant to the user. In addition, certain data may be treated in one or more ways before it is stored or used, so that personally identifiable information is removed.

CLAIMS

What is claimed is:

1. A device comprising:
a magnetometer, wherein the magnetometer is configured to be positioned proximate to a body, wherein the magnetometer is configured to detect magnetic fields produced by magnetic nanoparticles in the body that are proximate the magnetometer; and
a controller operably coupled to the magnetometer, wherein the controller comprises a computing device programmed to perform controller operations comprising:
operating the magnetometer to detect a magnetic field; and
determining a property of magnetic nanoparticles in the body based on the detected magnetic field.
2. The device of claim 1, wherein determining a property of magnetic nanoparticles in the body based on the detected magnetic field comprises determining a degree of aggregation of the magnetic nanoparticles in the body.
3. The device of claim 1, wherein the controller operations further comprise determining a property of an analyte bound to the magnetic nanoparticles based the determined property of the magnetic nanoparticles.
4. The device of claim 3, wherein determining a property of an analyte bound to the magnetic nanoparticles comprises determining an amount of the analyte in the body.
5. The device of claim 3, wherein the magnetometer being configured to be positioned proximate to the body comprises the magnetometer being configured to be positioned on an external body surface of the body.
6. The device of claim 1, further comprising:
a further magnetometer, wherein the further magnetometer is configured to be positioned proximate to the body, wherein the further magnetometer is configured to detect further magnetic fields produced by magnetic nanoparticles in the body that are proximate the further magnetometer, wherein the controller operations further comprise operating the

further magnetometer to detect the further magnetic fields, and wherein determining the property of magnetic nanoparticles in the body comprises determining the property of magnetic nanoparticles in the body based on the further magnetic fields detected using the further magnetometer.

7. The device of claim 1, wherein the magnetometer comprises a spin-exchange relaxation-free atomic magnetometer.

8. The device of claim 1, wherein the magnetometer comprises a superconducting quantum interference device.

9. The device of claim 1, further comprising:
a magnetic flux source, wherein the magnetic flux source is configured to be positioned proximate to the body and to magnetize magnetic nanoparticles in the body that are proximate the magnetic flux source, and wherein operating the magnetometer comprises operating the magnetometer to detect magnetic fields produced by magnetic nanoparticles in the body that have been magnetized by the magnetic flux source.

10. The device of claim 1, further comprising:
a collection magnet, wherein the collection magnet is configured to be positioned proximate to the body, wherein the collection magnet is configured to exert an attractive magnetic force on magnetic nanoparticles in the body proximate to the collection magnet, and wherein the attractive magnetic force is sufficient to collect the magnetic nanoparticles proximate to the collection magnet.

11. The device of claim 1, further comprising an excitation coil, wherein the excitation coil is configured to be positioned proximate to the body and to produce an oscillating magnetic field in the body, and wherein operating the magnetometer comprises operating the magnetometer to detect time-varying magnetic fields produced by magnetic nanoparticles in the body in response to the oscillating magnetic field produced by the excitation coil.

12. The device of claim 1, further comprising:

at least one bias coil, wherein the at least one bias coil is configured to produce a bias magnetic field such that the magnetic field detected by the magnetometer is reduced by an amount related to the bias magnetic field, and wherein the controller operations further comprise:

determining a bias field magnitude; and

operating the at least one bias coil to produce the bias magnetic field according to the determined bias field magnitude .

13. A method comprising:

positioning a magnetometer on a body surface of a body;

detecting, using the magnetometer, a magnetic field produced by magnetic nanoparticles in the body that are proximate the magnetometer; and

determining a property of magnetic nanoparticles in the body based on the detected magnetic field.

14. The method of claim 13, wherein determining a property of magnetic nanoparticles in the body based on the detected magnetic field comprises determining a degree of aggregation of the magnetic nanoparticles in the body.

15. The method of claim 13, further comprising:

determining a property of an analyte bound to the magnetic nanoparticles based on the determined property of the magnetic nanoparticles.

16. The method of claim 15, wherein determining a property of an analyte bound to the magnetic nanoparticles comprises determining an amount of the analyte in the body.

17. The method of claim 13, further comprising:

producing an oscillating magnetic field in the body, wherein detecting a magnetic field proximate to the body comprises detecting a time-varying magnetic field produced by magnetic nanoparticles in the body in response to exposure to the produced oscillating magnetic field.

18. The method of claim 17, wherein detecting a time-varying magnetic field produced by magnetic nanoparticles in the body in response to exposure to the produced oscillating magnetic field comprises detecting a time-varying magnetic field at a frequency that is a multiple of the frequency of the produced oscillating magnetic field.

19. The method of claim 13, further comprising:

exerting, using a collection magnet, an attractive magnetic force on magnetic nanoparticles in the body proximate to the collection magnet, wherein the attractive magnetic force is sufficient to collect the magnetic nanoparticles proximate to the collection magnet.

20. The method of claim 13, further comprising:

detecting, using a further magnetometer, a further magnetic field proximate to a body, wherein detecting the further magnetic field proximate to a body comprises detecting a further magnetic field produced by magnetic nanoparticles in the body that are proximate the further magnetometer, and wherein determining the property of magnetic nanoparticles in the body comprises determining the property of magnetic nanoparticles in the body based on the further magnetic field detected using the further magnetometer.

21. A device comprising:

a magnetometer, wherein the magnetometer is configured to detect magnetic fields at a first location of subsurface vasculature;

a magnetic flux source, wherein the magnetic flux source is configured to magnetize nanoparticles in a second location of subsurface vasculature, wherein the second location is located upstream from the first location relative to a direction of blood flow in the subsurface vasculature; and

a controller operably coupled to the magnetometer, wherein the controller comprises a computing device programmed to perform controller operations comprising:

operating the magnetometer to detect a magnetic field at the first location; and

determining a property of magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the second location.

22. The device of claim 21, wherein determining the property of the magnetized nanoparticles based on the detected magnetic field comprises determining a degree of aggregation of the magnetized nanoparticles.

23. The device of claim 21, wherein the controller operations further comprise determining a property of an analyte bound to the magnetized nanoparticles based on the determined property of the magnetized nanoparticles.

24. The device of claim 23, wherein determining the property of the analyte bound to the magnetized nanoparticles comprises determining an amount of the analyte.

25. The device of claim 21, wherein the magnetometer is configured to be positioned on an external body surface proximate the first location of subsurface vasculature, wherein the magnetic flux source is configured to be positioned on an external body surface proximate the second location of subsurface vasculature.

26. The device of claim 21, wherein the magnetometer comprises a spin-exchange relaxation-free atomic magnetometer.

27. The device of claim 21, wherein the magnetometer comprises a multipass scalar atomic magnetometer.

28. The device of claim 21, further comprising an excitation coil, wherein the excitation coil is configured to be positioned proximate to the first location of subsurface vasculature and to produce an oscillating magnetic field in the subsurface vasculature, and wherein operating the magnetometer comprises operating the magnetometer to detect time-varying magnetic fields produced by the magnetized nanoparticles proximate the second location of subsurface vasculature in response to the oscillating magnetic field produced by the excitation coil.

29. The device of claim 21, further comprising a pulse emitter, wherein the pulse emitter is configured to be positioned proximate to the first location of subsurface vasculature and to rotate the magnetic spins of atomic nuclei by producing a time-varying magnetic field in the subsurface vasculature, and wherein operating the magnetometer comprises operating

the magnetometer to detect time-varying magnetic fields produced by atomic nuclei in the subsurface vasculature in response to rotation of the spins of the atomic nuclei by the pulse emitter.

30. The device of claim 21, further comprising:

at least one bias coil, wherein the at least one bias coil is configured to produce a bias magnetic field such that the magnetic field detected by the magnetometer is reduced by an amount related to the bias magnetic field, and wherein the controller operations further comprise:

determining a bias field magnitude; and

operating the at least one bias coil to produce the bias magnetic field according to the determined bias field magnitude .

31. The device of claim 21, further comprising :

a permanent magnet, wherein the permanent magnet is configured to produce an offset magnetic field such that the magnetic field detected by the magnetometer is reduced by an amount related to the offset magnetic field, wherein a magnitude and a direction of the offset magnetic field are selected such that the offset magnetic field at least partially cancels a magnetic field produced by the magnetic flux source at the first location.

32. The device of claim 21, wherein the nanoparticles have magnetic relaxation times within a specified range of relaxation times, wherein the specified range of relaxation times is between approximately 1 second and approximately 2 seconds, wherein the first and second locations are separated by a specified distance such that nanoparticles magnetized by the magnetic flux source during a first period of time while in the second location are still substantially magnetized during a second period of time while in the first location.

33. The device of claim 21, wherein the nanoparticles comprise first nanoparticles having magnetic relaxation times within a first specified range of relaxation times and second nanoparticles having magnetic relaxation times within a second specified range of relaxation times, and further comprising:

a further magnetometer, wherein the further magnetometer is configured to be positioned proximate to a third location of subsurface vasculature and configured to detect magnetic fields at the third location, and wherein the third location is located downstream

from the first location relative to a direction of blood flow in the subsurface vasculature, and wherein the controller operations further comprise:

operating the further magnetometer to detect a further magnetic field at the third location, wherein determining a property of magnetized nanoparticles based on the detected magnetic field comprises determining a property of magnetized nanoparticles based on the detected further magnetic field.

34. A method comprising:

magnetizing, using a magnetic flux source, nanoparticles in a first location of subsurface vasculature;

detecting, using a magnetometer, a magnetic field at a second location of the subsurface vasculature, wherein the second location is located downstream from the first location relative to a direction of blood flow in the subsurface vasculature; and

determining a property of magnetized nanoparticles based on the detected magnetic field, wherein the magnetized nanoparticles include nanoparticles that were magnetized by the magnetic flux source at the first location.

35. The method of claim 34, wherein determining a property of magnetized nanoparticles based on the detected magnetic field comprises determining a degree of aggregation of the magnetized nanoparticles.

36. The method of claim 34, further comprising:

determining a property of an analyte bound to the magnetized nanoparticles based on the determined property of the magnetized nanoparticles.

37. The method of claim 36, wherein determining a property of an analyte bound to the magnetized nanoparticles comprises determining an amount of the analyte.

38. The method of claim 34, further comprising:

producing an oscillating magnetic field in the second location of subsurface vasculature, wherein detecting a magnetic field at the second location of subsurface vasculature comprises detecting a time-varying magnetic field produced by magnetized nanoparticles proximate the second location of subsurface vasculature in response to the produced oscillating magnetic field.

39. The method of claim 38, wherein detecting a time-varying magnetic field produced by magnetized nanoparticles in response to exposure to the produced oscillating magnetic field comprises detecting a time-varying magnetic field at a frequency that is a multiple of the frequency of the produced oscillating magnetic field.

40. The method of claim 34, further comprising:

rotating the magnetic spins of atomic nuclei by producing a time-varying magnetic field in the second location of subsurface vasculature, wherein detecting a magnetic field in the second location of subsurface vasculature comprises operating the magnetometer to detect time-varying magnetic fields produced by atomic nuclei in the second location of subsurface vasculature in response to rotation of the spins of the atomic nuclei.

41. The method of claim 34, wherein the nanoparticles comprise first nanoparticles having magnetic relaxation times within a first specified range of relaxation times and second nanoparticles having magnetic relaxation times within a second specified range of relaxation times, and further comprising:

detecting, using a further magnetometer, a further magnetic field produced in a third location of subsurface vasculature, wherein the third location is located downstream from the second location relative to a direction of blood flow in the subsurface vasculature, and wherein determining a property of magnetized nanoparticles based on the detected magnetic field comprises determining a property of magnetized nanoparticles based on the detected further magnetic field.

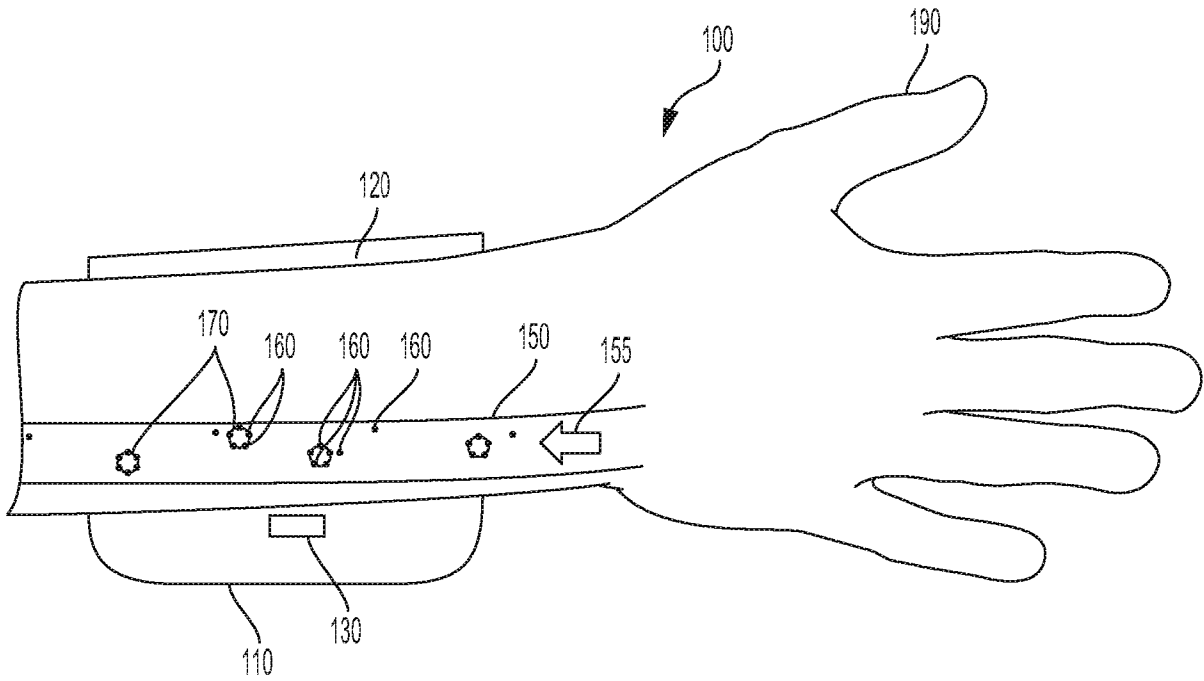


FIG. 1A

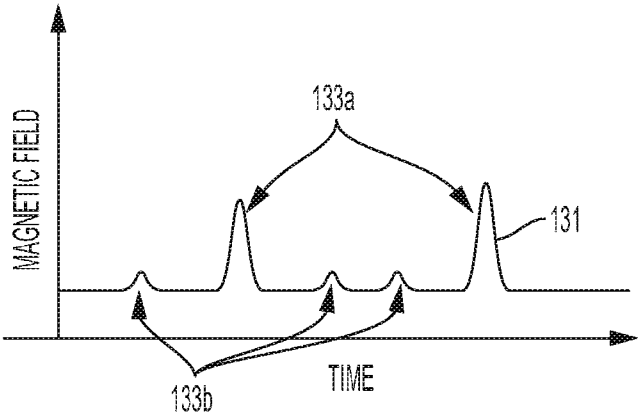


FIG. 1B

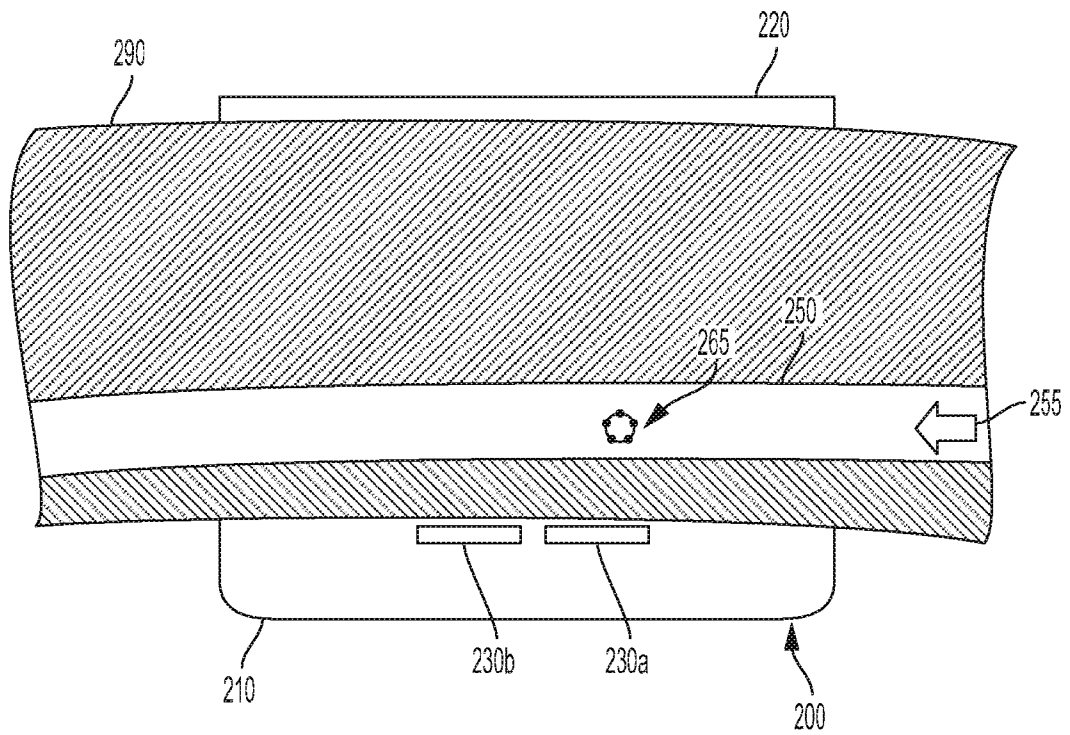


FIG. 2A

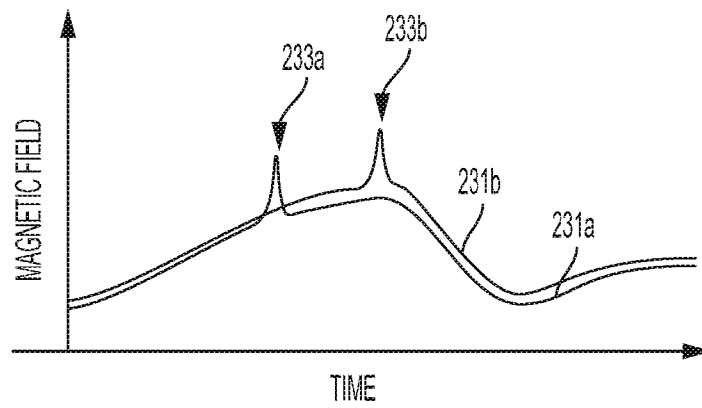


FIG. 2B

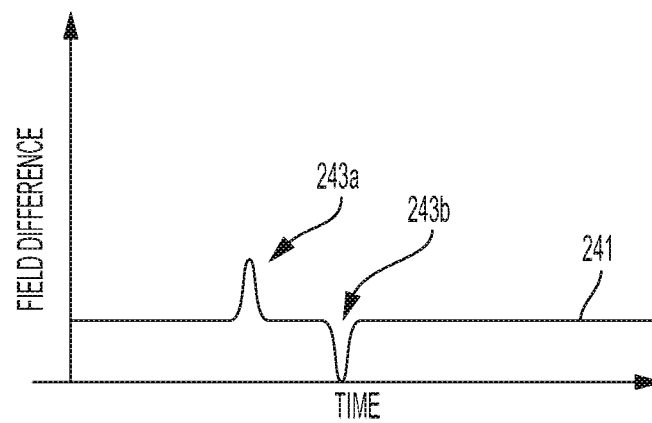


FIG. 2C

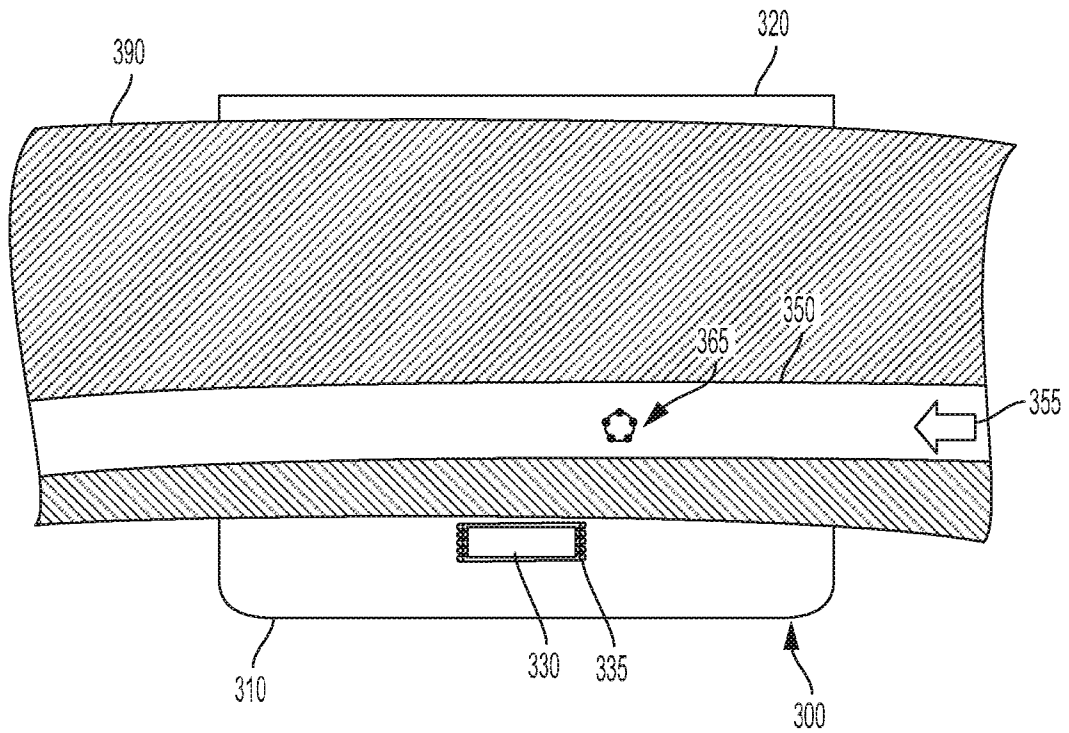


FIG. 3A

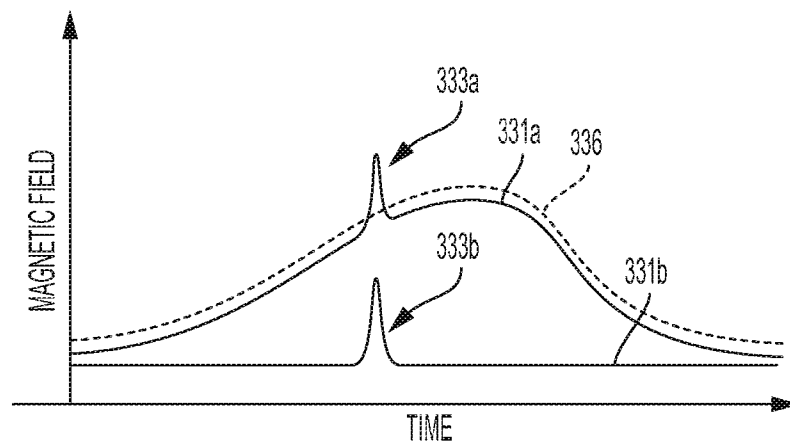


FIG. 3B

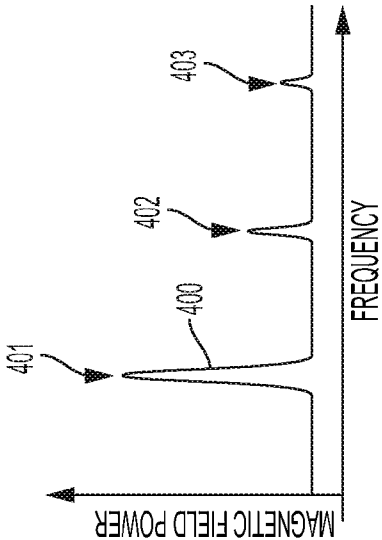


FIG. 4

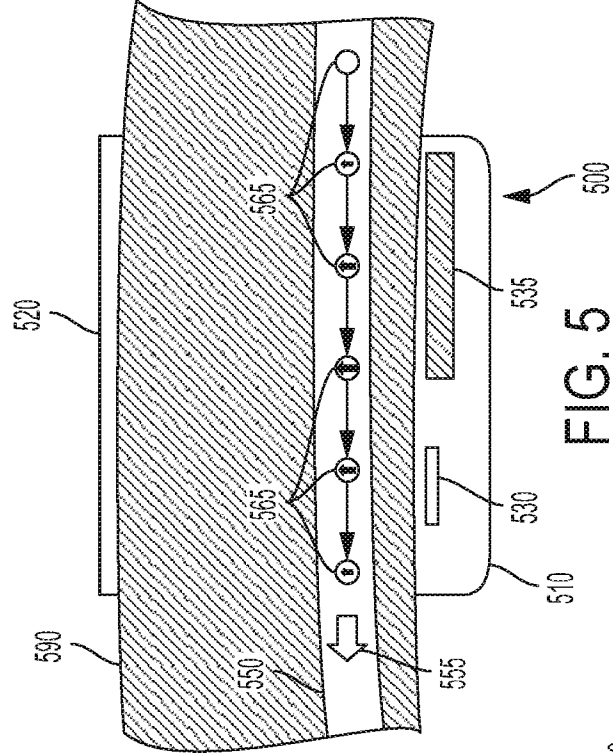


FIG. 5

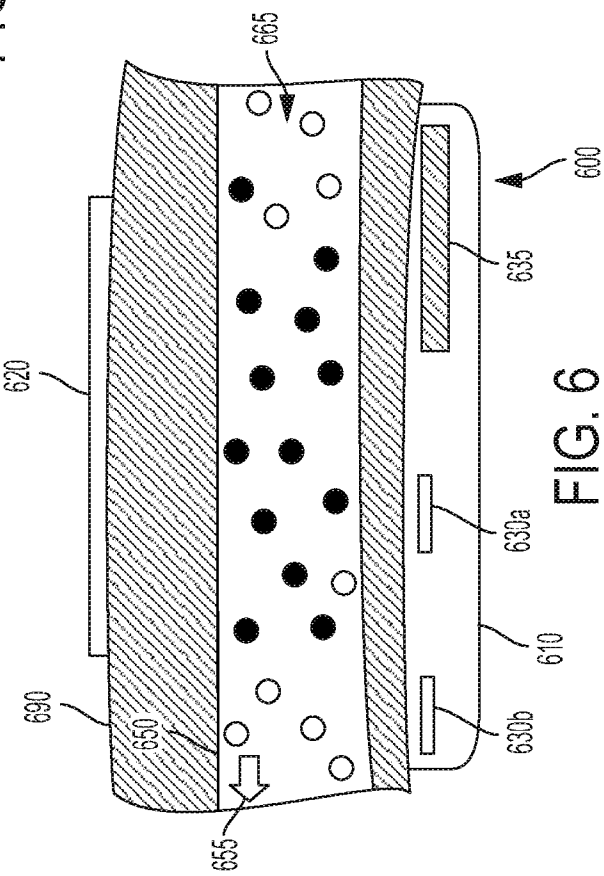
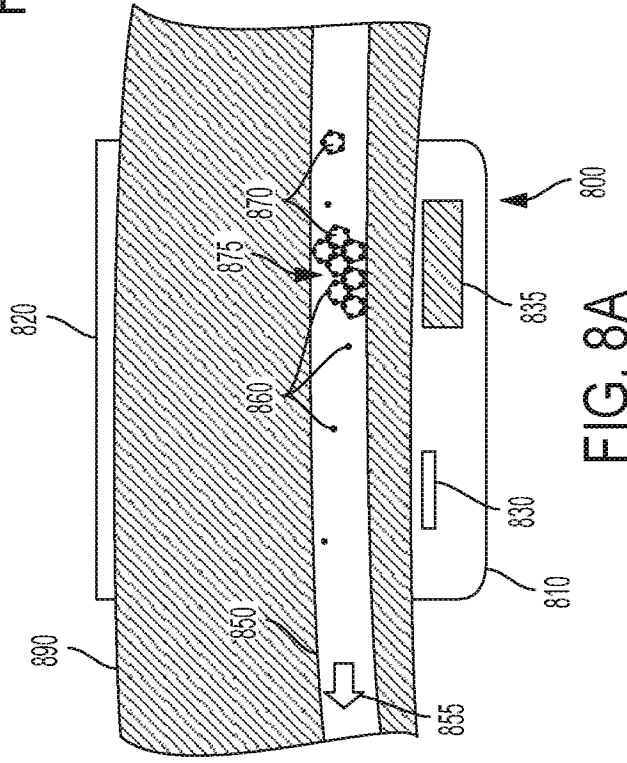
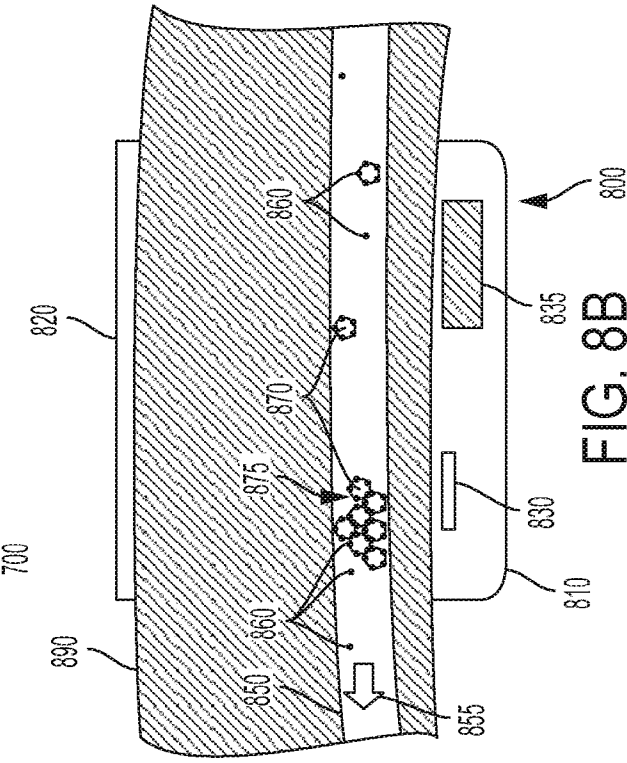
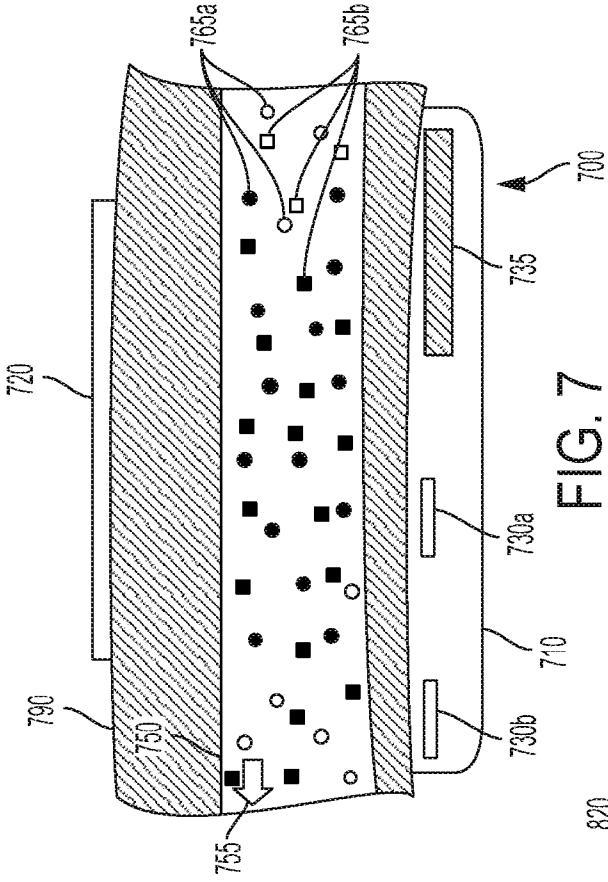


FIG. 6



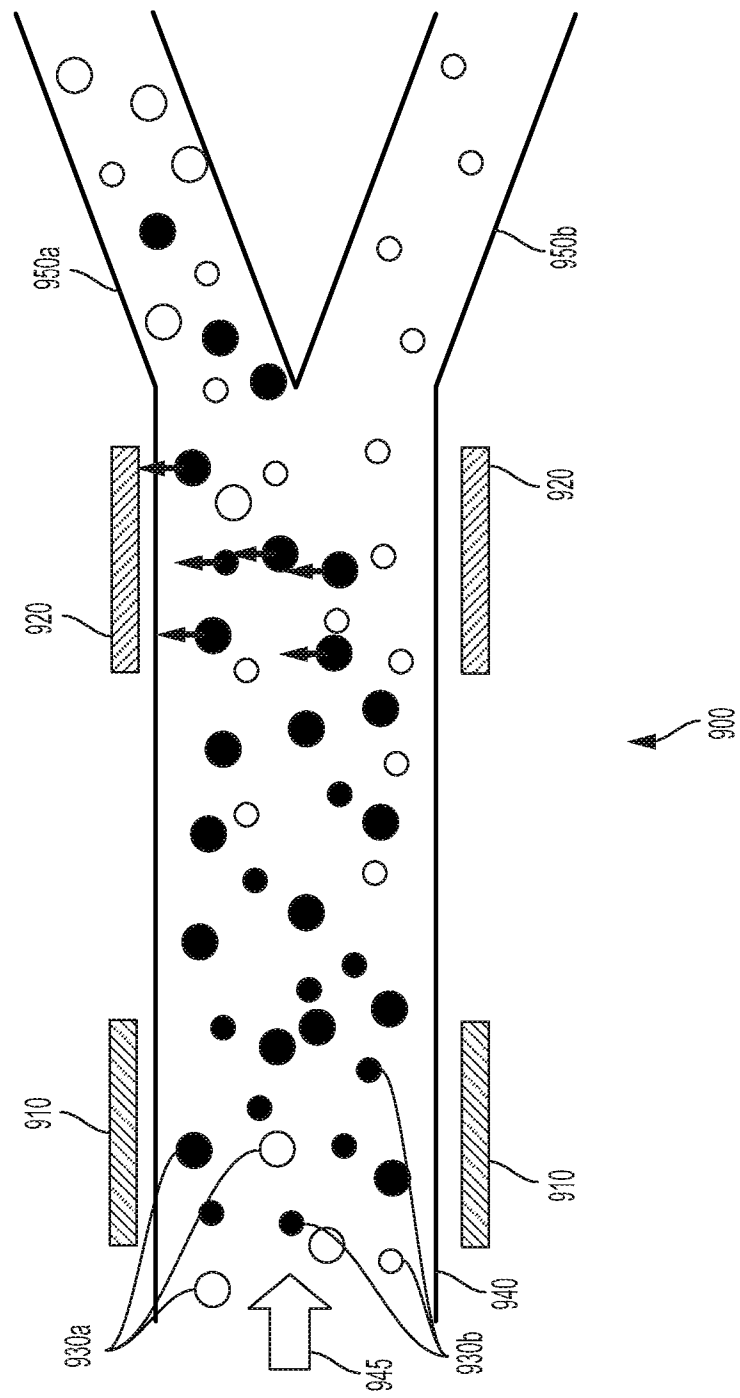


FIG. 9

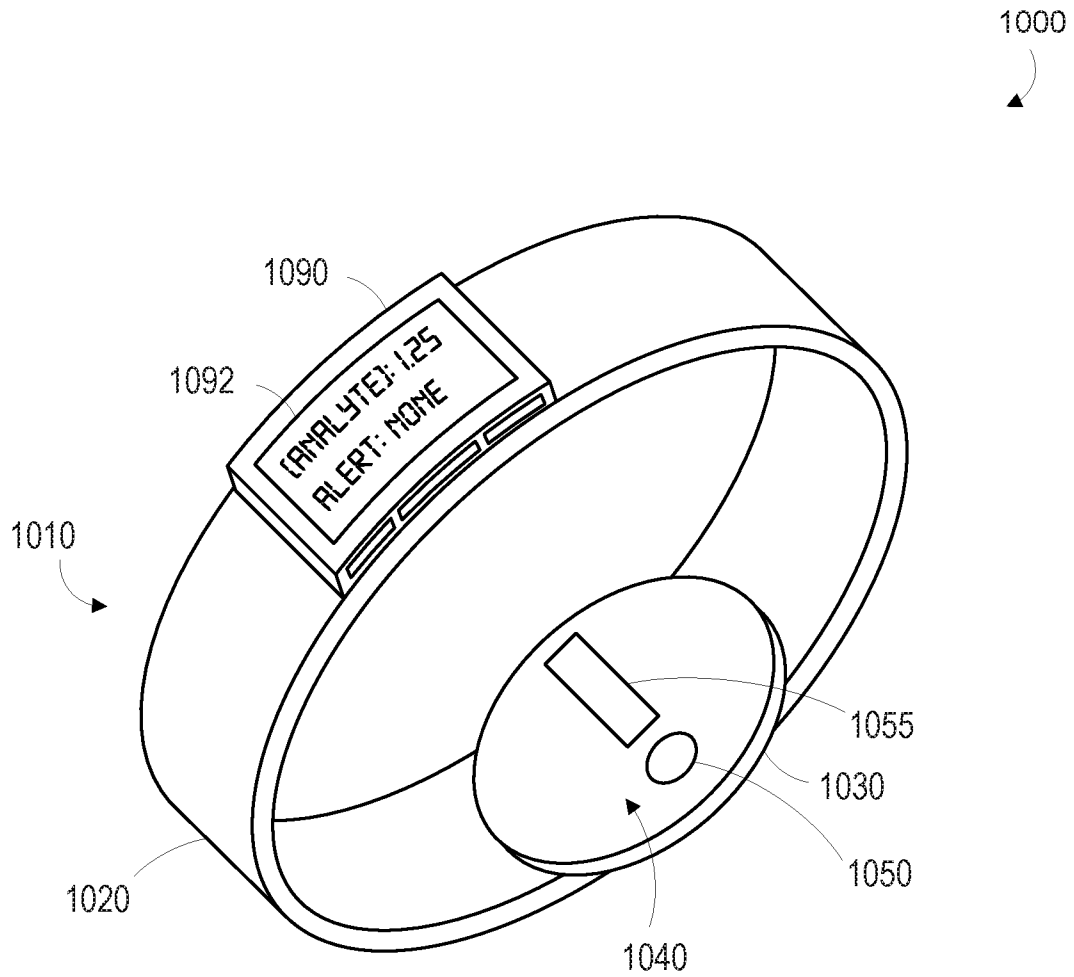


FIGURE 10

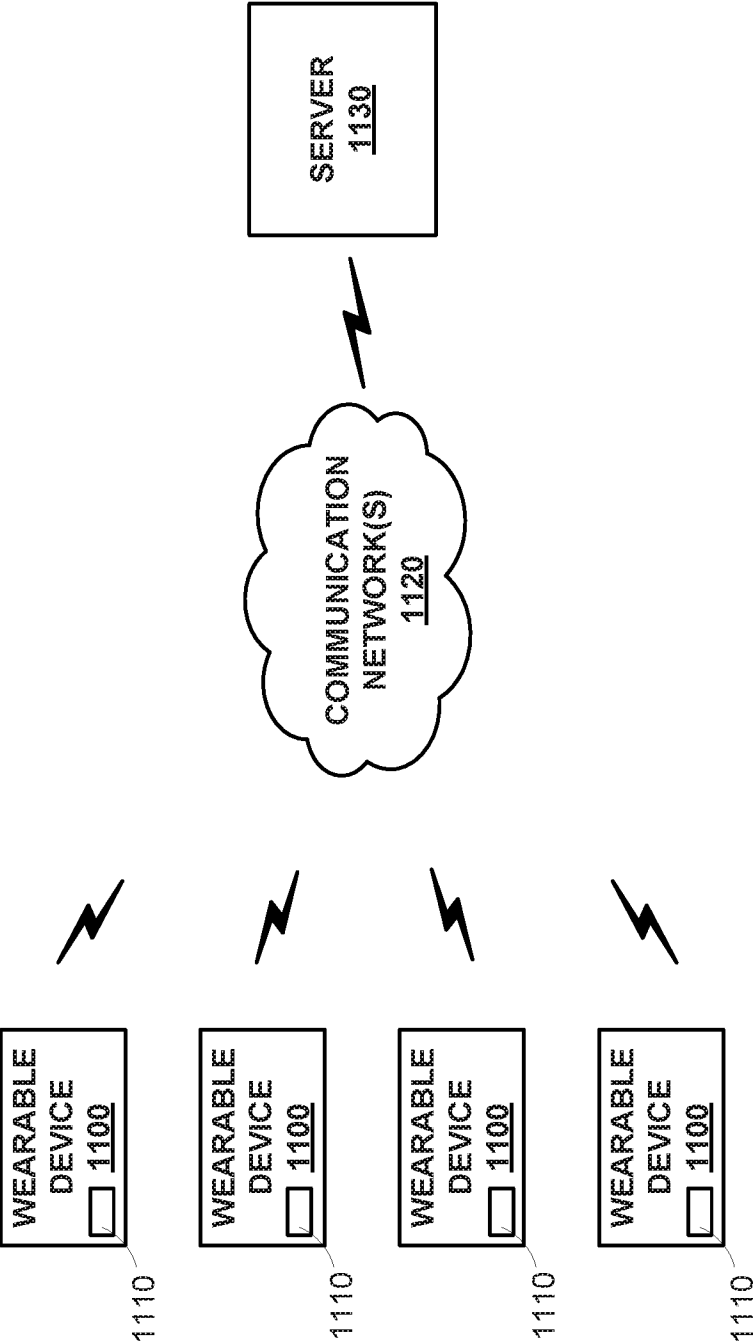


FIGURE 11

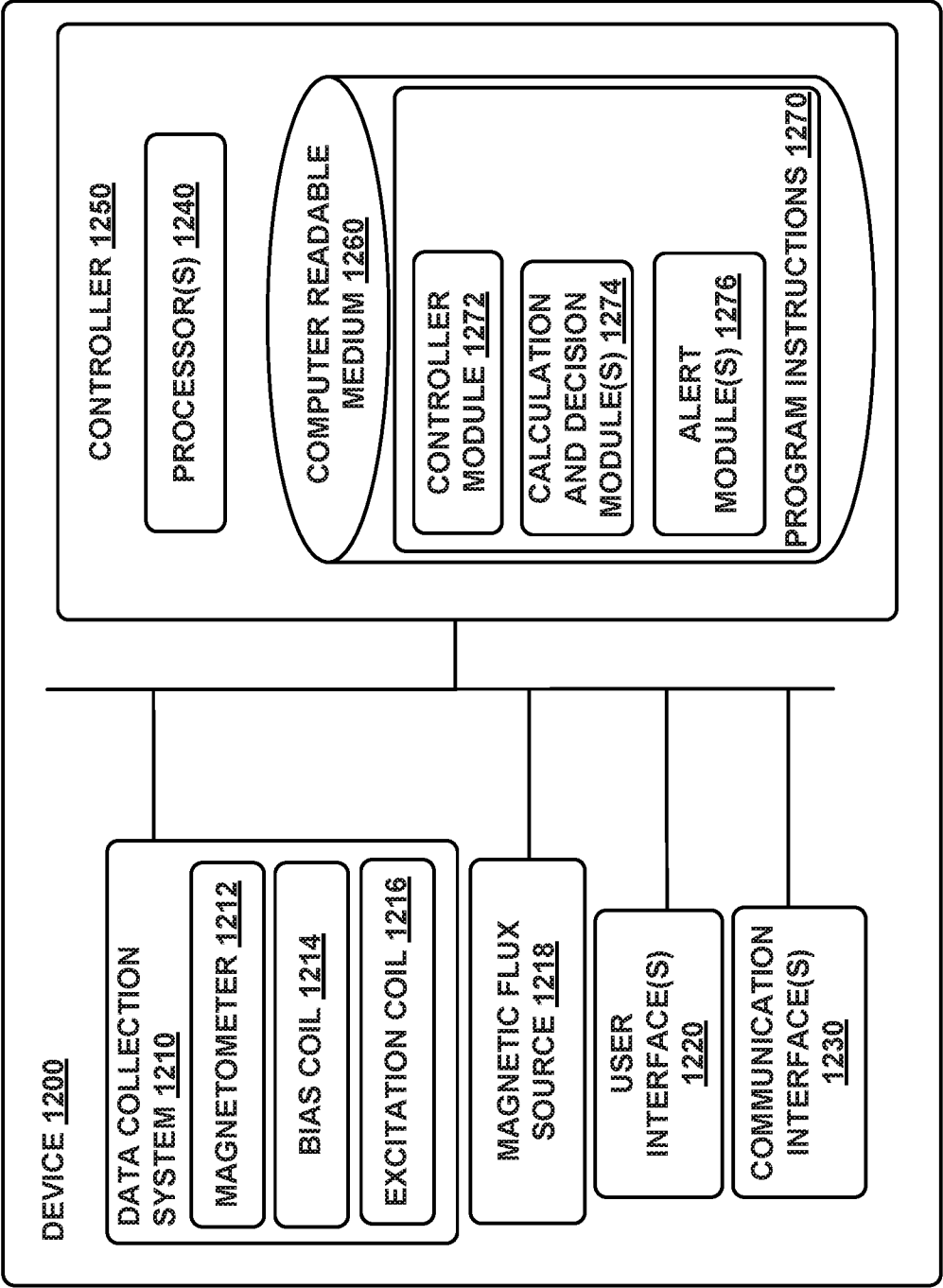


FIGURE 12

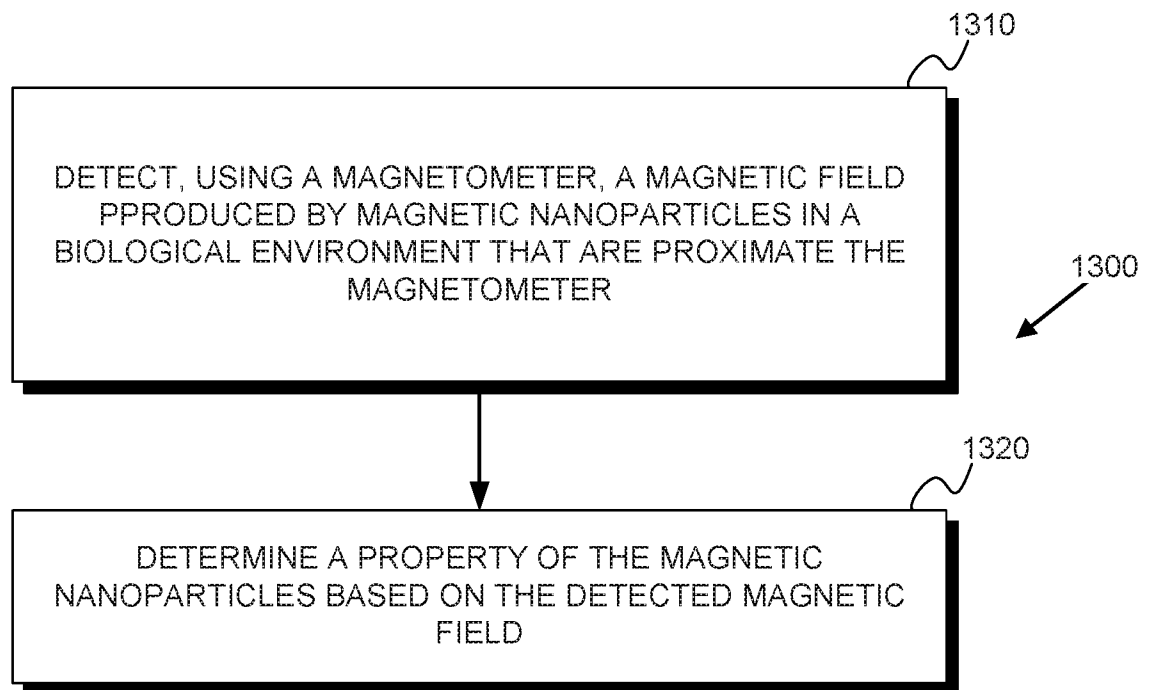


FIGURE 13

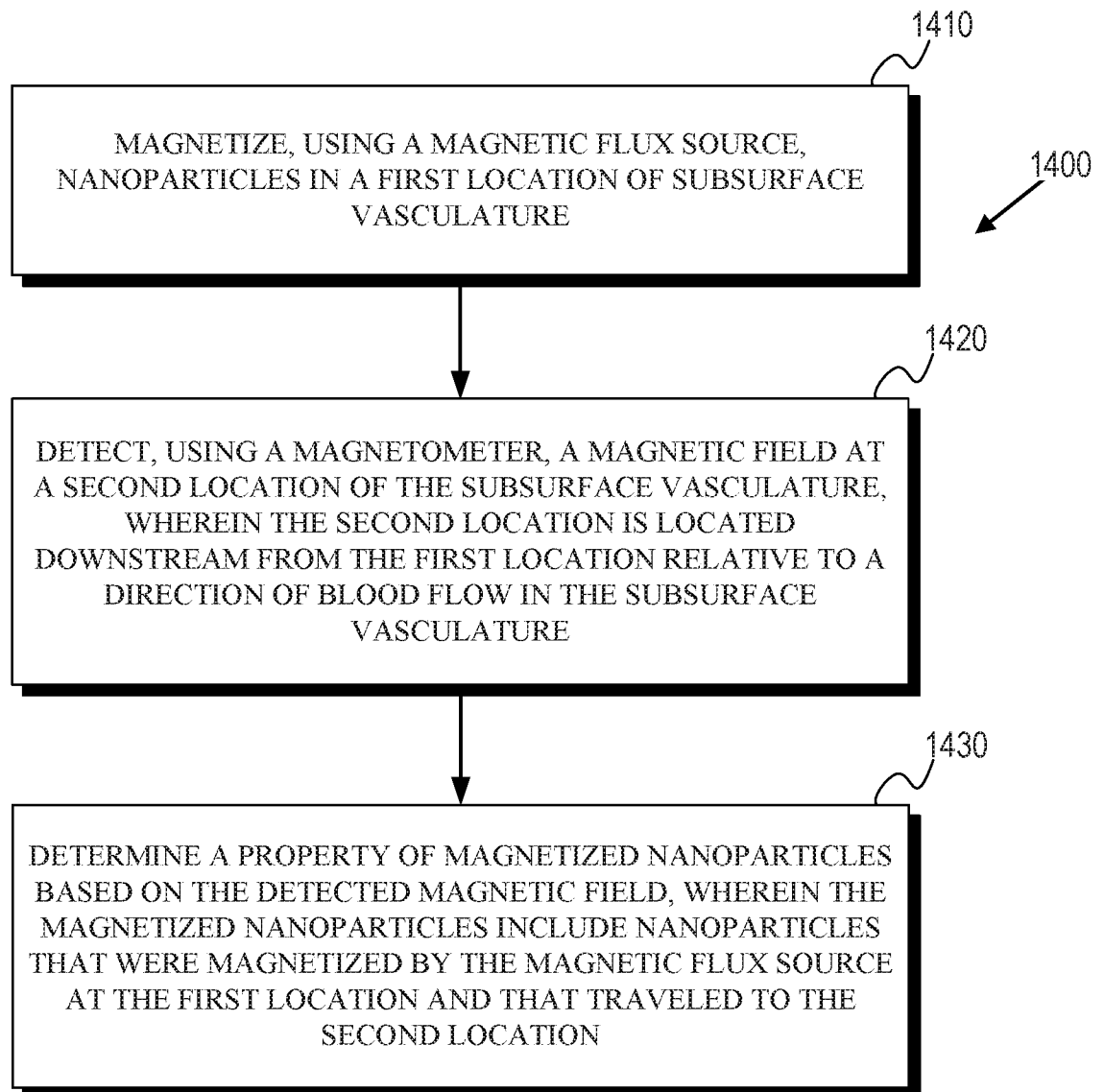


FIGURE 14

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/025220

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61B5/05 A61B5/055 A61B5/145 A61B5/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, COMPENDEX, EMBASE, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2009/012372 A1 (ADVANTAGEOUS SYSTEMS LLC [US]; STEIN ADAM LEON [US]; WHITE JACOB MEYER) 22 January 2009 (2009-01-22)	1-10, 13-16, 19,20
Y	abstract	11,12, 17,18
A	page 2, paragraph 1 - page 3, paragraph 4 page 5, paragraph 3 - page 11, paragraph 5; figures 1,3	21-41
Y	----- WO 2008/057578 A1 (T2 BIOSYSTEMS INC [US]; LEE W DAVID [US]; BERRY DAVID A [US]) 15 May 2008 (2008-05-15)	11,12, 17,18
A	abstract page 2, line 27 - page 3, line 25 page 8, paragraph 2 page 10, line 15 - page 12, line 21 page 17, paragraph 1; claim 1; figures 1,3 ----- -/-	1-10, 13-16, 19-41



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/025220

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Information on patent family members

International application No

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