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**Masters et al.**(10) **Pub. No.: US 2007/0042441 A1**(43) **Pub. Date: Feb. 22, 2007**(54) **METHOD AND APPARATUS FOR  
DETECTING ESTRADIOL AND  
METABOLITES THEREOF USING AN  
ACOUSTIC DEVICE**(60) Provisional application No. 60/690,592, filed on Jun.  
15, 2005. Provisional application No. 60/676,759,  
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**C12M 3/00** (2006.01)  
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977/902

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**BOSTON, MA 02110 (US)**(73) Assignee: **BioScale, Inc.**, Cambridge, MA(21) Appl. No.: **11/417,000**(22) Filed: **May 2, 2006****Related U.S. Application Data**(63) Continuation-in-part of application No. 11/183,484,  
filed on Jul. 18, 2005.(57) **ABSTRACT**

Methods for detecting estradiol and metabolites thereof in a sample are provided. A plurality of particles, each of which is coated with a capture agent having an affinity for estradiol, is combined with the sample to form a plurality of estradiol-particle complexes. The system also includes a transport arrangement for transporting the sample and/or particles to the sensor surface, and optionally a magnetic field inducing structure constructed and arranged to establish a magnetic field at and adjacent to the sensor surface. The resonant sensor produces a signal corresponding to an amount of estradiol-particle complexes that are bound to the sensor surface.

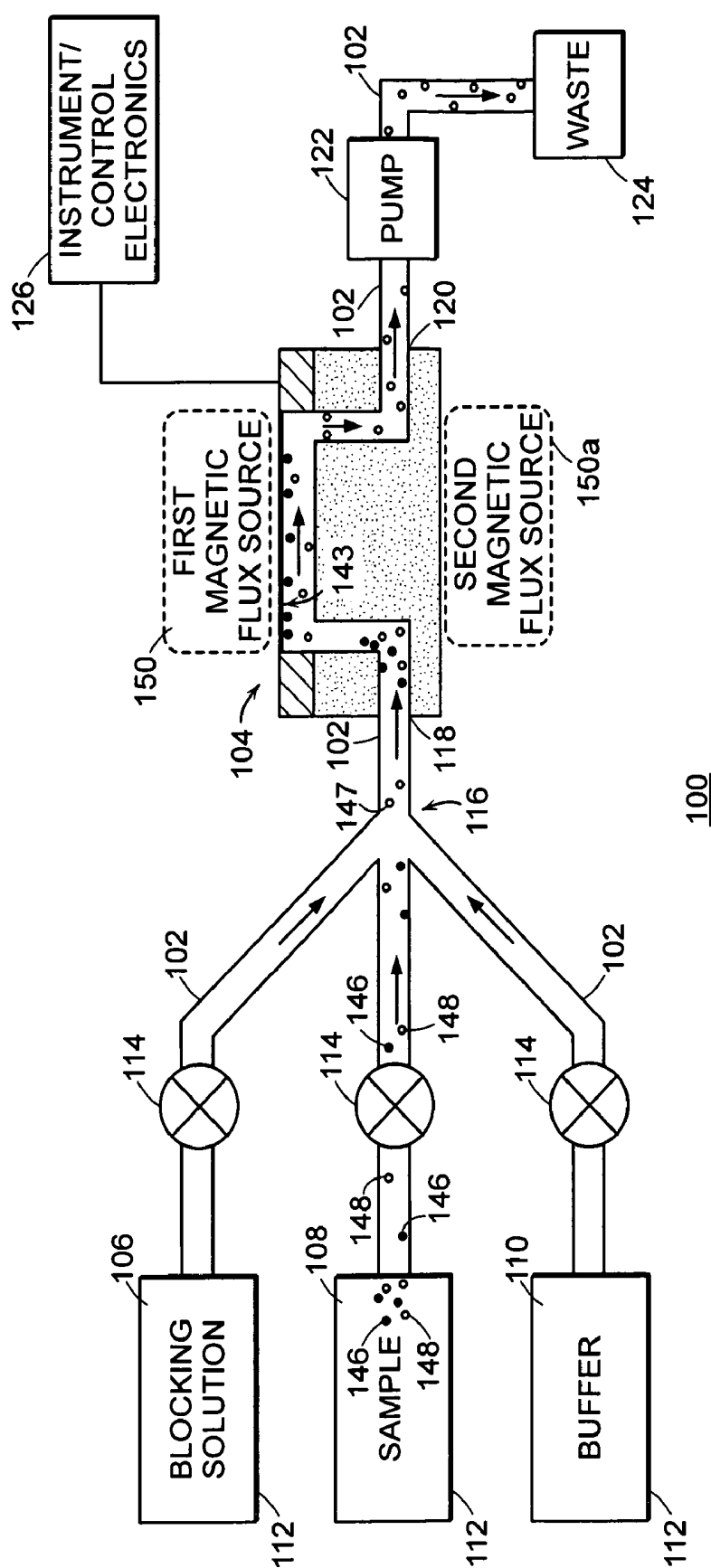


FIG. 1A

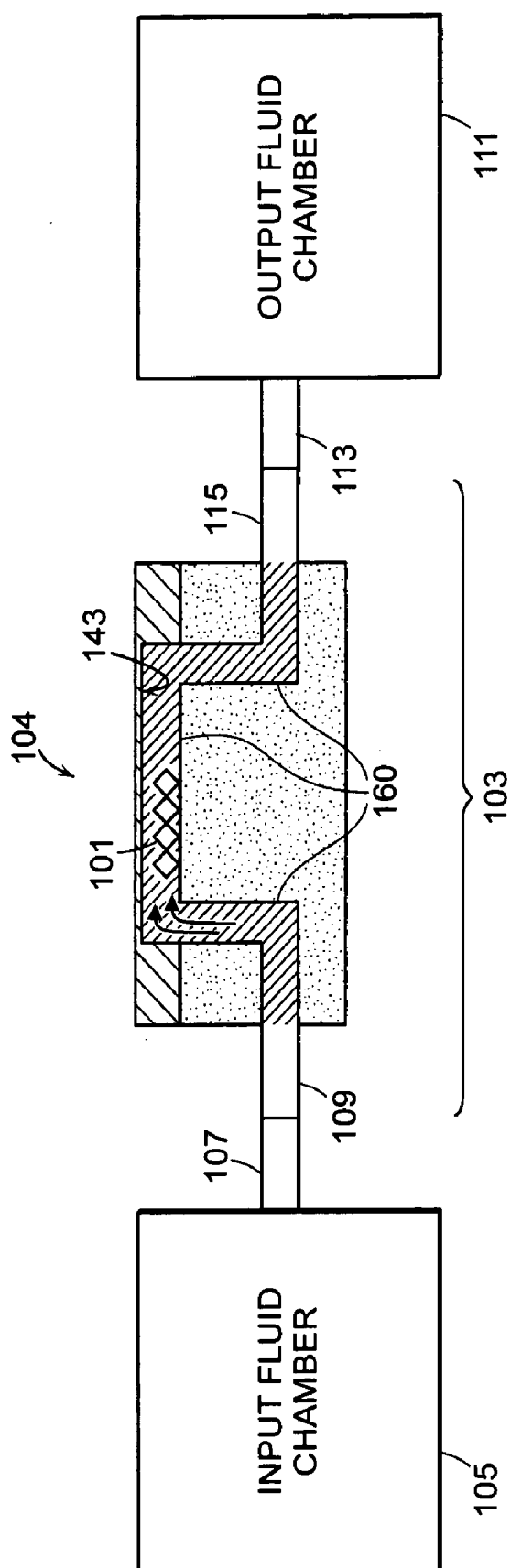


FIG. 1B

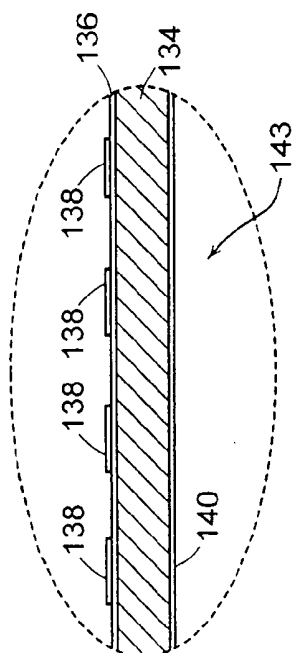


FIG. 2A

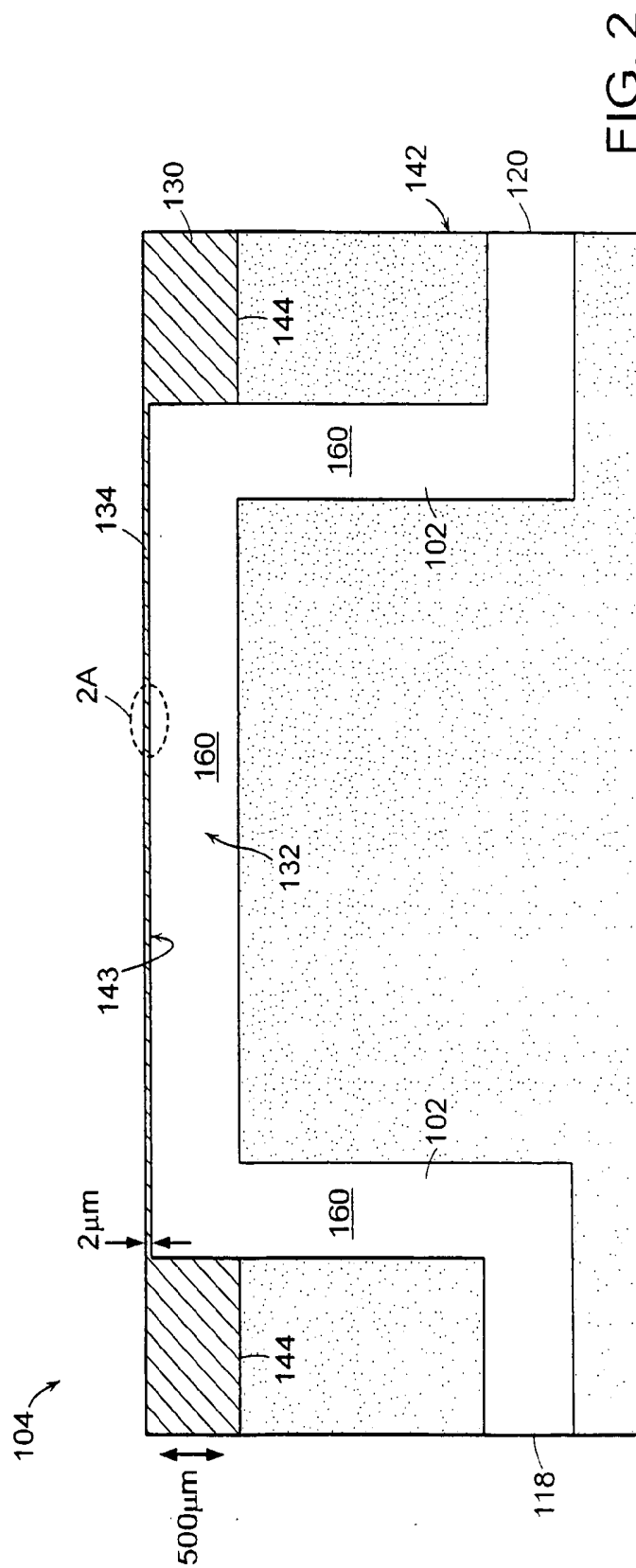
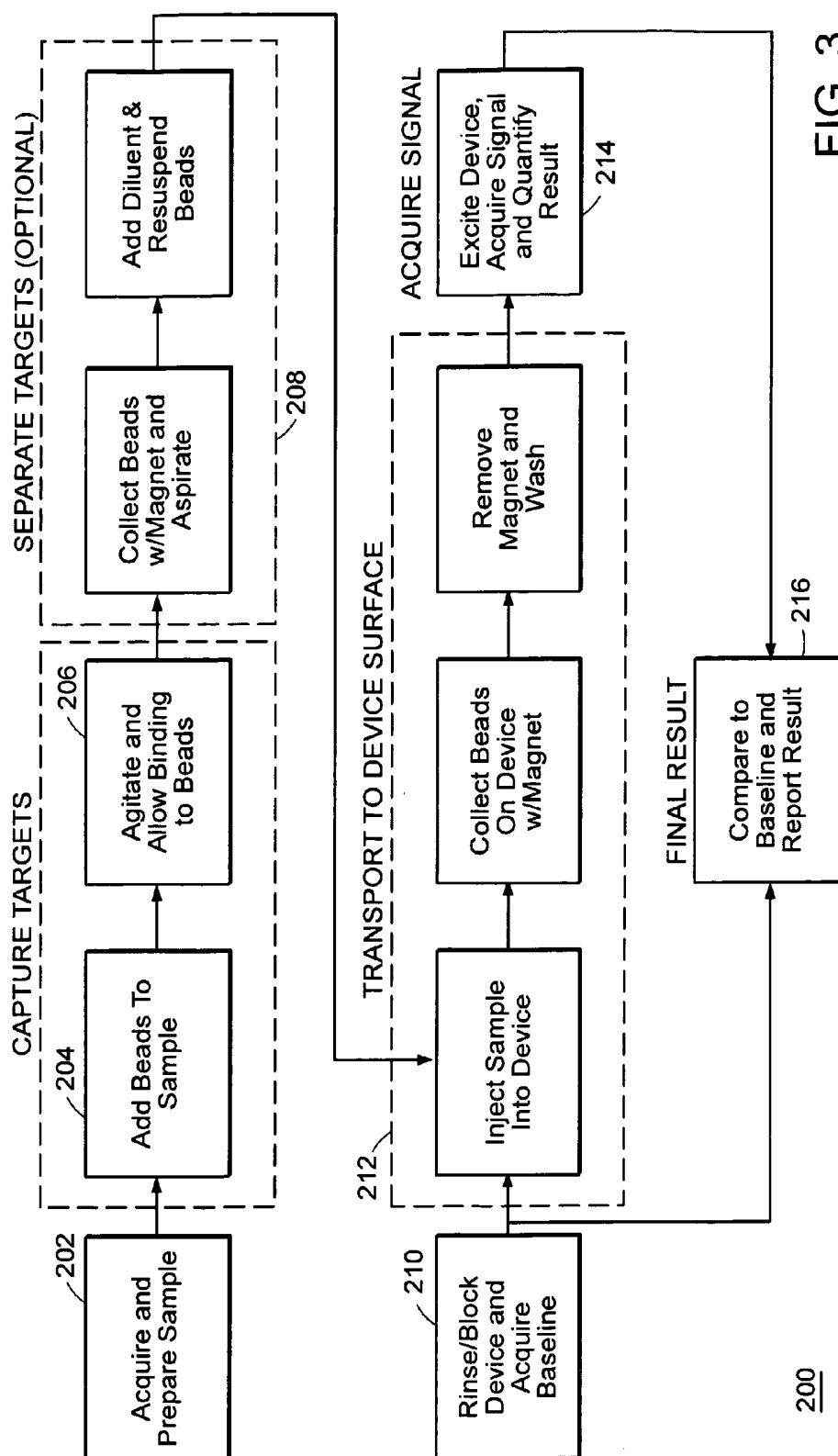


FIG. 2



200

FIG. 3

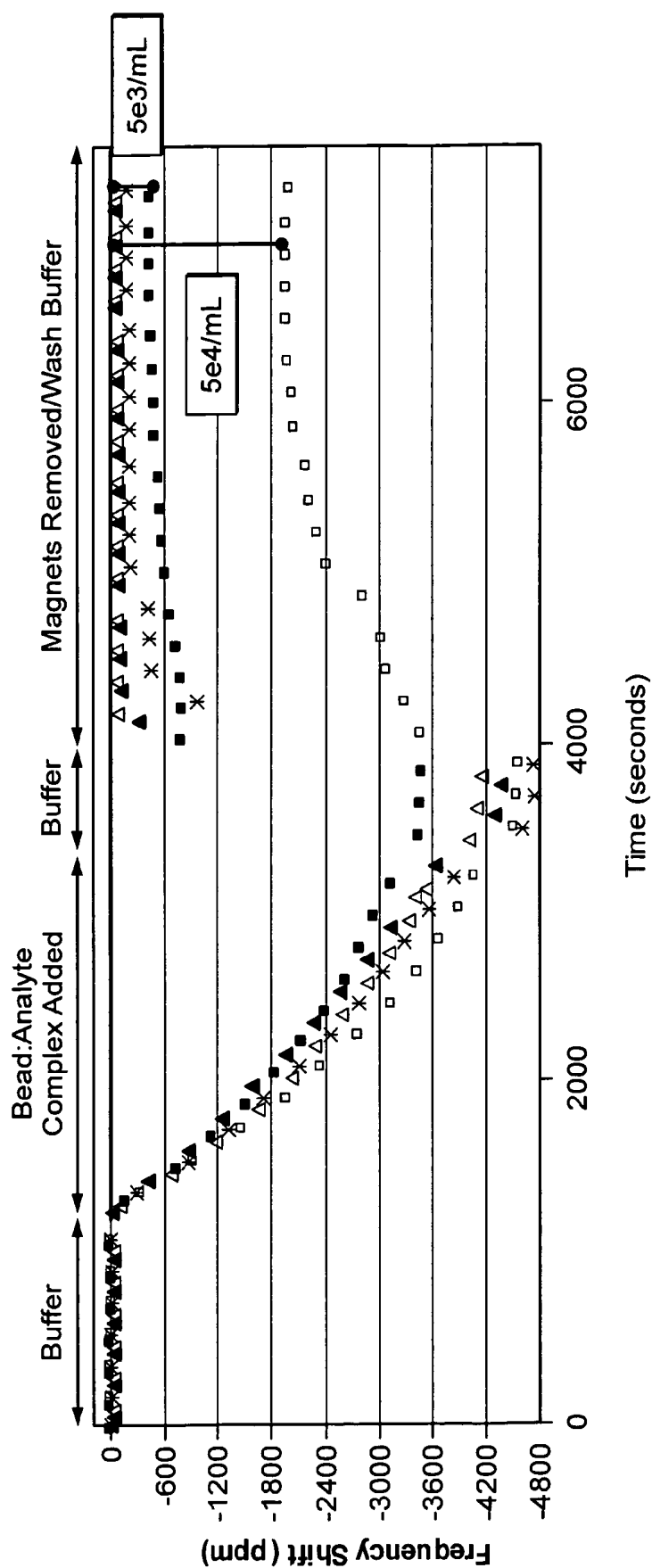


FIG. 4

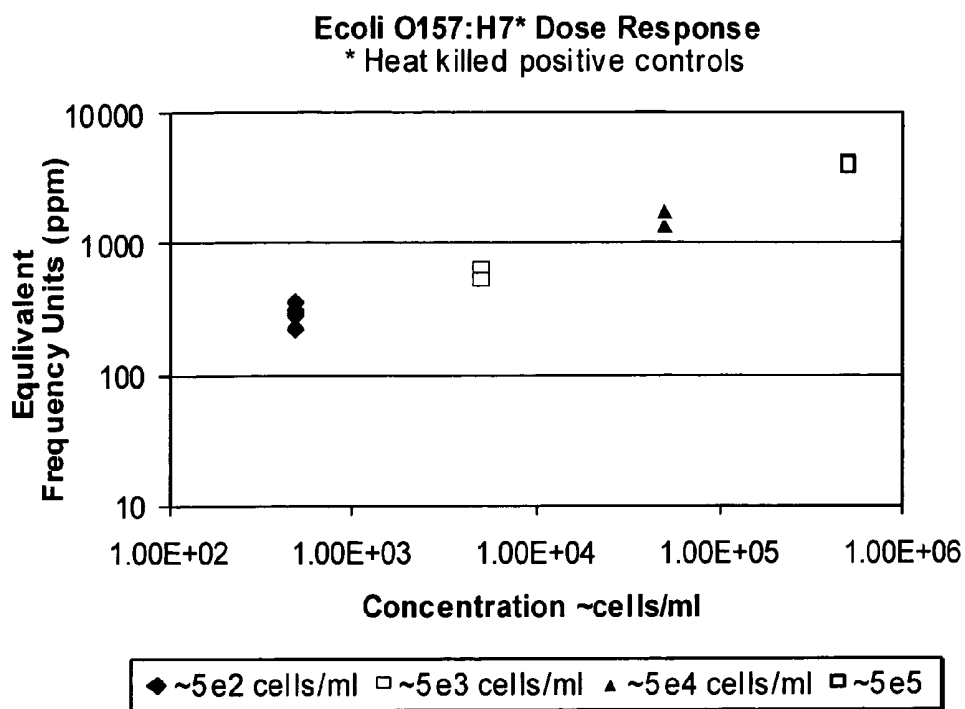


FIG. 5

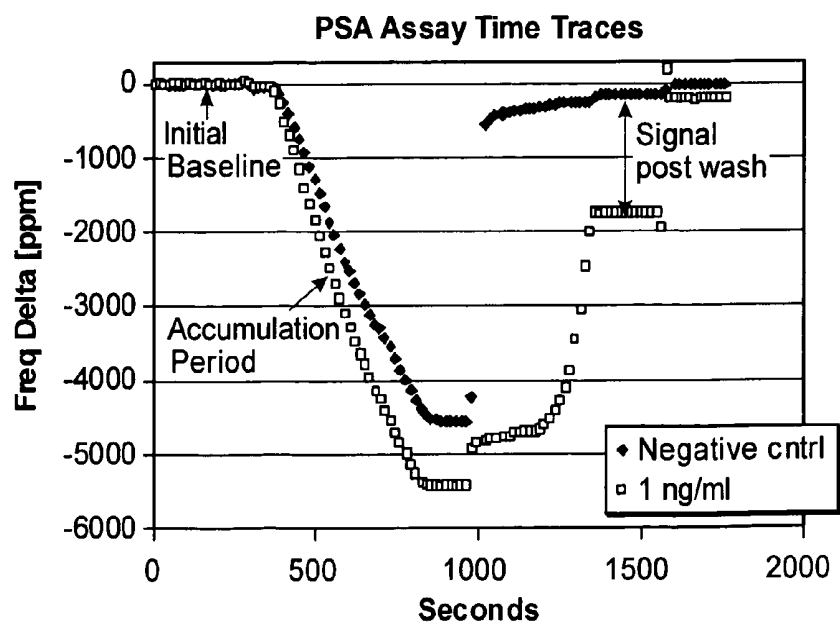
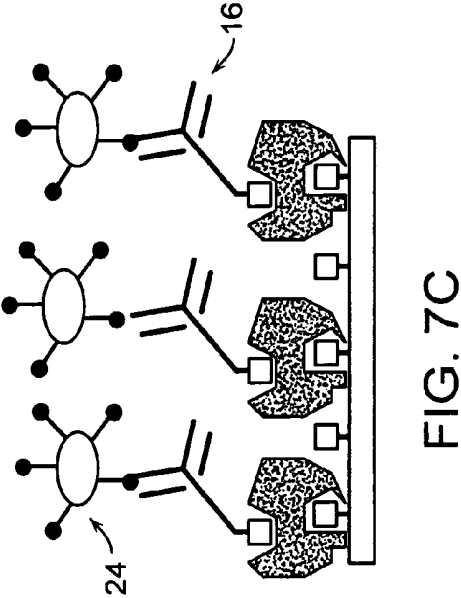
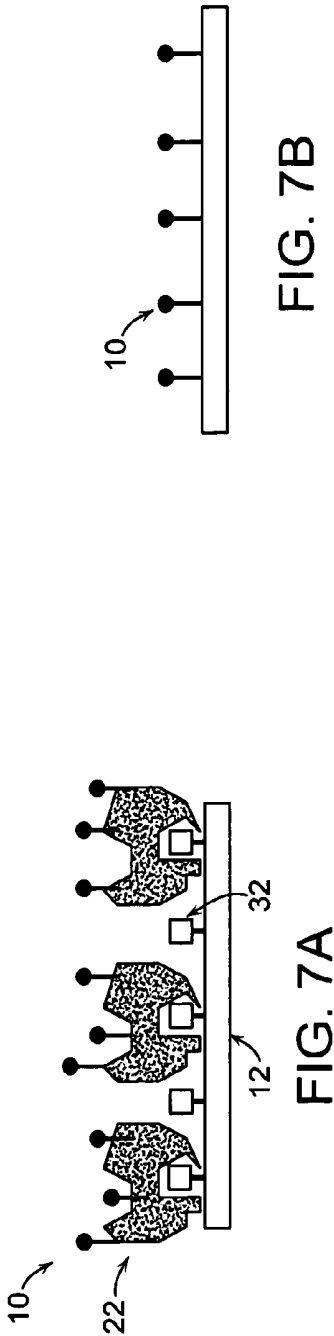


FIG. 6





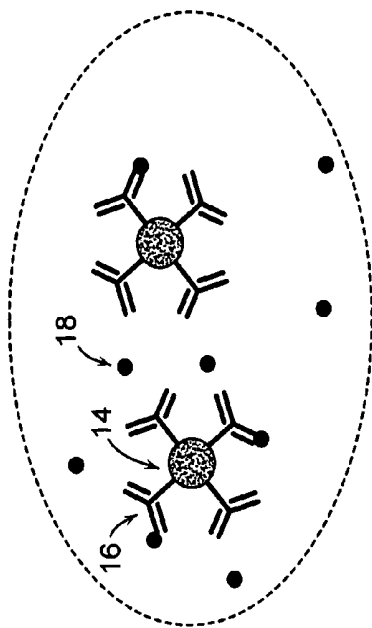


FIG. 8B

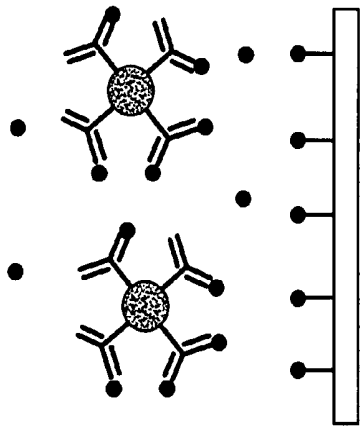


FIG. 8D

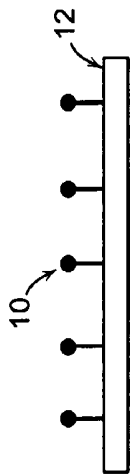


FIG. 8A

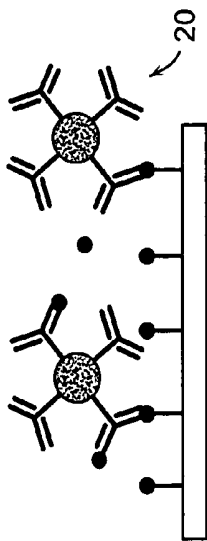
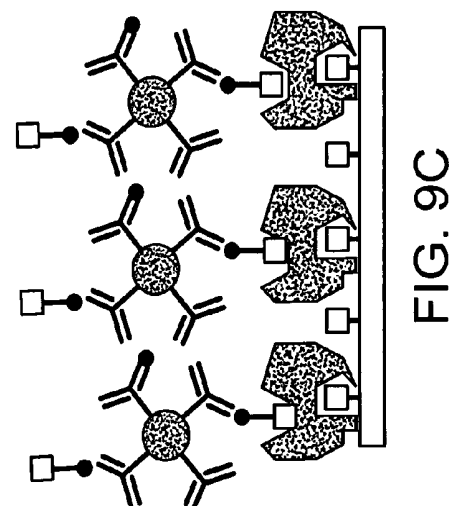
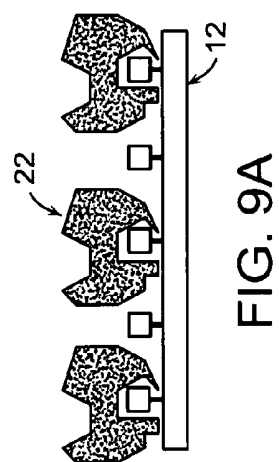
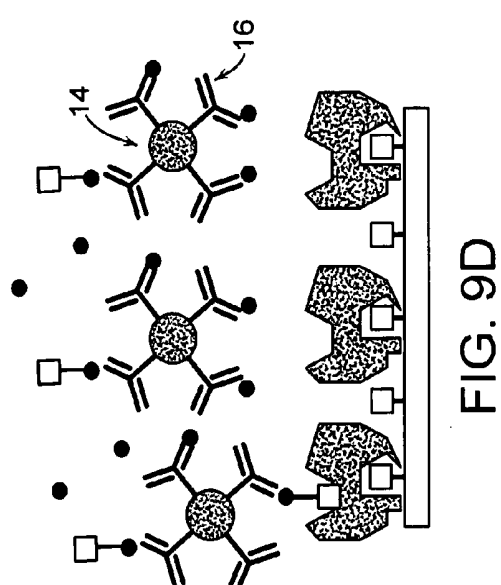
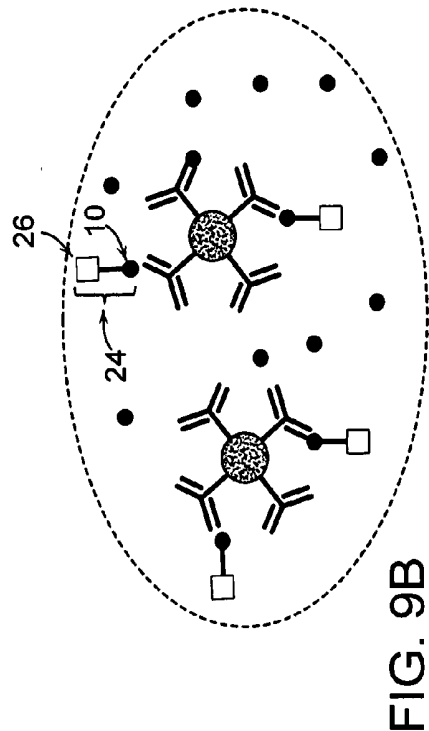


FIG. 8C



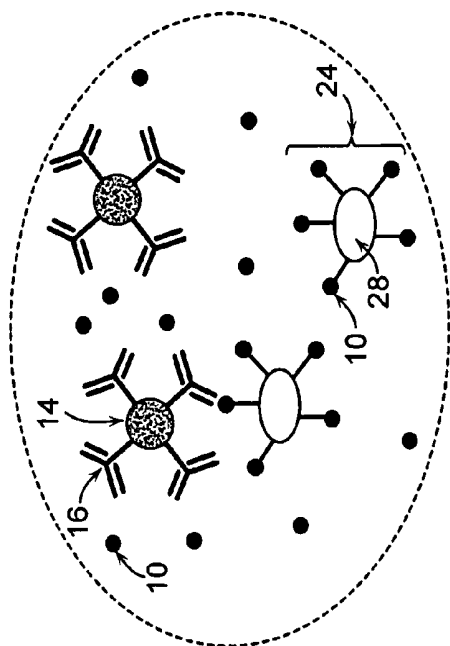


FIG. 10B

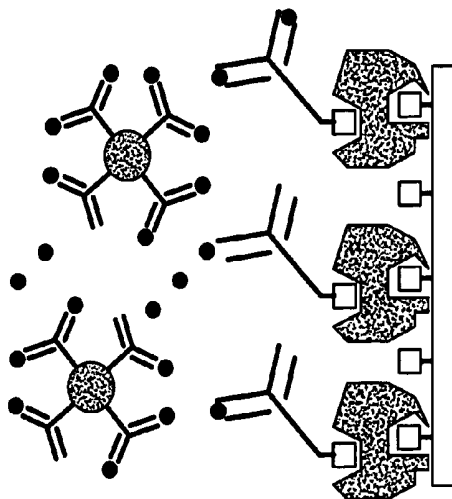


FIG. 10D

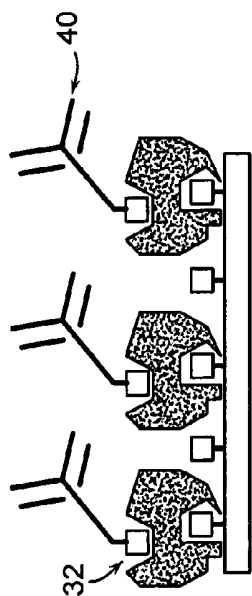


FIG. 10A

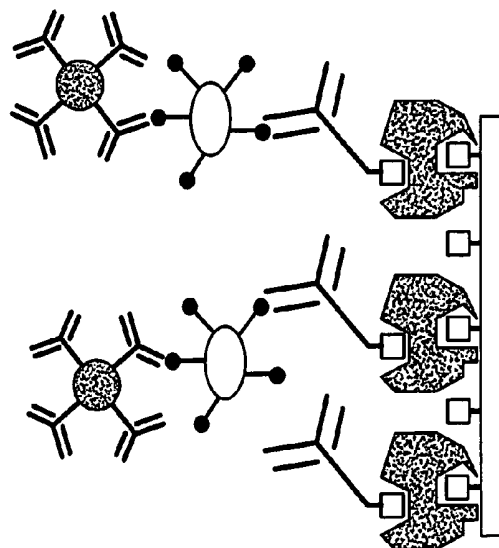


FIG. 10C

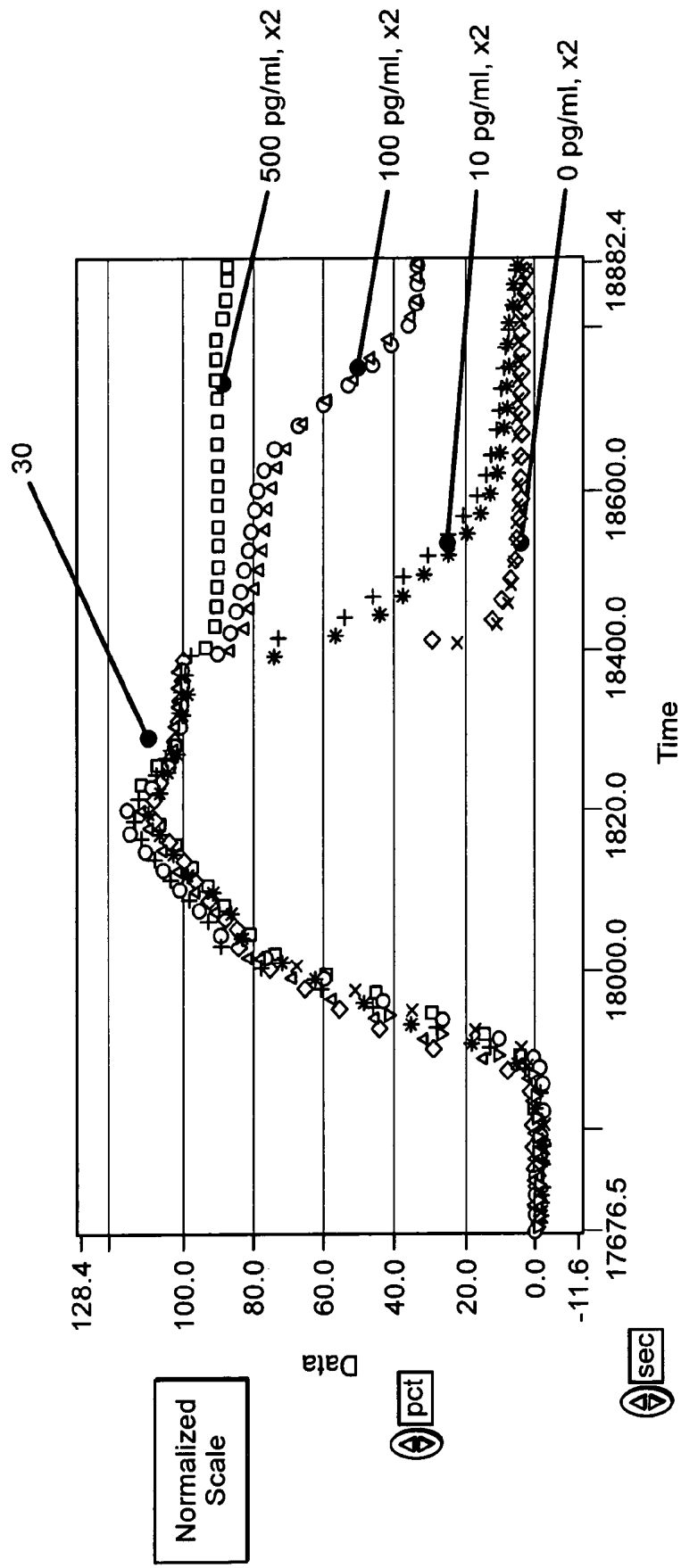
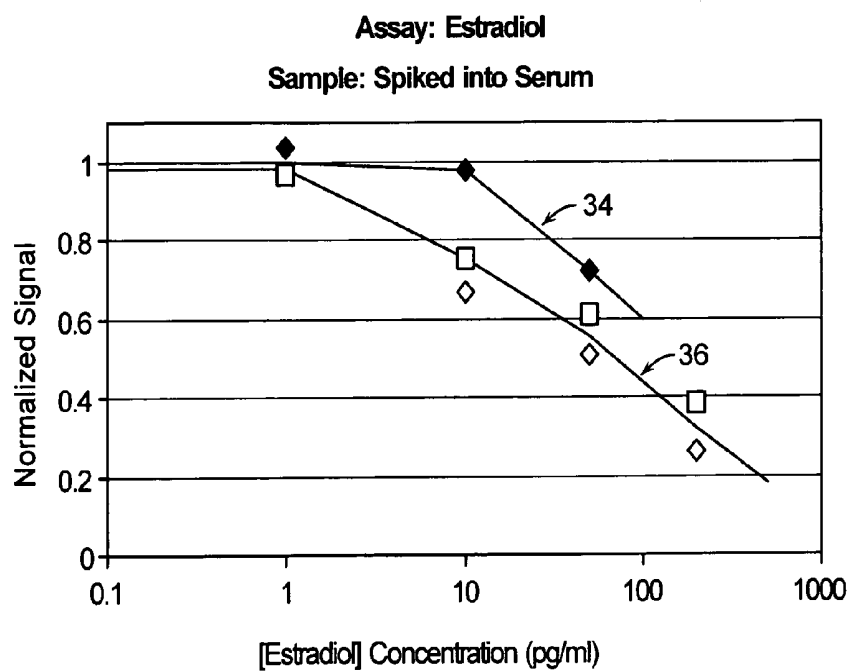
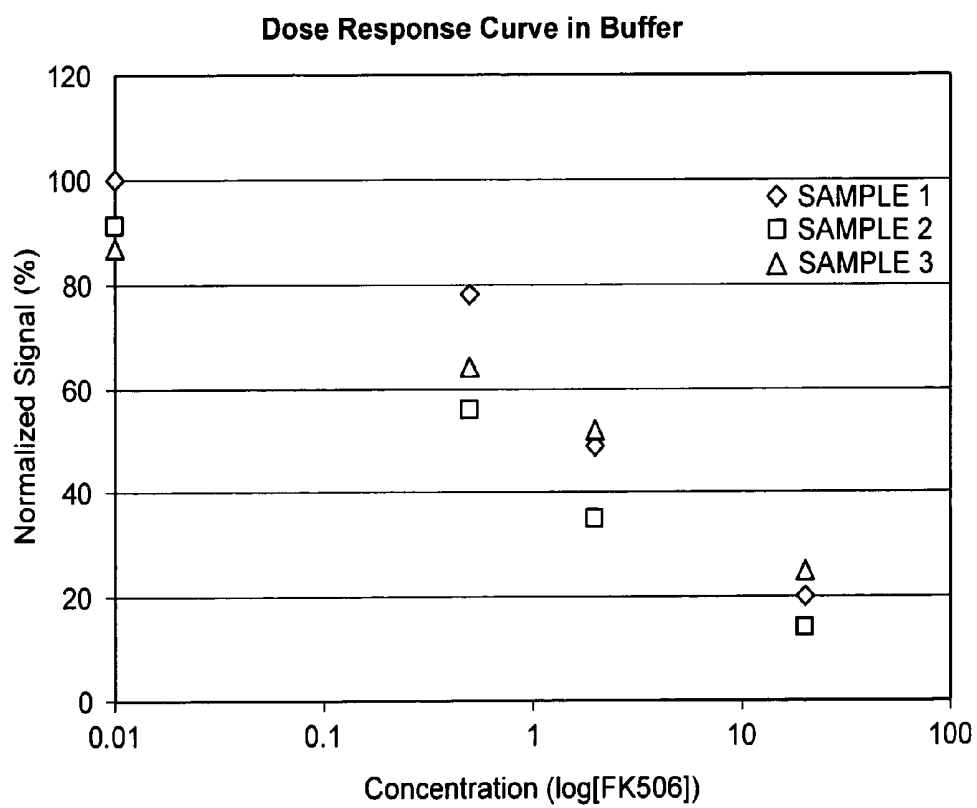


FIG. 11



NB. Negative sample responses plotted at 1 pg/ml

FIG. 12

**FIG. 13**

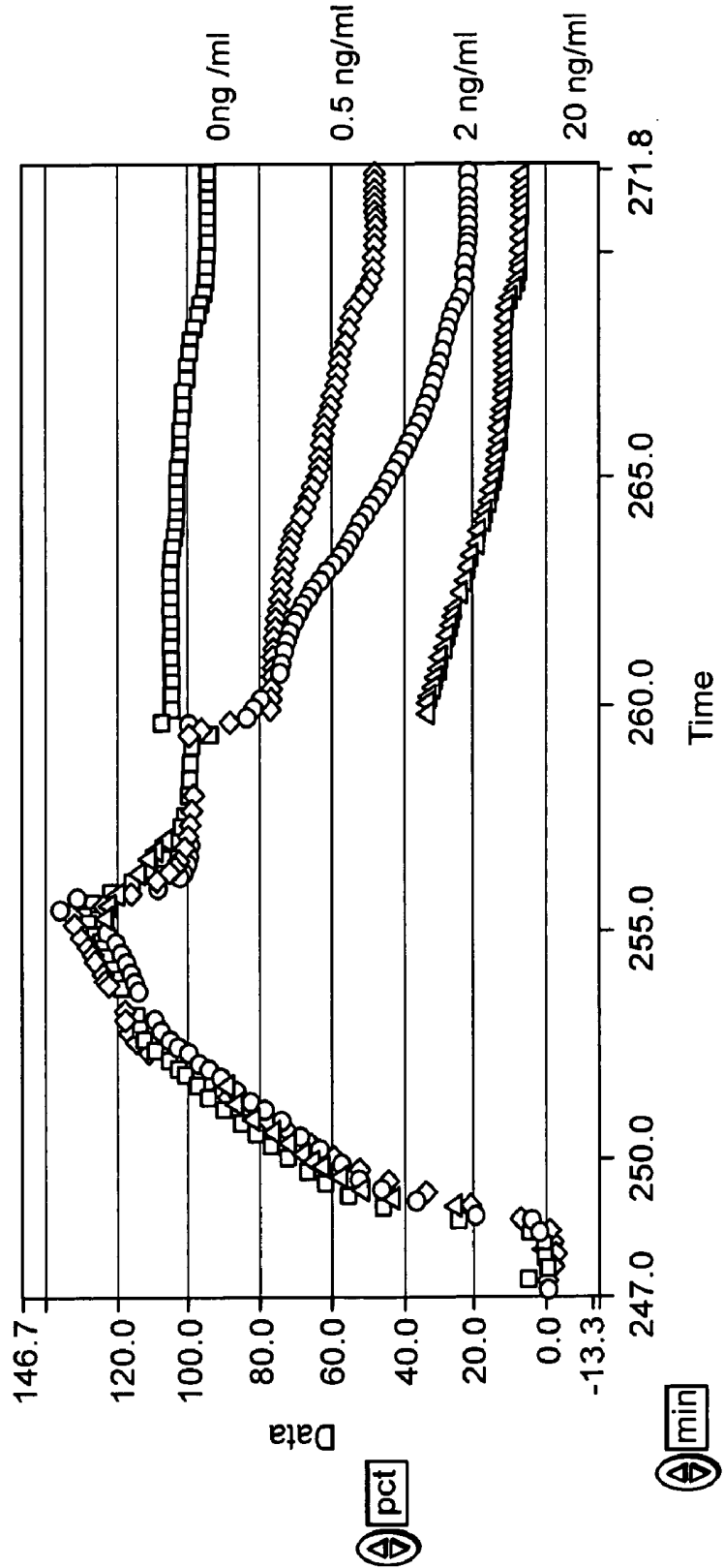


FIG. 14

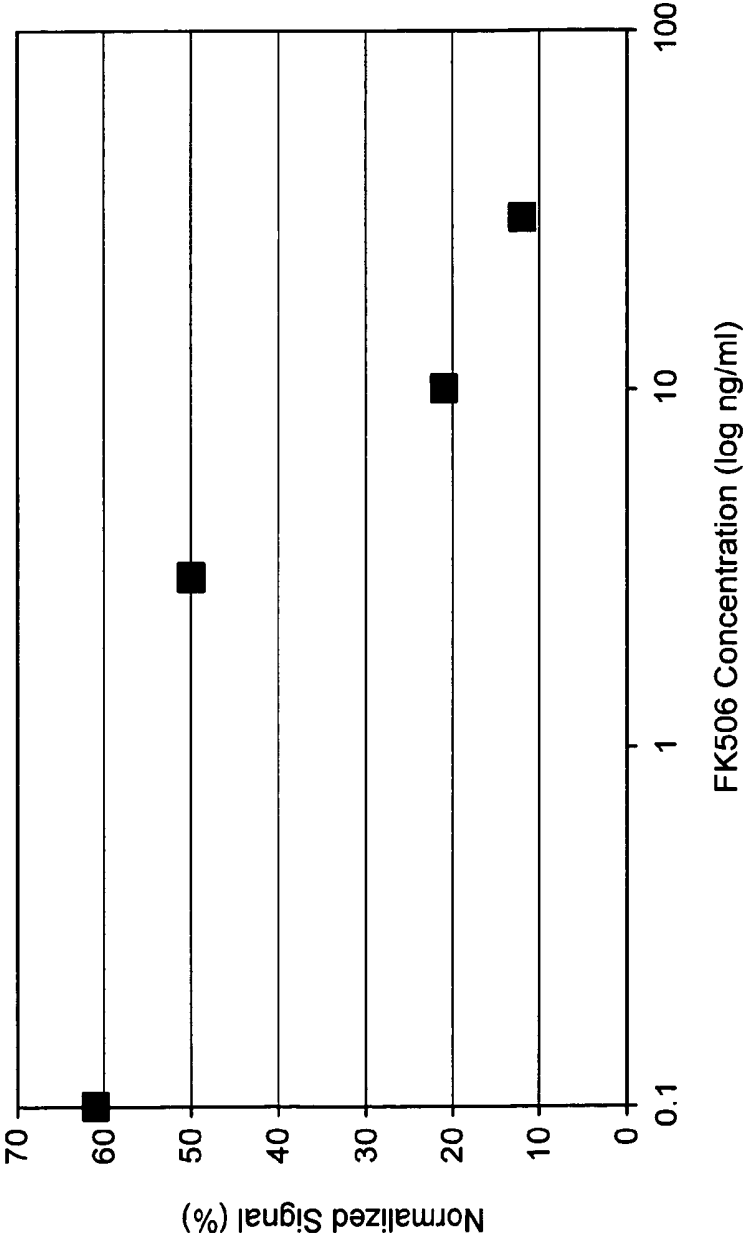


FIG. 15



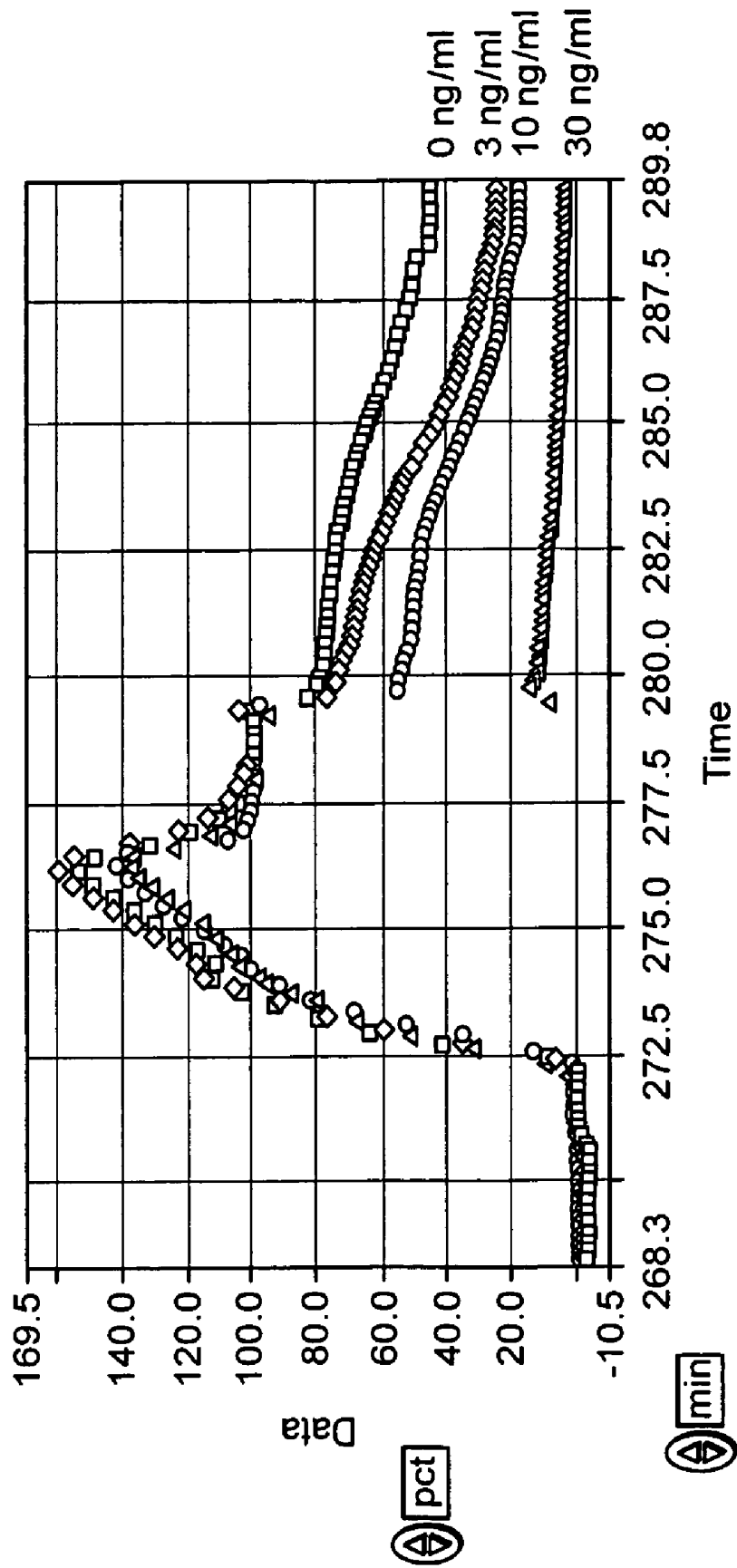


FIG. 16

## METHOD AND APPARATUS FOR DETECTING ESTRADIOL AND METABOLITES THEREOF USING AN ACOUSTIC DEVICE

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. Ser. No. 11/183,484 filed on Jul. 18, 2005, which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/690,592, filed Jun. 15, 2005. This application also claims the benefit of U.S. Provisional Patent Application Ser. No. 60/676,759, filed on May 2, 2005, entitled "Methods and Apparatus for Viral Load Detection and Measurement."

### TECHNICAL FIELD

[0002] The present invention relates to methods for detecting one or more analytes such as estradiol and metabolites thereof in fluid samples.

### BACKGROUND OF THE INVENTION

[0003] Significant challenges for a system that detects analytes (e.g., chemical and biological agents) in liquid media include concentration of the analyte in the media, and transport of the analyte to a sensor surface. For biological applications, concentration issues generally arise since the concentrations of such analytes tend to be low. Additionally, biological analytes (e.g., cells, cell fragments and macromolecules such as proteins and nucleic acids) tend to be relatively large; hence, transport issues arise because these larger analytes diffuse in fluid solution very slowly.

[0004] In addition to cells, cell fragments, and molecules such as proteins and nucleic acids, the detection of small molecule analytes can be a useful marker for diagnosing disease, monitoring drug pharmacokinetics in a patient, and for screening small molecule libraries for potential drug targets. Many therapeutic drugs, including small molecule drugs, require frequent monitoring in patients in order to maximize the beneficial effects of the drug and avoid adverse effects that may result.

[0005] For example, estradiol is a small molecule that is used to assess a number of health conditions. For example, blood tests for follicle stimulating hormone (FSH) and estradiol (E2) can be used to check ovarian reserves and for adequate egg function. In addition, estradiol and metabolites thereof can be used as a risk factor determinant for breast cancer. An elevated level of estradiol is correlated with increased risk of developing breast cancer. However, a low estradiol level is correlated with an increased risk for vertebral fractures. The U.S. Food and Drug Administration has approved the use of the drug tamoxifen in the prevention of breast cancer in certain patients. However, tamoxifen can lower serum estradiol levels to a point that increases the incidence of vertebral fracture. It is therefore desirable for a physician to be able to frequently monitor estradiol levels in a patient to ensure that estradiol levels remain within a certain range to reduce the risk of breast cancer while not increasing the risk of vertebral fracture.

[0006] Therapeutic drugs also require frequent monitoring in patients. Therapeutic drugs include, for example, immunosuppressant medications such as cyclosporin, tacrolimus (FK-506), rapamycin, and mycophenolic mofetil. Immuno-

suppressants have a narrow therapeutic index and high degree of inter- and intra-patient variability in bioavailability. Immunosuppressants require careful, frequent monitoring in patient samples in order to balance the level of immunosuppression needed to prevent transplant rejection while avoiding the adverse effects of excessive immunosuppression such as toxicity, infection, and increased risk of developing cancer.

[0007] The detection of small molecules such as estradiol is often difficult not only because of potentially low levels in the sample, but also because of the limited number of suitable capture agents that can be used to bind the small molecule analyte. As a result of such limitations, it is often difficult to design or modify existing assays, such as enzyme-linked immunosorbent assays that are sensitive and specific enough to detect low levels of the small molecule analyte.

[0008] Typically, detection of analytes in patient samples requires obtaining the sample in the doctor's office or clinic and sending the sample off site for analysis. Depending on the analyte, the analysis can take one day to several weeks. The results of the analysis are transmitted to the doctor, who then uses the information to adjust treatment as necessary, and contacts the patient to convey the new treatment regimen. The delay associated with analyzing a sample makes it difficult for a doctor to accurately specify a proper treatment.

[0009] There is a need for improved assays that can be used to more readily detect small molecule analytes, and to detect low concentrations of analyte. In addition, there is a need for improved measurement of analytes including small molecule analytes in order to customize drug regimens to maintain efficacy of the drug while reducing unwanted side effects in individual patients. Furthermore, there is a need for methods and apparatus that can be used at the point of care to measure biologically and/or clinically relevant analytes in order to reduce the delay between obtaining the sample and obtaining the results of the assay.

[0010] A key metric for competitive detection is the amount of analyte accumulated on a sensor per unit time. For good performance, the rate of accumulation (and the resulting signal transient) needs to be fast relative to the sensor drift rate. Another key performance metric for an analyte detection system is the degree to which the system can preferentially collect the analyte of interest on the sensor surface. Since many biological samples contain extraneous background components (e.g., other proteins, cells, nucleic acids, dirt), it is necessary to prevent these background components from interfering with the desired measurement. So, a transport method that selectively draws the analyte to the sensor and allows interfering background components to pass by has definite advantages. Such a method used in concert with selective binding of the analyte (e.g., antibody, complimentary DNA strands, etc.) to the sensor surface can deliver high sensitivity measurements for samples with large amounts of extraneous background components relative to the amount of analyte.

[0011] Various methods for improving transport of analyte to a sensor surface have been proposed, including filtration, novel flow geometries, acoustic fields, electrical fields (time varying and static) and magnetic fields.

[0012] Acoustic excitation has been used to draw cells to field nodes, but it is difficult to use this technique alone to transport material to a surface.

[0013] Electrical fields (electrophoresis and dielectrophoresis) have been used to enhance transport but are not universally applicable to all analytes and sample types. They are generally more effective for larger analytes (e.g., cells). Furthermore, the electrical properties of microbes can vary within a given species and strain, making it hard to predict system performance under all intended operating conditions. Sometimes it is necessary to tailor the ionic strength of the sample to improve the performance of the transport. This requirement can conflict with the optimum binding or wash conditions in an assay. Also, electrical fields can dissipate energy and heat conductive fluids (e.g., 0.1 M phosphate buffer solution), which is undesirable since heating can damage the biological analytes.

[0014] Immunomagnetic separation (IMS) methods are known in the art for isolating analyte from a sample.

#### SUMMARY OF THE INVENTION

[0015] The present invention is drawn to methods for detecting whether one or more analytes is present in a sample. In one embodiment, the method comprises the steps of introducing a plurality of magnetic particles coated with a capture agent into a fluid chamber, wherein at least one surface of the fluid chamber comprises an acoustic device having a first analyte bound thereto. The plurality of magnetic particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. A magnetic flux can be created in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward said surface. Signal output by said acoustic device is monitored, thereby detecting whether one or more analytes is present in the sample.

[0016] In another embodiment, the method for detecting whether one or more analytes is present in a sample comprises the steps of introducing a plurality of particles and a competitor molecule into a fluid chamber, said particles being coated with a first capture agent capable of binding the analyte. In certain embodiments, the particles can be magnetic particles. At least one surface of the fluid chamber comprises an acoustic device that has been coated with a second capture agent capable of binding to the competitor molecule. A magnetic flux can be created in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward said surface, and signal output by said acoustic device is monitored, thereby detecting whether one or more analytes is present in the sample. The plurality of particles can be contacted with the sample and competitor molecule prior to introducing the particles into the chamber, or the sample and competitor molecule can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting the analyte.

[0017] The present invention is also drawn to methods for determining whether to adjust drug dosage in an individual. The method comprises detecting a level of one or more analytes in a sample. In one embodiment, the method of detecting a level of one more analytes in a sample comprises introducing a plurality of magnetic particles coated with a capture agent into a fluid chamber, wherein at least one surface of the fluid chamber comprises an acoustic device

having a first analyte bound thereto as described above. A magnetic flux is created in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward said surface. Signal output by said acoustic device is monitored, thereby detecting the level of one or more analytes in the sample. Whether to adjust the dosage of the drug is determined based on the level of the one or more analytes in the sample.

[0018] In still another embodiment, the method for detecting an analyte capable of binding a capture agent comprises introducing a plurality of particles into a fluid chamber. Each magnetic particle is coated with a different analyte and at least one surface of the fluid chamber comprises an acoustic device having a capture agent bound thereto. Signal output by said acoustic device is monitored, thereby detecting the analyte capable of binding a capture agent. The plurality of magnetic particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting the analyte.

[0019] The present invention is drawn to methods for detecting estradiol in a sample. In one embodiment, the method comprises the steps of introducing a plurality of particles coated with a capture agent capable of binding estradiol into a fluid chamber, wherein at least one surface of the fluid chamber comprises an acoustic device having estradiol bound thereto. The plurality of magnetic particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting estradiol in the sample.

[0020] In another embodiment, the method comprises the steps of introducing a plurality of particles and a competitor molecule into a fluid chamber, said particles being coated with a first capture agent capable of binding estradiol. At least one surface of the fluid chamber comprises an acoustic device that has been coated with a second capture agent capable of binding to the competitor molecule. The plurality of magnetic particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting estradiol.

[0021] The present invention is drawn to methods for detecting one or more immunosuppressants in a sample. The method comprises the steps of introducing a plurality of particles coated with a capture agent capable of binding the immunosuppressant into a fluid chamber, wherein at least one surface of the fluid chamber comprises an acoustic device having said immunosuppressant bound thereto. The plurality of particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting the immunosuppressant in the sample.

[0022] In another embodiment, the method for detecting one or more immunosuppressants comprises introducing a

plurality of particles and a competitor molecule into a fluid chamber, said particles being coated with a first capture agent capable of binding an immunosuppressant, wherein at least one surface of the fluid chamber comprises an acoustic device that has been coated with a second capture agent capable of binding to the competitor molecule. The plurality of particles can be contacted with the sample prior to introducing the particles into the chamber, or the sample can be introduced into the fluid chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting the immunosuppressant.

[0023] The present invention provides improved measurement of analytes. In certain embodiments, the analytes can include small molecules including but not limited to estradiol and therapeutic drugs. As a result of the present invention, the pharmacokinetics of a given drug can be readily determined and drug regimens can be more readily customized (by, for example, a physician) to maintain efficacy of the drug while reducing unwanted side effects. In addition, the present invention can be used at the point of care to measure biologically and/or clinically relevant analytes while avoiding delays (associated with, for example, sending samples to an off-site testing facility) in order to customize care and increase the level of patient compliance. As used herein, the term point of care can include, for example, the doctor's office, clinic, emergency room, and mobile treatment facility (e.g., an ambulance). In one embodiment, the method further comprises adjusting dosage of said therapeutic drug administered to an individual based on the level of said drug in the sample. The level of the therapeutic drug can be varied based on the known therapeutic range for the therapeutic drug being tested.

[0024] The present invention can be used to diagnosis disease or assess the risk of developing a disease based on the level of analyte detected in a sample. In one embodiment, the disease is breast cancer. The method of detecting a breast cancer marker can be used, for example in conjunction with other diagnostic tests such as a mammogram, to detect breast cancer in an individual. In another embodiment, the method of detecting a breast cancer marker can be used to determine the likelihood that the individual will develop breast cancer. In addition, the invention can be used to assess a condition of the patient, for example, fertility of a patient can be determined based on the estradiol level. The present invention can be used to monitor the level of biologically or clinically relevant substances in a patient. Furthermore, the present invention can be used to determine whether a patient is eligible to receive a drug, or eligible to be included in a drug study, based on the level of a given analyte in the patient.

[0025] The efficiency and low operating cost associated with the system 100 of FIG. 1 is well-suited for running individual samples in a manner that does not require operating in a batch mode where many samples are acquired prior to running an assay. In this manner, embodiments of the present invention are well suited for analyzing samples on an individual basis.

[0026] In one embodiment of an analyte detection system, an analyte binds to a magnetic particle (e.g., a magnetic bead) to form an analyte-particle complex. The analyte-particle complex is transported and localized onto the sur-

face of a sensing device by applying a gradient magnetic field. The magnetic field induces a polarization in the magnetic material of the particle that is aligned with the local magnetic field lines. The particle experiences a net force in the direction of the gradient, causing the particle to migrate toward regions of higher field strength. The magnetic field distribution is tailored to draw analyte-particle complexes from a sample flow and distribute them across the surface of the sensing device. The extraneous, background components of the sample (e.g., cells, proteins) generally have a much lower magnetic susceptibility as compared to the magnetic particles, and so the magnetic field does not significantly influence them. Hence, only a very small fraction of this background material interacts with the sensor surface.

[0027] In one embodiment, the sensing device is a flexural plate wave (FPW) device, which functions particularly well with the magnetic particles for two reasons. First, the presence of the magnetic particles on the surface of the sensing device results in an amplified FPW signal response. The larger combined size and density of the analyte-particle complex yields a larger FPW signal response than the analyte alone. Second, the surface of the sensor in the FPW device consists of a thin membrane that is typically only a few micrometers thick, which allows larger magnetic fields and field gradients to be created at the sensor surface because the field source can be positioned closer to the sample flow. This results in higher fractional capture of the analyte from the sample. With this higher capture rate and efficiency, it is possible to process larger sample volumes in shorter times than would be otherwise possible.

[0028] In one aspect, an apparatus for detection of an analyte includes a fluid chamber having at least one opening for fluid to enter, and a flexural plate wave device defining at least a portion of at least one interior surface of the fluid chamber. The apparatus further includes a monitoring device to monitor at least one signal output by the flexural plate wave device, a plurality of magnetic particles coated with a capture agent having an affinity for the analyte, and a first source of magnetic flux to selectively attract magnetic particles to the at least one interior surface of the fluid chamber.

[0029] In another aspect, a cartridge for a resonant device system includes a first fluid chamber having at least one opening for fluid to enter, and a flexural plate wave device defining at least one interior surface of the fluid chamber. The apparatus further includes a first source of magnetic flux to selectively attract magnetic particles to the at least one interior surface of the first fluid chamber.

[0030] In another aspect, a method for detection of an analyte includes combining a fluid containing an analyte with a plurality of magnetic particles that comprise a capture agent having an affinity for the analyte to produce at least some magnetic particles bound to at least some analyte. The method further includes directing the combined fluid into a first fluid chamber, wherein at least one surface of a flexural plate wave device is in fluid communication with the fluid in the first fluid chamber. The method also includes creating a first magnetic flux in proximity to the flexural plate wave device to magnetically attract at least some of the bound magnetic particles to the at least one surface of the flexural plate wave device.

[0031] In another aspect, a method for detection of an analyte includes coating at least a portion of a surface of a flexural plate wave device located in a fluid chamber with a first capture agent, and directing a fluid containing an analyte into the fluid chamber to bind some of the analyte to the capture agent located on the flexural plate wave device. The method further includes directing a fluid containing a plurality of magnetic particles that comprise a second capture agent into the fluid chamber, and creating a magnetic flux in proximity to the flexural plate wave device to attract at least some of the magnetic particles towards the surface of the flexural plate wave device.

[0032] As a result of the present invention, much lower levels of analyte can be detected compared to conventional assays. The detection limit of analyte is improved by a number of factors. In one embodiment, the present invention uses fewer particles per sample, thereby resulting in particles that are more densely coated with analyte, even where the concentration of analyte in the sample is low. As a result of the presence of higher levels of analyte per particle, each coated particle has a higher avidity for the sensing surface.

[0033] Where the assay format is a competition assay, that is, the sensing surface is coated with the analyte, particles that are more densely coated with analyte are more effectively blocked from binding to the sensing surface because each particle comprises fewer capture agent molecules that are free to bind to the analyte on the sensing surface. In other words, a lower particle to analyte ratio results in better competition between the analyte in the sample and the analyte on the sensing surface which allows for the detection of lower concentrations of analyte in the sample. Thus, the present invention improves the accuracy and the sensitivity of the system because the particles are more densely coated with analyte, and have a higher binding strength for the sensing surface.

[0034] In another embodiment, devices fabricated and methods performed according to the principles of the present invention are particularly useful for capturing low concentrations of particles because the sensor surface is thin (for example, in one embodiment, on the order of several microns). In one embodiment, the thin surface is used in conjunction with a magnetic field gradient and magnetic particles. Because the sensor surface is thin, a large magnetic field gradient can be induced on the side of the sensor surface. The large magnetic field gradient can enhance the attraction of the particles to the sensor surface by focusing the field close to the surface of the sensor, while allowing other material contained in the sample to flow by. The large magnetic field gradient can enhance the attraction of the magnetic particles to the sensor surface by focusing the field close to the surface of the sensor, while allowing other material contained in the sample to flow by. In this way, lower numbers of particles can be used, thereby improving the detection limit of the system, because the magnetic field gradient serves to concentrate the particles near the sensing surface where they can interact with the bound analyte or capture agent, depending on the assay format. In various embodiments, the field gradient can be removed to allow any non-specifically bound particles to be washed away. In various embodiments, the magnetic field gradient can be removed to allow any non-specifically bound particles to be washed away.

#### BRIEF DESCRIPTION OF DRAWINGS

[0035] The foregoing and other objects of this invention, the various features thereof, as well as the invention itself, may be more fully understood from the following description, when read together with the accompanying drawings in which:

[0036] FIG. 1A shows one embodiment of an analyte detection system, constructed according to the invention.

[0037] FIG. 1B shows another embodiment of a portion of the analyte detection system shown in FIG. 1A.

[0038] FIG. 2 shows a more detailed view of the FPW sensor shown in FIG. 1A.

[0039] FIG. 3 shows a general detection protocol for using an FPW sensor in combination with analyte-particle complexes for detection of biological analytes.

[0040] FIG. 4 shows the change in the signal from multiple FPW sensors as a function of time for an exemplary detection protocol.

[0041] FIG. 5 is a summary plot showing the final signal change detected as a function of original analyte concentration.

[0042] FIG. 6 shows a time evolution plot for a detection protocol, similar to the plot shown in FIG. 4, but rather for a PSA analyte.

[0043] FIG. 7 is a schematic of three different formats for attaching an analyte to the sensing surface of the acoustic device.

[0044] FIG. 8 is a schematic of one embodiment of the present invention, where competitor molecule (e.g., analyte) is bound to the sensing surface.

[0045] FIG. 9 is a schematic of one embodiment of the present invention, where the competitor molecule is the analyte of interest linked to a tag and the sensing surface of the acoustic device is coated with a capture agent that is capable of binding to the tag.

[0046] FIG. 10 is a schematic of one embodiment of the present invention, where the competitor molecule comprises a carrier and two or more analyte molecules of interest bound thereto, and the sensing surface of the acoustic device is coated with a capture agent that is capable of binding to the analyte of interest.

[0047] FIG. 11 shows the change in signal from multiple FPW sensors as a function of PSA concentration.

[0048] FIG. 12 shows the change in signal from multiple FPW sensors as a function of estradiol concentration in serum.

[0049] FIG. 13 is a dose response curve of FK-506 in buffer.

[0050] FIG. 14 shows the change in signal from multiple FPW sensors as a function of FK-506 concentration in buffer.

[0051] FIG. 15 is a dose response curve of FK-506 in serum.

[0052] FIG. 16 shows the change in signal from multiple FPW sensors as a function of FK-506 concentration in serum.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0053] The present invention is drawn to methods of detecting analytes, including small molecule analytes, using an acoustic device. Typically, small molecule analytes contain a single or only a few binding sites that can be recognized by capture agents. Because a small molecule has a few or only one binding site, one embodiment of the present invention uses competitive binding to detect and/or quantify the analyte. Where the analyte has binding sites that can be recognized by two or more capture agents, the analyte can be detected, for example, using a sandwich assay with two different capture agents.

[0054] Increased endogenous estradiol is clinically correlated with the prevalence of breast cancer in women. It has been shown, for example, that women with increased mammographic breast density, a clinical manifestation of excessive breast tissue estrogen synthesis, are at a higher risk of breast cancer (Boyd, N. F. et al., *N. Engl. J. Med.*, 347:886-94 (2002)). In addition, it has been shown that women with levels of serum estradiol levels in the upper quartile are at higher risk of developing breast cancer than postmenopausal women with normal serum estradiol levels in the lower quartile (Cauley, J. A. et al., *Ann. Intern. Med.*, 130(4 Pt 1):270-7 (1999)). Therefore, the method of detecting estradiol can be used to detect breast cancer. In addition, the method of the present invention can be used in conjunction with other diagnostic tests such as a mammogram, to detect breast cancer in an individual. In another embodiment, the method of detecting estradiol can be used to determine the likelihood that the individual will develop breast cancer.

[0055] The method of detecting estradiol can be used to assess or develop a treatment plan for the individual or to determine whether an individual is suitable or eligible for a particular therapy, treatment, or clinical study. For example, the method can be used to assess whether the individual is a candidate for treatment with tamoxifen. In another embodiment, estradiol levels can be used to monitor hormone replacement therapy in a patient in order to balance the benefits of hormone replacement with the risks of elevated estradiol levels.

[0056] In general terms, an analyte is detected based on the ability of particles coated with a capture agent (also referred to herein as a first capture agent) to alter the resonating frequency of an acoustic device. The capture agent is capable of binding to the analyte. In one embodiment, a plurality of particles coated with a capture agent is exposed to the sensing surface of the acoustic device in the presence of the sample and a competitor molecule. The sensing surface can be part of a fluid chamber or channel as described herein. In addition, the coated particles can be exposed to the sensing surface in a static mode, for example, the coated particles can be introduced into the chamber and incubated for a given period of time. In another embodiment, the coated particles can be exposed to a sensing surface in a non-static mode, for example, by flowing the coated particles through the fluid chamber or channel.

[0057] As described herein, it was surprisingly found that using a lower concentration of particles allowed for the

detection of lower concentrations of analytes. The finding was unexpected because conventional wisdom, in assays involving capture by particles, calls for the use of a high quantity of particles in order to maximize capture efficiency.

[0058] Generally, in the competitive binding format of the present invention, the amount of particles capable of binding to the sensing surface of the acoustic device is inversely proportional to the amount of analyte of interest present in the sample. Higher levels of analyte in the sample results in more of the capture agent on the particles being occupied by analyte from the sample, and fewer capture agents on the particles being available to bind to the competitor molecule, thereby affecting the number or amount of particles that can interact with the sensing surface of the acoustic device. As described below, the competitor molecule can be present in solution or can be bound to the sensing surface of the acoustic device. In a preferred embodiment, the particles are magnetic, and a magnetic flux is applied in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward the sensing surface.

[0059] In one embodiment, a method for detecting one or more analytes comprises introducing a plurality of particles coated with a capture agent capable of binding the analyte into a fluid chamber, wherein at least one surface of the fluid chamber comprises an acoustic device having a capture agent capable of binding the analyte bound thereto. This format is referred to herein as a sandwich format. The plurality of particles can be contacted with the sample prior to introducing the particles into the chamber or the sample can be introduced into the chamber prior to or simultaneously with the introduction of the particles. Signal output by said acoustic device is monitored, thereby detecting one or more analytes in the sample.

#### Assay Formats

[0060] While not wishing to be bound by theory, in the case of a small molecule analyte, where the assay format is a competition assay, that is, the sensing surface is coated with the analyte, use of few particles or a lower concentration of particles allows the particles to become more densely coated with analyte. Particles that are more densely coated with analyte are more effectively blocked from binding to the sensing surface because each particle comprises fewer capture agent molecules that are free to bind to the analyte on the sensing surface. In other words, a lower particle to analyte ratio results in better competition between the analyte in the sample and the analyte on the sensing surface which allows the detection of lower concentrations of analyte in the sample. The particles can be used in a concentration from about  $1 \times 10^2$  to about  $1 \times 10^7$  per mL. In another embodiment, the particles are at a concentration of about  $5 \times 10^4$  to about  $5 \times 10^5$  per mL. FIG. 7 shows three embodiments where the sensing surface of the acoustic device is coated with an analyte. In panel, B, the analyte 10 is bound directly to the surface 12 via a chemical linker. In panels A and C, the analyte is indirectly bound to the surface. In panel A, the surface, 12 is coated with a first member of a binding pair 32. The second member of the binding pair 22, having one or more analyte molecules 10 bound thereto is allowed to bind to the first member of the binding pair coating the surface. In panel C, the surface, 12 is coated with a first member of a binding pair. The second member of the binding pair 22, is allowed to bind to the surface bound first

member of the binding pair, and capture agent **16** labeled with the first member of a binding pair **32** is allowed to bind the second member of the binding pair. Competitor molecule **24** comprising a carrier having one or more analyte molecules bound thereto is allowed to bind to the capture agent **16**.

[0061] As shown in FIG. 8, in one embodiment, the competitor molecule comprises the analyte of interest **10** bound to the sensing surface **12** of the acoustic device (panel A). Particles **14** coated with capture agent **16** are exposed to sample containing the analyte **18** (panel B). Particle-bound capture agent that has not bound analyte from the sample **20** is free to bind the analyte bound to the surface of the acoustic device (panel C). As shown in panels C and D, higher levels of analyte in the sample result in fewer particles binding the acoustic device sensing surface because more of the capture agent present on the particles is occupied with analyte from the sample. Signal output by the acoustic device is monitored to determine the amount and/or number of particles that have bound to the surface, thereby detecting whether one or more analytes is present in a sample. In addition, the presence or amount of analyte present in the sample can be determined, for example by comparing the signal to a control. In an alternative embodiment, as described herein, the particles can be magnetic particles. After introducing the particles into the fluid chamber, magnetic flux is created in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward the sensing surface (similarly as described, for example, in FIGS. 1A, 1B and 2).

[0062] In another embodiment, as shown in FIG. 9, the sensing surface **12** of the acoustic device is coated with a capture agent **22** (also referred to herein as a second capture agent) that is capable of binding to the competitor molecule **24**. The competitor molecule can be, for example, the analyte of interest **10** bound to a tag **26**, and the second capture agent is capable of binding to the tag. As shown in FIG. 9, higher levels of analyte in the sample results in fewer particles **14** binding to the sensing surface of the acoustic device because more of the capture agent present on the particles **16** is occupied with analyte from the sample. Because the second capture agent is capable of binding to the tag portion of the competitor molecule, the coated particles bind to the sensing surface of the acoustic device only if the particles have bound the competitor molecule.

[0063] In another embodiment, as shown in FIG. 10, the competitor molecule **24** can be, for example, two or more analyte molecules or moieties of interest **10** bound to a carrier **26**, and the second capture agent **40** is capable of binding the analyte. As shown in FIG. 10, the second capture agent can be indirectly bound to the acoustic device sensing surface. The surface-bound and particle-bound capture agents can be the same capture agent. Particles **14** coated with capture agent **16** are exposed to sample containing the analyte **10** and the competitor molecule **24** (panel B). Particle-bound capture agent that has not bound analyte from the sample is free to bind the competitor molecule, which in turn is bound by the capture agent that is bound to the sensing surface (panel C). As shown in panel D, higher levels of analyte present in the sample results in fewer particles binding the sensing surface of the acoustic device because more of the capture agent present on the particles is occupied with analyte from the sample. Where the analyte is a small molecule having only one copy of a given epitope or

binding site, the coated particles will bind to the acoustic device sensing surface only if the particles have bound to the competitor molecule.

[0064] The present invention can be used to screen for one or more small molecules of interest. In this embodiment, a plurality of particles is introduced into a fluid chamber. The plurality of particles includes particles coated with different analytes. At least one surface of the fluid chamber comprises an acoustic device having a capture agent bound thereto, wherein the capture agent is capable of binding the analyte of interest. Signal output by said acoustic device is monitored, thereby detecting an analyte capable of binding the capture agent.

[0065] The method of the present invention can be used to detect the presence of the analyte and/or to determine the concentration or level of the analyte in the sample. The concentration detected or measured by the method of the present invention can be an absolute concentration or a relative concentration. For example, the concentration may be a ratio relative to the concentration of a reference analyte present in the same sample of body fluid. The concentration can be obtained by comparing the data with similar data obtained at a different time, to determine whether a significant change in actual concentration has occurred. In any of the embodiments described herein, the read-out can be provided by the method as a positive or negative read-out. In other embodiments, the method can provide a positive read-out if a certain threshold level of analyte is detected.

[0066] For each of the embodiments described herein, a number of variations can be made to the method as described below, without departing from the scope of the invention.

#### Samples

[0067] Samples suitable for use in the present invention includes any material suspected of containing the analyte. The sample can be used directly as obtained from the source or following one or more steps to modify the sample. In one embodiment, the sample is a biological sample. The sample can be derived from any biological source, such as a physiological fluid (e.g., blood, saliva, sputum, plasma, serum, ocular lens fluid, cerebrospinal fluid, sweat, urine, milk, ascites fluid, synovial fluid, peritoneal fluid, amniotic fluid, and the like) and fecal matter. The sample can be obtained from biological swabs such as nasal or rectal swabs. In addition, the sample can be biopsy material. The sample can be obtained from a human, primate, animal, avian or other suitable source.

[0068] The sample can be pretreated prior to use, such as preparing plasma from blood, diluting viscous fluids, and the like. The sample can also be filtered, distilled, extracted, or concentrated. For example, some small molecule drugs permeate blood cells and bind to proteins in blood (e.g., FK506). Small molecules can be extracted by adding a protein precipitation agent and cell lysing agent. For example, a mixture of zinc sulphate, polyethylene glycol and methanol can be added to blood and the solvent phase eluted after centrifugation. An alternative preparation method is to add a mixture containing protein digestion enzymes and detergents to break down the proteins and cells to release the small molecule. After centrifugation, the liquid phase is eluted and analyzed to determine the small molecule concentration in the original sample. The sample can also be

treated to inactivate or modify certain activities in the sample capable of interfering with the analyte or the detection process. For example, a decomplexing antagonist can be added to the sample to disassociate the analyte from other molecules that may be bound to and/or may interfere with the ability of the capture agent to bind to the analyte. Such antagonists can be, for example, steroid antagonists. In the case of estradiol detection, the sample can be treated by adding danazol to disassociate estradiol from sex hormone binding protein.

[0069] Other liquid samples besides physiological fluids can be used, such as water, food products, and the like, for the performance of environmental or food production assays. In addition, a solid material suspected of containing the analyte can be used as the test sample. A solid test sample can be modified (e.g., homogenized, extracted, or solubilized) to form a liquid medium or to release the analyte.

[0070] The sample volume can be as little as 10  $\mu$ L or as much as 250 mL. In one embodiment, the sample volume can be as little as 50  $\mu$ L or as much as 5 mL. In one embodiment, the sample volume is about 1 to about 5 mL.

[0071] In one embodiment, a single sample can be run on a single cartridge as described below. In addition, in order to test a panel of one or more analytes, a single sample can be divided into two or more aliquots. Each aliquot can be tested for a different analyte, for example, using a different cartridge for each analyte to be tested. In this way, samples can be analyzed on an individual basis, that is, as they are acquired from the patient, rather than in batch mode, e.g., accumulating multiple samples to analyze at the same time or in the same machine run.

#### Capture Agents

[0072] Suitable capture agents for use in the present invention include any molecule capable of binding to an analyte of interest. The term "capture agent" includes molecules or multi-molecular complexes that can bind to an analyte of interest. Capture agents preferably bind to their binding partners in a substantially specific manner. Capture agents with dissociation constants (KD) of less than about  $10^{-6}$  are preferred. The capture agent can also be, for example, polypeptides, nucleic acids, carbohydrates, nucleoproteins, glycoproteins, glycolipids and lipoproteins. Antibodies or antibody fragments are highly suitable as capture agents. Antibodies capable of binding to the analyte of choice may be obtained commercially or may be prepared using standard methods for generating antibodies.

[0073] Antigens may also serve as capture agents, since they are capable of binding antibodies. A receptor which binds a ligand is another example of a possible capture agent. Protein-capture agents are understood not to be limited to agents which only interact with their binding partners through noncovalent interactions. Capture agents may also optionally become covalently attached to the proteins which they bind. For example, the capture agent may be photocrosslinked to its binding partner following binding.

[0074] The term "antibody" includes any immunoglobulin, whether naturally produced or synthetically produced in whole, or in part. Derivatives of antibodies that maintain the ability of the antibody to bind to the analyte of interest are also included in the term. The term also includes any protein having a binding domain which is homologous or largely

homologous to an immunoglobulin binding domain. These proteins may be derived from natural sources, produced synthetically in whole or in part. An antibody may be monoclonal or polyclonal. The antibody may be a member of any immunoglobulin class, including IgG, IgM, IgA, IgD, and IgE. Where the analyte is known to bind a carrier protein, the antibody can be specific for the free form of the analyte or the carrier-bound form of the analyte. Antibodies that are capable of binding an analyte of choice can be obtained commercially or produced using known methods for generating antibodies.

[0075] The term antibody also includes antibody fragments. The term "antibody fragments" refers to any derivative of an antibody which is less than full-length. Preferably, the antibody fragment retains at least the ability to bind the analyte of interest. Examples of antibody fragments include, but are not limited to, Fab, Fab', F(ab')<sub>2</sub>, scFv, Fv, dsFv diabody, and Fd fragments. The antibody fragment may be produced by any means. For instance, the antibody fragment may be enzymatically or chemically produced by fragmentation of an intact antibody or it may be recombinantly produced from a gene encoding the partial antibody sequence. Alternatively, the antibody fragment may be synthetically produced in whole or in part. The antibody fragment may optionally be a single chain antibody fragment. Alternatively, the fragment may comprise multiple chains which are linked together, for instance, by disulfide linkages. The fragment may also optionally be a multimolecular complex. A functional antibody fragment will typically comprise at least about 50 amino acids and more typically will comprise at least about 200 amino acids.

[0076] Single-chain Fvs (scFvs) are recombinant antibody fragments consisting of only the variable light chain (V<sub>L</sub>) and variable heavy chain (V<sub>H</sub>) covalently connected to one another by a polypeptide linker. Either V<sub>L</sub> or V<sub>H</sub> may be the NH<sub>2</sub>-terminal domain. The polypeptide linker may be of variable length and composition so long as the two variable domains are bridged without serious steric interference. Typically, the linkers are comprised primarily of stretches of glycine and serine residues with some glutamic acid or lysine residues interspersed for solubility. "Diabodies" are dimeric scFvs. The components of diabodies typically have shorter peptide linkers than most scFvs and they show a preference for associating as dimers. An "Fv" fragment is an antibody fragment which consists of one V<sub>H</sub> and one V<sub>L</sub> domain held together by noncovalent interactions. The term "dsFv" is used herein to refer to an Fv with an engineered intermolecular disulfide bond to stabilize the V<sub>H</sub>-V<sub>L</sub> pair. A "F(ab')<sub>2</sub>" fragment is an antibody fragment essentially equivalent to that obtained from immunoglobulins (typically IgG) by digestion with an enzyme pepsin at pH 4.0-4.5. The fragment may be recombinantly produced. A "Fab" fragment is an antibody fragment essentially equivalent to that obtained by reduction of the disulfide bridge or bridges joining the two heavy chain pieces in the F(ab')<sub>2</sub> fragment. The Fab' fragment may be recombinantly produced. A "Fab" fragment is an antibody fragment essentially equivalent to that obtained by digestion of immunoglobulins (typically IgG) with the enzyme papain. The Fab fragment may be recombinantly produced. The heavy chain segment of the Fab fragment is the Fd piece.

[0077] Suitable polypeptide capture agents also include virtually any peptide, polypeptide, or protein that is capable



of binding to an analyte of interest, or a small molecule such as a small organic molecule. In one embodiment, the capture agent is an antibody that is capable of binding to the analyte of interest. In preferred embodiments, the capture agent is capable of binding to a small molecule. Suitable polypeptide capture agents may be obtained, for example, commercially, using recombinant methods, using synthetic production methods, or by purification from a natural source. Polypeptides include, for example, cell surface and soluble receptor proteins, such as lymphocyte cell surface receptors, steroid receptors, nuclear proteins, signal transduction molecules, transcription factors, allosteric enzyme inhibitors, clotting factors, enzymes (e.g., proteases and thymidylate synthetase, serine/threonine kinases, threonine kinases, phosphatases, bacterial enzymes, fungal enzymes and viral enzymes), proteins associated with DNA and/or RNA synthesis or degradation and the like. As described in more detail below, where more than one capture agent is used, the capture agents can be, for example, isoforms of each other.

**[0078]** The capture agent can also be a nucleic acid such as RNA or DNA, or peptide nucleic acid. In one embodiment, the nucleic acid or peptide nucleic acid is capable of hybridizing to nucleic acid or peptide nucleic acid analyte. In addition, the capture agent can be an aptamer, a nucleic acid capable of binding to non-nucleotide analyte (e.g., proteins, small organic molecules, or inorganic molecules). As used herein, an aptamer can be either an RNA or a DNA chain composed of naturally occurring or modified nucleotides.

**[0079]** Suitable capture agents also include members of binding pairs. Suitable binding pairs include, for example, biotin and avidin or biotin and derivatives of avidin (e.g., streptavidin and neutravidin).

**[0080]** Capture agents can be bound to the surface or to the bead as described below or by using standard techniques for attaching polypeptides, nucleic acids, and the like to surfaces.

#### Analytes

**[0081]** As used herein, the term "analyte" refers to, for example, the molecular structure that is recognized by a capture agent. For example, the term analyte can refer to the epitope recognized by an antibody, or can include that part of a ligand that is bound by a receptor. The term analyte also includes larger molecules that contain a molecular structure that is recognized by a capture agent. The analyte can be part of a cell, for example a cell surface protein. The analyte can be an analyte of interest, chosen by the user (e.g., preselected). The analyte can be selected based on the ability to bind a capture agent of interest, for example in small molecule library screening.

**[0082]** As described herein, the present invention can be used to measure one or more analytes of a panel of analytes. The panel of analytes can include one or more analytes that are detected using a competition format as described herein. The panel of analytes can include one or more analytes detected using the sandwich assay format as described herein. In one embodiment, each analyte is detected using a separate cartridge as described below. In order to test a panel of one or more analytes, a single sample can be divided into two or more aliquots. Each aliquot can be tested for a different analyte, for example, using a different cartridge for

each analyte to be tested. In this manner, panels of different analytes may be tested without requiring that multiple samples be acquired and/or that different types of apparatus be employed to test the detect the different analytes.

**[0083]** In one embodiment, the analyte of interest is a small molecule. Small molecules include organic or inorganic molecules having a molecular weight on the order of about 1000 g/mol or less. Typically, small molecule analyte will contain a single or only a few binding sites. Because a small molecule has a few or only one binding site, the present invention uses competitive binding to detect and/or quantify small molecule analytes.

**[0084]** It is understood, however, that some small molecules can be detected in a sandwich assay format. For example, the detection of rapamycin can be achieved by direct sandwich immunoassay with one capture agent or protein interaction partner immobilized on the sensor surface and the other capture agent or protein partner on the magnetic bead. Two proteins responsible for binding rapamycin are the 12-kD FK506 binding protein (FKBP) and the 100-amino acid domain of the mammalian target of rapamycin (mTOR) known as the FKBP-rapamycin binding domain (FRB). It has been shown that FKBP and FRB do not exhibit apparent affinity toward each other in the absence of rapamycin.

**[0085]** The small molecule can include, for example, steroids, lipids, carbohydrates, peptides, and heterocyclic compounds (e.g. bases, including co-factors such as FAD and NADH). The analyte (e.g., small molecule) can be part of a library of small organic molecules which comprise aldehydes, ketones, oximes, hydrazones, semicarbazones, carbazides, primary amines, secondary amines, tertiary amines, N-substituted hydrazines, hydrazides, alcohols, ethers, thiols, thioethers, thioesters, disulfides, carboxylic acids, esters, amides, ureas, carbamates, carbonates, ketals, thioketals, acetals, thioacetals, aryl halides, aryl sulfonates, alkyl halides, alkyl sulfonates, aromatic compounds, heterocyclic compounds, anilines, alkenes, alkynes, diols, amino alcohols, oxazolidines, oxazolines, thiazolidines, thiazolines, enamines, sulfonamides, epoxides, aziridines, isocyanates, sulfonyl chlorides, diazo compounds and/or acid chlorides, preferably aldehydes, ketones, primary amines, secondary amines, alcohols, thioesters, disulfides, carboxylic acids, acetals, anilines, diols, amino alcohols and/or epoxides, most preferably aldehydes, ketones, primary amines, secondary amines and/or disulfides and combinations thereof.

**[0086]** In a particular embodiment, the analyte is estradiol. The term estradiol includes estradiol and all measurable estradiol metabolites. The term estradiol can include; therefore, estrone-3-glucuronide (E3G), estradiol-3-glucuronide, estradiol-17-glucuronide, estriol-3-glucuronide, estriol-16-glucuronide and estrone-3-sulphate.

**[0087]** In one embodiment, estradiol levels can be used to determine the status of ovarian reserves in a patient and/or predict fecundity in a patient. The present invention can be measured as part or a panel of analytes to determine ovarian reserve status or fertility status. The analyte panel can include, for example, estradiol and FSH. Methods for predicting are known in the art, for example, as described in Buyalos, et al., *Fertil Steril* 68:272-277, 1997, the teachings of which are incorporated herein by reference in their entirety.

[0088] The analyte of interest can also be a biologic analyte, such as a polypeptide, a nucleic acid, a carbohydrate, a nucleoprotein, a glycopeptide or a glycolipid. Useful analytes include, for example, enzymes, steroids, hormones, transcription factors, growth factors, immunoglobulins, steroid receptors, nuclear proteins, signal transduction components, allosteric enzyme regulators, and the like. Analytes of interest can be obtained, for example, commercially, recombinantly, synthetically, or by purification from a natural source. In preferred embodiments, the analyte of interest is associated with a specific human disease or condition. Suitable growth factors include, for cytokines such as erythropoietin/EPO, granulocyte colony stimulating receptor, granulocyte macrophage colony stimulating receptor, thrombopoietin (TPO), IL-2, IL-3, IL-4, IL-5, IL-6, IL-10, IL-11, IL-12, growth hormone, prolactin, human placental lactogen (LPL), CNTF, and octostatin. Suitable steroids include, but are not limited to, estradiol, progesterone, testosterone, and derivatives thereof. Other suitable analytes include, for example, insulin, insulin-like growth factor 1 (IGF-1), epidermal growth factor (EGF), vascular endothelial growth factor (VEGF), placental growth factor (PLGF), TGF- $\alpha$  and TGF- $\beta$ ), other hormones and receptors such as bone morphogenic factors, follicle stimulating hormone (FSH), and luteinizing hormone (LH), tissue necrosis factor (TNF), apoptosis factor-1 and -2 (AP-1 and AP-2), and mdm2. A biologic analyte also includes cellular analytes that include, for example, a suitable detectable marker, such as a surface receptor.

[0089] In one embodiment, the analyte is a breast cancer marker. Breast cancer markers include for example, estradiol and metabolites thereof as described above. In addition, breast cancer markers include, but are not limited to proteins described in U.S. Pat. No. 6,936,424 to Watkins, et al., the teachings of which are incorporated herein in their entirety.

[0090] The analyte of interest can also be a therapeutic drug where it would be useful to measure the levels of the drug in a patient sample, for example for drug management purposes. Suitable therapeutic drugs include, but are not limited to protease inhibitors and immunosuppressants. Suitable protease inhibitors include ageneraser, reyataz, lexiva, telzir, crivivan, kaletra, viracep, norvi, invirase, aortovase, aptivus and the like). Suitable immunosuppressants include cyclosporin, tacrolimus (FK-506), rapamycin, mycophenolic mofetil and the like. In one embodiment, the therapeutic drug of interest is detected using a competition assay.

[0091] In another embodiment the therapeutic drug is detected in a sandwich assay format. As described above, the therapeutic drug can be bound to a carrier or binding protein and can be detected in a sandwich assay using a capture agent that is capable of binding the carrier. In another embodiment, the therapeutic drug is a biological therapeutic. Examples of biological therapeutics include: monoclonal antibodies, enzymes, hormones and other proteins. Since these molecules are much larger, they generally have multiple epitopes and can be detected in a sandwich assay.

[0092] Transplant patients are usually prescribed a combination of immunosuppressant drugs. For example, calcineurin inhibitors, such as cyclosporine and tacrolimus, are often prescribed together with mycophenolic mofetil. Additionally, rapamycin (sirolimus) can be used alone or in combination with tacrolimus and cyclosporine. As such, it is

beneficial to provide a panel of measurements from a single patient to aid the physician in determining modifications to their drug levels. The panel of analytes can include small molecules and biologicals (also referred to herein as biomarkers). The analyte panel can include, for example, one or more of the prescribed therapeutic drugs and optionally an immune response marker, such as one or more inflammatory cytokines. Furthermore, it is possible to combine the measurements of therapeutic drugs and biomarkers to monitor infection or rejection. Similar strategies could be used for other patient conditions and therapeutics.

[0093] The analyte of interest can be a pathogen or microbe, such as bacteria or bacterial spores, viruses, parasites, prions or other pathogens or their cell wall or surface components such as gram-positive peptidoglycans, lipoteichoic and teichoic acids, and gram-negative endotoxin (e.g.) lipopolysaccharide). Bacterial analytes include, for example, *Shigella* sp. such as *Shigella dysenteriae*, *Campylobacter* sp. such as *Campylobacter jejuni*, *Enterococcus* sp. such as *Enterococcus faecalis*, *Bacillus anthracis*, *Yersinia pestis*, *Bordetella pertussis*, *Streptococcal* species, *Staphylococcus aureus*, *Mycobacterium tuberculosis*, *Clostridium difficile*, *Clostridium tetani*, *Clostridium botulinum*, *Escherichia coli*, *Salmonella thyphimurim*, *Salmonella enterica*, *Chlamydia* species, *Treponema pallidum*, *Neisseria gonorrhoeae*, *Borrelia burgdorferi*, *Vibrio cholerae*, *Corynebacterium diphtheriae*, and *Helicobacter pylori*. Parasites include, for example, *Giardia*, malaria and cryptosporidia. Viral analytes include, for example, Rhinovirus, Yellow Fever, Group B Coxsackieviruses, (CB1, CB2, CB3, CB4, CB5, and CB6), Canine Parvovirus (CPV), Herpes Simplex virus type 1 (HSV 1), Vaccinia Virus, T4-like virus, Adenovirus, Influenza B virus, Influenza A, Avian flu, rhinovirus, coronavirus (e.g., SARS), Human Immunodeficiency virus (HIV), Hepatitis viruses, Herpes virus, West Nile Virus, and Ebola virus.

[0094] As described above, in some embodiments, more than one analyte is detected. In one embodiment, the analytes have the same molecular structure. The analytes can be, for example, the same molecular species of interest. In another embodiment, the different analytes (also referred to herein as the first and second analytes) are part of a larger molecule. Therefore, the analyte can be a particular binding site (such as an epitope) attached to or contained within a larger molecule. As such, the different analytes being detected can be part of different molecules.

[0095] Analytes can be bound to the surface or to the bead as described below or by using standard techniques for attaching small molecules, polypeptides, nucleic acids, and the like to surfaces. In one embodiment, the analyte is indirectly bound to the surface. The analyte can be indirectly bound to the surface, for example, by coating the surface with a first member of a binding pair. The analyte is bound or attached to a second member of the binding pair and then the analyte is bound to the surface via the interaction between the first and second members of the binding pair. Suitable binding pairs include, for example, biotin and avidin or biotin and derivatives of avidin such as streptavidin and neutravidin.

[0096] According to one embodiment of the method of the present invention, the plurality of particles can be exposed to the sample using a variety of different formats. For

example, in one embodiment, the plurality of particles is exposed to the sample and then introduced into the fluid chamber. The sample may be concentrated prior to introducing the sample-exposed particles into the fluid chamber. The sample may be concentrated, for example by removing the beads from the solution and resuspending in a smaller volume of liquid.

[0097] In another embodiment, the sample is introduced into the fluid chamber prior to introducing the plurality of particles. In still another embodiment, the plurality of particles is introduced into the fluid chamber prior to adding the sample to the fluid chamber.

[0098] In another embodiment, as described above, the plurality of particles is exposed to the sample and to a competitor molecule. The plurality of particles can be exposed to the sample and to the competitor molecule in a number of different formats. For example, in one embodiment, the plurality of particles is exposed to the sample and to the competitor molecule and then introduced into the fluid chamber. In another embodiment, the sample and the competitor molecule are introduced into the fluid chamber prior to introducing the plurality of particles. In still another embodiment, the plurality of particles is introduced into the fluid chamber prior to adding the sample and/or the competitor molecule to the fluid chamber.

[0099] As described above, in one embodiment of the present invention, a plurality of magnetic particles and a competitor molecule are introduced into a fluid chamber. The magnetic particles are coated with a first capture agent capable of binding the analyte and at least one surface of the fluid chamber comprises an acoustic device that has been coated with a second capture agent capable of binding to the competitor molecule. In one embodiment, the competitor molecule comprises the analyte linked or bound to a tag, and the second capture agent is capable of binding to the tag. The tag can be any moiety that can be recognized by a capture agent. In one embodiment, the tag is one member of a binding pair and the capture agent is the other member of the binding pair. For example, the tag can be biotin, and the capture agent can be avidin, streptavidin, or neutravidin. In this embodiment, the biotin is linked to the analyte using known methods for linking molecules to biotin, to form the competitor molecule. The surface can be coated with the second member of the binding pair using any suitable method. For example, the surface can be coated with biotin as described below and then the biotinylated surface can be exposed to avidin or a derivative of avidin.

[0100] In another embodiment, the competitor molecule comprises two or more analyte molecules bound to a carrier, and the second capture agent is capable of binding the analyte. The carrier can be any molecule to which two or more analyte molecules can be linked or bound. The carrier can be a protein, a nucleic acid, or other polymer. In one embodiment, the carrier is an albumin, such as bovine serum albumin. In another embodiment, the carrier is horseradish peroxidase. In this embodiment, two or more analyte molecules can be linked to the carrier as described below, or known linking technology can be used to form the competitor molecule. The surface can be coated with the capture agent as described below.

[0101] As described above, the present invention can be used to screen a small molecule library for one or more small

molecules of interest. Small molecule libraries of the type useful in methods of the present invention may be formed by methods well known in the art or may be obtained commercially (e.g., from ChemBridge on the world wide web at chembridge.com). Small molecule libraries include combinatorial libraries. A combinatorial library can be a library of molecules containing a large number, typically between  $10^3$  and  $10^6$ , of different-sequence oligomers, typically characterized by different sequences of subunits, or a combination of different sequences of side chains and linkages, or different-substituent compounds. Various solid-phase or solution-phase synthetic methods for preparing small molecule libraries are known. In one approach, beads containing successive precursors to the target compounds that form the library are alternately mixed and separated, with one of a selected number of reagents being added to each group of separated beads at each step (Furka, et al., *Int. J. Pept. Protein Res.* 37:487-493 (1991); Chen et al., *J. Am. Chem. Soc.* 116:2661-2662 (1994); Pham, et al., WO 9513538 (1995); Dillard, et al., WO 9408051 (1994). In this embodiment, each bead contains only one chemical species. The plurality of particles can be prepared by synthesizing analytes on a surface of each particle using known methods as described above. In one embodiment, a different analyte is synthesized on each particle.

[0102] In one embodiment, the method comprises preparing the plurality of particles having different analytes bound thereto. In one embodiment, the plurality of particles includes two or more groups of particles, wherein each group of particles is coated with a different analyte. The particles can be prepared by exposing separate groups of particles to different analytes such that the particles in the group become coated with the different analytes. The groups of particles can then be used in the method of the present invention or can be mixed together prior to use in the method of the present invention.

#### Control Signal/Normalization

[0103] In another embodiment, the signal output of the acoustic device in response to sample exposure is compared to or normalized with a control signal. The control signal can be provided to or obtained by the user. For example, the control signal can be a value provided to the user based on the specific analyte, capture agent, or particular model, version or type of device being used. In one embodiment, the control signal is obtained on a lot basis. For example, the control signal can be a signal that is representative of a particular lot of analyte acquired by the user. The representative signal can be, for example, experimentally derived before, during or after testing of a sample. In some embodiments, the control signal is a standard curve that is obtained by, for example, analyzing known quantities of analyte with a specific capture agent and specific version of an acoustic device.

[0104] In another embodiment, the control signal is obtained on a use basis. For example, a unique control signal can be obtained each time a particular analyte and/or capture agent is tested on a particular acoustic device. In one embodiment, the control signal is obtained using the same analyte and/or capture agent, however, in the absence of sample. The control signal can be obtained by introducing a second plurality of particles into the fluid chamber that are coated with a capture agent. At least one surface of the fluid

chamber comprises an acoustic device that has a second analyte bound thereto. Signal output by said acoustic device is monitored to determine a control signal to be used in subsequent testing.

#### Acoustic Devices

[0105] Acoustic devices couple to fluids predominantly through acoustic interaction between the device and the fluid. Typical acoustic devices include surface acoustic wave devices, flexural plate wave devices, lamb wave devices and cantilever devices. Acoustic devices also couple to fluids through some viscous interaction between the device and the fluid, however, the coupling is predominantly acoustic coupling. Viscous interaction devices couple to fluids predominantly through viscous interaction between the devices and the fluid. Typical viscous interaction devices include quartz microbalance (QCM) devices, shear harmonic surface acoustic wave devices, and acoustic plate mode devices. The term “surface acoustic wave” refers to the manner in which energy is carried in the device structure rather than how the device couples to the fluid. Acoustic devices are devices where fluid interacts over a substantial area of a plane of the device. Acoustic devices respond with substantial out of plane motion that couples acoustically to fluid in proximity to the plane of the device (i.e., kinetic energy, potential energy and losses are carried predominantly in the fluid). Viscous interaction devices respond primarily with in-plane motion that does not couple acoustically to fluid in proximity to a plane of the device.

#### General Considerations

[0106] For applications involving, for example, the detection and quantification of biological or chemical substances in a fluid, the coupling between an acoustic device and a fluid is typically between about 100 nm and about 10 microns in thickness relative to the plane of the device where the coupling between a viscous interaction device and a fluid is between about 10 nm and about 100 nm in thickness relative to the plane of the device.

[0107] Surface acoustic wave devices and shear harmonic surface acoustic wave devices both carry energy in their respective structures in similar manners. Surface acoustic wave devices acoustically couple significantly to fluids while shear harmonic surface acoustic wave devices couple to fluids predominantly through viscous interaction.

[0108] One embodiment of an analyte detection system 100, constructed according to the invention, is shown in FIG. 1A. The system 100 includes a network of channels 102 for transporting various test solutions (also referred to herein as “test fluids” or “fluids”) through an FPW device 104. The following U.S. patents and patent applications, all of which are hereby incorporated by reference, describe examples of the various types of FPW devices suitable for use in the present invention: U.S. Pat. No. 5,129,262, U.S. Pat. No. 5,189,914, U.S. Pat. No. 6,688,158 B2, U.S. patent application Ser. No. 10/324,685, U.S. Pat. No. 5,668,303, U.S. Pat. No. 5,836,203, and U.S. Patent Application 20040038195.

[0109] For example, U.S. Pat. No. 5,129,262 describes an ultrasonic sensor that has a thin planar sheet of material forming a Lamb wave propagation medium. Lamb waves, also known as plate-mode waves, can propagate only through a material of finite thickness. In contrast to surface

acoustic waves (SAWs), which require a propagation medium having a thickness on the order of hundreds of times the wavelength of the propagating SAW, Lamb waves require a propagation medium which is at most only several wavelengths thick, and typically only a fraction of the wavelength of the propagating Lamb wave. The thickness of the sheet is no greater than about twenty microns. A Lamb wave generator generates Lamb waves in the planar sheet, and an output device produces an electrical signal that represents the propagation characteristics of the Lamb waves propagating along the sheet. A measuring device measures selected characteristics of the output electrical signal. The planar sheet has some physical characteristics that depend upon the value of a measurand acting on the sheet, and those physical characteristics consequently determine the propagation characteristics of the Lamb waves that propagate along the sheet. Since the electrical signal from the output device represents the propagation characteristics, the electrical signal also represents the value of the measurand acting on the sheet.

[0110] The Lamb wave device described in U.S. Pat. No. 5,129,262 can be employed, for example, in biological sensing. The planar sheet described above can be pre-coated with antibody molecules, so that the frequency of the device changes upon immersion in or contact with a liquid that contains the corresponding antigen. Antigen-antibody attachment at the surface of the propagation medium acts to alter the wave velocity of the Lamb waves in the sheet. The change in wave velocity causes the oscillation frequency to change in a delay line oscillator form of the device. Also, the sheet may be made of a porous and permeable material, allowing the coating of antibody molecules over a greater surface area of the sheet and also allowing the antigen-containing liquid to be flowed through the membrane, in order to speed up the antigen-antibody attachment. Other biological interactions may also be sensed, and additional applications include immunoassay, clinical laboratory testing, in vivo biomedical monitoring, and biomedical research.

[0111] The test solutions used in the described embodiment, for example a blocking solution 106, a sample 108, and a buffer 110, are sourced from reservoir containers 112. The channel path from each of the reservoirs 112 is gated with a valve 114 to control the flow of a particular test solution to a combination point 116 leading to an entry port 118 of the FPW device 104. The test solution flows through the FPW device 104 and exits via an exit port 120, which leads to a pump 122. The pump 122 draws the test solution through the network of channels 102 and through the FPW device 104, and directs the test solution to a waste receptacle 124.

[0112] FIG. 1B shows another embodiment of the analyte detection system 100. This embodiment packages the FPW device 104 and its associated fluid chamber 160 as a cartridge 103, i.e., a consumable component that can be removed and replaced. Some embodiments may include a fluid control device 101 such as a plug, obstruction or baffle that alters the flow through the device 104. In one embodiment, the fluid control device 101 operates to cause the fluid flow through the device 104 to pass closer to the sensor surface 143 than if the fluid control device 101 was not present. Further, the source of input test solutions is shown as an input fluid chamber 105 that has an outlet 107 for

directing the test solutions into the inlet **109** of the cartridge **103**. In some embodiments, the magnetic particles are initially located in the input fluid chamber **105** and the fluid containing analyte is mixed with the magnetic particles in the input fluid chamber **105** and then directed into the cartridge **103** in which the FPW device **104** is located. The magnetic particles may be combined within the input fluid chamber **105** with the fluid containing analyte by a device (e.g., by the action of a pump or a magnetic agitator). FIG. 1B further shows an output fluid chamber **111** with an inlet **113** that receives fluid from the outlet **115** of the cartridge **103**. This output fluid chamber **111** may include one or more of the fluid control devices described herein, and it may include one or more mechanisms for storing and/or treating waste fluid.

[0113] In at least one embodiment, the junction where the outlet **107** of the input fluid chamber **105** meets the inlet **109** of the cartridge **103** is constructed and arranged to allow repeatable connection and disconnection. Similarly, the junction where the outlet **115** of the cartridge **103** meets the inlet **113** of the output fluid chamber **111** is constructed and arranged to allow repeatable connection and disconnection. In some embodiments, these junctions are constructed and arranged to require tools for connection and disconnection, such as threaded couplings that require a wrench or other such tool to affect the coupling and decoupling. In other embodiments, these junctions are constructed and arranged to allow quick and easy manual connection and disconnection, without any extra tools or accessories. Such couplings, both requiring and not requiring tools, are known in the art. In some embodiments, there are multiple input fluid chambers and output fluid chambers. In some embodiments, one or more input and/or output fluid chambers are part of the cartridge **103**. Further, in some embodiments, one or more sources of magnetic flux are part of the cartridge.

[0114] The FPW device **104** is shown in more detail in FIG. 2. In an FPW device **104**, strain energy is carried in bending and tension in the device. In some embodiments, it is desirable for the thickness-to-wavelength ratio of the FPW device **104** to be less than one, and in some cases much less than one. In general, the wavelength " $\lambda$ " of the FPW device **104** is approximately equal to the pitch of the interdigitated electrodes as described herein. In one embodiment, the thickness-to-wavelength ratio of the FPW device **104** is 2  $\mu\text{m}/38 \mu\text{m}$ . In other embodiments, the FPW device **104** is designed to isolate a particular mode (e.g., any mode from the zero<sup>th</sup> order mode to higher order modes) or bandwidth of modes associated with the device. For example, an FPW device **104** having a thickness/wavelength of 2  $\mu\text{m}/38 \mu\text{m}$  as described above would isolate the 80<sup>th</sup> mode of the FPW device **104**. The FPW device **104** can be designed to achieve this effect by selecting a particular pattern for the interdigitated electrodes deposited on the device. In one embodiment, the FPW device **104** is rectangular in shape. The FPW device **104** can, alternatively, be circular or elliptical, or some other planar shape.

[0115] In general, the FPW device **104** is constructed from a silicon wafer **130**, using micro-fabrication techniques known in the art. In the described embodiment, a cavity **132** is etched into the wafer **130** to produce a thin, suspended membrane **134** that is approximately 1.6 mm long, 0.3 mm wide and 2  $\mu\text{m}$  thick. The overall wafer **130** thickness is approximately 500  $\mu\text{m}$ , so the depth of the cavity **132** is just

slightly less than the wafer **130** thickness. A 0.5  $\mu\text{m}$  layer **136** of aluminum nitride (AlN) is deposited on the outer surface (i.e., the surface opposite the cavity **132**) of the membrane **134**, as shown in the expanded view insert of FIG. 2. Two sets of inter-digitated metal electrodes **138** are deposited upon the AlN layer. A thin layer **140** of gold (approximately 500 angstroms) is deposited on the inner surface (i.e., the surface facing the cavity **132**) of the membrane **134** to facilitate immobilization of capture agents (described in more detail below).

[0116] In operation, instrument/control electronics **126** (referring to FIG. 1A) apply a time-varying electrical signal to at least one set of electrodes **138** to generate vibrations in the suspended membrane **134**. The instrument/control electronics **126** also monitor the vibrational characteristics of the membrane **134** by receiving a sensor signal from at least a second set of electrodes **138**. When liquid is in contact with the cavity side **132** of the membrane **134**, the maximal response of the plate structure is around 15-25 MHz. The instrument/control electronics **126** compare a reference signal to the sensor signal from the second set of electrodes to determine the changes in the relative magnitude and phase angle of the sensor signal as a function of frequency. The instrument/control electronics **126** interpret these changes to detect the presence of the targeted analyte. In some embodiments, the instrument/control electronics also determines, for example, the concentration of the targeted analyte on the inner surface of the membrane **134**.

[0117] Capture agents targeting the analyte of interest are immobilized on the thin layer of gold **140** covering the inner surface of the membrane **134**, as described above. The surface can be coated with a suitable linking compound. Suitable linking compounds are commercially available. In one embodiment, the linking compound comprises biotin PEG disulfide, as described below. In another embodiment, thiol-terminated alkyl chains are linked to the gold surface forming a self-assembled monolayer (SAM). A fraction of the SAM chains are terminated with reactive groups (e.g., carboxyl) to allow covalent linking of capture agents to the SAM chains using biochemical process steps known in the art. The remainder of the SAM chains are terminated with non-reactive groups, preferably ones that have a hydrophilic character to resist nonspecific binding (e.g., oligomers of ethylene glycol). Other surface chemistries are described in the literature and can be used to produce a capture surface.

[0118] The FPW device **104** is packaged to allow electrical connections to the electrodes **138** on the outer surface of the membrane **134**. Additionally, the FPW device **104** is mechanically supported by a channel block **142**, to allow for the inner surface of the membrane **134** to contact the test solutions and an interface is provided for contacting the sensor surface **143** with the liquid sample. The channel block **142** creates a path (fluid chamber **160**) for the test solutions to flow from an input port **118**, past the inner surface of the membrane **134** and then out of an exit port **120**. A seal **144** is formed between the FPW device **104** and the channel block **142** to prevent test solutions from escaping from the channels **102** formed within the combination of the FPW device **104** and the channel block **142**. The channel block **142** thus forms a fluid chamber, of which the FPW device **104** comprises one of the interior walls.

[0119] The channels **102** through the combination of the FPW device **104** and the channel block **142** are approxi-

mately 0.5 mm in diameter. The channel block **142** can be formed from a variety of materials, including plastic, metal or ceramic, among other materials.

[0120] The system **100** includes one or more fluid control devices for changing at least one fluid property, such as flow, pressure, or trajectory to name a few, within the system **100**. The pump **122** and valves **114** shown in FIG. 1A that direct and control the flows of various test solutions through the device and over the sensor surface **143** (as required to execute a test protocol) are all examples of fluid control devices. In general, a fluid control device changes the at least one fluid property in the vicinity of at least one surface within the fluid chamber **160** of the device **104**. Generally, this is done to distribute the magnetic particles along at least a portion of the sensor surface **143**. As described above, in some embodiments the fluid control device is a pump (e.g., a peristaltic pump, centrifugal pump, rotary pump, electro-osmotic pump). In some embodiments, the pump is located on the entrance side of the fluid chamber, and in other embodiments the pump is located on the exit side of the fluid chamber. In some embodiments, the device is a flow diverter (e.g., a plug, obstruction wall or baffle) that is disposed relative to the fluid chamber to alter the fluid flow in the vicinity of the at least one interior surface of the fluid chamber.

[0121] Referring to FIG. 1A, a single pump **122** is positioned on the waste side of the FPW device **104**. Suction that the pump **122** generates draws buffer **110** or analyte in the sample **108** from their respective reservoir containers **112** on the supply side of the FPW device **104**. Valves **114** are positioned on the supply side of the device **104** to control which test solution is directed over the sensor surface **143** at any time during the test protocol. The pump **122** controls the flow rate of the test.

[0122] A device for regulating temperature (e.g., a thermoelectric cooler) may be associated with the FPW device **104** and channel block **142**. This reduces the impact of variable environmental conditions on the FPW device **104** output by maintaining the device **104** at a relatively constant, known temperature. In an alternative embodiment, a temperature sensor is included within the system **100**, for example as part of the FPW device **104**. The sensor signal from the FPW device **104** is scaled, at a specific instant in time (or during a period of time), based on the output of the temperature sensor, in order to produce a signal that is independent of the effects of temperature variations. This scaling could be done based on a mathematical model, or an analytical model, or some hybrid combination of a mathematical and analytical model.

[0123] In some embodiments of the system **100**, a filter is included in the path of the test solution to selectively filter particles (e.g., magnetic particles and biological materials) of a particular size to prevent them from entering the fluid chamber. By way of example, a particular testing protocol may include steps for changing the filter during the test. This would allow different types (ie., sizes) of analytes and magnetic particles to be directed into the fluid chamber, and thereby tested by the system **100**, during different portions of the test.

[0124] In one embodiment, magnetic particles (e.g., paramagnetic or super-paramagnetic beads or microspheres), which have their surfaces coated with a capture agent, are

mixed with a sample containing the analyte. After a prescribed mixing time analyte-particle complexes **146** result as do particles **147** that have bound nonspecific materials and particles **148** that have bound nothing. The particles **146**, **147** and **148** are located in the sample reservoir **112**.

[0125] The system **100** further includes a magnetic field inducing structure **150** for producing magnetic flux in the vicinity of the membrane **134**. In FIG. 1A, the source of magnetic flux is a retractable magnet **150** arranged to normally be in close proximity to the membrane **134** of the FPW device **104**. When the magnet **150** is in close proximity to the membrane **134**, the magnet **150** produces a significant gradient magnetic field in the vicinity of the membrane **134**. Under control of the instrument/control electronics **126**, the retractable magnet **150** can be retracted away from the membrane **134** by a distance sufficient to substantially reduce magnetic fields in the vicinity of the membrane **134**. In one embodiment, when in close proximity to the membrane **134**, the magnet **150** is situated approximately 200  $\mu\text{m}$  from the sensor surface **143** of the membrane **134**. In another embodiment, when in close proximity to the membrane, the magnet **150** is situated between about 50  $\mu\text{m}$  to about 100  $\mu\text{m}$  from the sensor surface **143** of the membrane **134**.

[0126] When the magnet **150** is in close proximity to the membrane **134**, the magnet **150** provides a source of magnetic flux to draw the magnetic particles from the sample to the sensor surface **143**. The analyte-particle complexes **146**, as well as particles **147** with nonspecifically bound material and particles **148** with nothing bound, migrate from the liquid sample until they encounter the sensor surface **143**. The analyte binds with the capture agent on the sensor surface **143**. Thus, the analyte forms a link between the magnetic particle and sensor surface. The particles **147** with non-specifically bound material and particles **148** with nothing bound are held at the sensor surface **143** by the magnetic field. Additionally, weak binding forces can act between the particles **146**, **147**, and **148** and the sensor surface **143**. During the wash step of the protocol (described in more detail below), the magnet **150** is retracted to reduce the magnetic force experienced by the particles that have accumulated at the sensor surface **143**. The wash flow rate is increased to remove particles **147** and **148** that are not bound to the surface by analyte. Since the particles **147** with nonspecifically bound material as well as particles **148** with nothing bound are more weakly linked to the sensor surface **143** than the analyte-particle complexes **146**, they release from the sensor surface **143** at a lower wash flowrate (and corresponding hydrodynamic force). Hence, removing the magnet **150** (i.e., substantially reducing the magnetic force experienced by the particles **146**, **147**, and **148** at the sensor surface **143**) is used to distinguish between particles with analyte **146** from those without (particles **147** and **148**). One technique for engaging and retracting the magnet **150** is to mount it on a carriage (not shown) that is actuated by a cam system (not shown).

[0127] The magnet **150** material, geometry and distance from the sensor surface **143** determine the field shape and field gradient, and therefore, the force that the analyte-particle complexes **146** experience. High strength permanent magnets for use as the retractable magnet **150** are available commercially. For example, 1 mm diameter cylindrical NdFeB magnets can be purchased from several vendors (e.g., Dexter Magnetic Technologies). In one embodiment, a

1 mm diameter and 5 mm long NdFeB magnet **150** is positioned within 0.1 mm of the sensor surface **143** when engaged. When retracted the magnet **150** is at least 0.5 mm from the sensor surface **143**. Since the membrane **134** of the FPW device **104** is very thin (2  $\mu\text{m}$ ) and made of nonmagnetic materials (e.g., silicon, aluminum nitride or gold), the membrane **134** does not significantly perturb the magnetic field on the sensor surface **143** side of the device **104**. As a result, very high magnitude magnetic fields and large field gradients can be achieved, as is necessary for high collection efficiencies.

[0128] The sample flow rate through the channels **102** is determined (e.g., specified by an operator) by the residence time necessary for good collection efficiency. The sample flow rate is adjusted so that the average velocity over the sensor surface **143** is between about 1 and about 5 mm/s. With an iron oxide paramagnetic particle with a diameter of approximately 3  $\mu\text{m}$ , collection efficiencies approaching 50% can be achieved.

[0129] Other configurations of the source **150** of magnetic flux (i.e., the magnet) may be used. For example, an electromagnet can be used instead of a permanent magnet. The electromagnet includes pole pieces that extend to focus the field flux near the sensor surface **143** of the device **104**.

[0130] Alternatively, a magnetizable material can be fashioned and positioned adjacent to the sensor surface **143** (within 0.1 mm), and a separate magnet combined with an open face of the magnetizable material to induce a magnetic field in the magnetizable material. The magnetic field induced in the material serves to locate desirable field gradients near the sensor surfaces **143**. In this way, large, low cost magnets can be used, and a single magnet can be used to address multiple sensors, depending on the fashioning of the material. Examples of useful materials for this purpose are pure iron, high  $\mu$  metals such as alloy 49 (high nickel content iron), and silicon steels (1-2% silicon typical). An advantage of using such a magnetizable material with an associated magnet is that the sensor assembly can be simplified, allowing lower cost manufacturing. A low precision actuator can be used for engaging and retracting the magnet since the magnet need only contact the ferromagnetic core or be fully withdrawn. In the described embodiment where the magnet **150** is positioned in close proximity to the sensor surface **143**, a higher level of precision is required to achieve good assay repeatability. Although there is some loss of field strength with this approach, it is still possible to design the overall system to achieve good capture efficiencies (e.g., >10%).

[0131] The shape of the tip of the field inducing structure (e.g., magnet or ferromagnetic material) may be tailored to enhance and/or concentrate the field gradient at the surface. Since the size of the FPW device **104** (e.g., 0.3 mm $\times$ 1.6 mm) is typically smaller than conventionally formed magnets or machined inductors, the portion of the field inducing structure adjacent to the membrane **134** can be tapered to concentrate the magnetic field in one or more locations on the sensor surface **143**. Tapering the tip acts to increase both the local field magnitude and the local field gradients. For example, a wedge-shaped tip is well suited to the current FPW device geometry.

[0132] One embodiment of the system **100** includes an optional second source **150a** of magnetic flux that opposes

or partially opposes the first source **150** of magnetic flux. This second source **150a** of magnetic flux can be used to dislodge some of the magnetic particles that have adhered to the sensor surface **143**. It may, for example, dislodge magnetic particles **148** that do not have any bound analyte; they would not be as strongly attached to the sensor surface **143** as the particles **146** that do have bound analyte. In some embodiments, the first source **150** of magnetic flux is turned off or moved away from the sensor surface **143** and then, the second source **150a** of magnetic flux is positioned relative to the at least one surface of the fluid chamber to selectively remove magnetic particles. This may be done, for example, to remove magnetic particles **148** that do not have any bound analyte and therefore they are not as strongly bound to the sensor surface **143**. This would achieve a similar effect as increasing the flow of fluid to remove magnetic particles **148** that do not have any bound analyte.

[0133] Controlling the distribution of the analyte-particle complexes **146** on the surface **143** of the device **104** can improve the device performance, since the device **104** has a suspended membrane **134** and not all parts of the membrane **134** contribute equally to the moving mass of the detectable resonance. For example, the system **100** can be constructed and arranged to distribute the analyte-particle complexes **146** within one third of the FPW device **104** width along the middle two-thirds of the centerline of the long axis of the membrane **134**. Taking into account flow field effects, the shape of the tip of the field-inducing structure (e.g., magnet **150**) can be such that the field magnitude and field gradient increase in the direction of the flow over the sensor membrane **134**. That is, analyte-particle complexes **146** in the downstream regions, where the boundary layer is partially depleted of analyte, experience a higher field and field gradient than do analyte-particle complexes **146** in the upstream regions.

[0134] In general, the system **100** can be constructed and arranged to concentrate magnetic particles in one or more particular regions of the sensor surface **143**. The response of the device **104** may not be uniform over the sensor surface **143** due to characteristics of the fabrication materials or the specifics of the sensor design. Thus, high sensitivity regions of the device **104** may be non-uniform and asymmetrical with respect to the long and short axis centerlines of the device **104**. Thus, the tip of the field inducing structure may be shaped to concentrate magnetic particles in the region or regions of highest sensitivity.

[0135] Varying the flow rate through the device **104** can also be used to achieve a more uniform coverage of analyte-particle complexes **146** for a given magnetic field distribution. For a given field, magnetic particles interact with the sensor surface **143** as determined by the bulk fluid flow rate, much like a ballistic object might fall in the presence of the gravity body force. In this case, however, the magnetic induced force dominates. By varying the flow rate, the analyte-particle complexes **146** can be caused to interact with the sensor surface **143** at substantially different locations along the stream-wise flow direction. Furthermore, as the magnetic particles pile up (a non-desirable occurrence if they are to be exposed to the sensor surface **143**) the flow can be reversed and subsequently pulsed forward in order to pull the pile over and thus communicate more particles with the sensor surface **143**. In one embodiment of the system **100**, selective location of the magnetic particles along the sensor



surface **143** is achieved by selectively altering, over the course of the detection protocol, either one or both of the magnetic flux source and the property or properties of the fluid flow along the sensor surface **143**.

[0136] One embodiment of the system **100** includes a device (e.g., optical, magnetic) for characterizing at least one property of the magnetic particles that are attached or attracted to the sensor surface **143**. This device could be an integral part of the FPW device **104**, or it could be a part of the magnet **150**, or it could be a discrete component apart from other components of the system **100**. Such a device may be used to detect the presence of the particles, and also to determine parameters related to the particle, for example, the size, quantity, concentration, or density of the particles that are attracted to the sensor surface **143**.

[0137] One embodiment of the system **100** includes an identification device for allowing an operator or computer to identify the system **100** or a particular component of the system for tracking usage of the system or component. The identification device may include a symbol or image such as a bar code, an identification number, or other identifying mark. The identification device may include an actual component, passive or active, such as an RFID tag, an integrated circuit or other such component known in the art for providing identifying information. Many such devices are known in the art, although any contemplated identification device may be used.

[0138] A general detection protocol **200** for using an FPW device **104** in combination with analyte-particle complexes **146** for detection of biological analytes is shown in FIG. 3.

[0139] The first step **202** of the detection protocol **200** is acquiring and preparing **202** the analyte sample. Various preparation processes may need to be performed prior to testing, depending upon the particular type of analyte being tested. For example, to detect microbes in food (e.g., *E. coli* in ground beef), a sample would be first mixed with enrichment broth, stomached, incubated and filtered. For detecting proteins in blood, the sample would first be filtered or centrifuged and the serum separated. Specific examples of test protocols that include sample preparation steps are described herein.

[0140] The next step **204** of the detection process is mixing affinity-coated paramagnetic particles (i.e., beads) with the prepared analyte sample. Paramagnetic or super-paramagnetic particles are available commercially from a number of vendors (e.g., Dynal Biotech, Oslo, Norway). Typical diameters range from 50 nm to 10  $\mu$ m, and such particles can be procured already coated with affinity agents (e.g., antibodies, proteins, and nucleic acid probes) targeting a variety of analytes (e.g., cells, proteins and nucleic acids). Alternatively, the particles can be purchased with various reactive chemical groups (e.g., epoxy, carboxyl, and amine) in order to attach a capture agent of choice. Standard biochemical protocols are available for this purpose.

[0141] The sample with paramagnetic particles added is agitated **206** for an amount of time determined by the particular analyte and capture agent. During this process, the particles bind with analyte so that the analyte is captured on the particles. In some cases, the sample can be tested directly at this point. But, in other cases it is advantageous to perform separation steps **208** to isolate the analyte bound to the

particles from the rest of the original sample. These separation steps **208** reduce interference from other biological material in the assay. Manual or automated equipment for performing such separation steps is available commercially (e.g., Dexter Magnetic Technologies, Dynal Biotech). The basic process uses a magnet to localize the paramagnetic particles on a surface so that the majority of the sample liquid can be aspirated. The magnet (e.g., magnet **150** of FIG. 1A) is then removed, and clean buffer solution is added to re-suspend the particles.

[0142] In one embodiment, a baseline step **210** is executed prior to testing the processed analyte sample with the FPW device **104**. During the baseline step **210**, a reference solution **106** is flowed through the system to rinse/block the sensor **104**, and the instrument/control electronics **126** excite the device **104** and records the resulting initial baseline signal from the device **104**.

[0143] A sample transport step **212** follows the baseline step **210**. The sample **108** containing the analyte-particle complexes **146** is flowed over the sensor surface **143** with the magnet **150** engaged. Analyte-particle complexes **146** are collected on the sensor surface **143**. After a prescribed volume of sample **108** has flowed through the device **104**, the magnet **150** is retracted to release the particles **147** and **148** from the sensor surface **143** that do not have bound analyte, and the flow is switched to a wash solution (e.g., buffer solution **110**). The flow rate of the wash solution is increased to help remove loosely bound particles **147** and **148**, as well as other material in the sample that may have bound to the sensor surface **143**.

[0144] An acquisition step **214** follows the sample transport step **212**. Reference solution **106** is again run through the device **104**, and the instrument/control electronics **126** excite the device **104** to acquire and record a final baseline signal from the device **104**.

[0145] The system **100** determines the amount of analyte accumulated on the sensor surface **143** during the transport step **212** by comparing **216** the initial baseline signal and the final baseline signal, which correspond to the vibrational characteristics of the FPW device **104** in the reference solution before and after, respectively, the acquisition step **214**. Analyte-particle complexes **146** bound to the sensor surface **143** change the vibrational characteristics of the FPW device **104**, and the amount of change to the vibrational characteristics correspond to the amount of analyte-particle complexes bound to the sensor surface **143**.

[0146] FIG. 4 shows the change in the signal from multiple FPW devices **104** as a function of time for an exemplary detection protocol. The square symbols correspond to a device **104** exposed to an analyte; the triangles and stars correspond to negative controls (in which there is no analyte on the beads). The data shown in FIG. 4 (and FIG. 5 as described below) represent an exemplary detection protocol for which the analyte is *E. coli* bacteria, or generally a cellular analyte.

[0147] In this particular experiment, the frequency of a resonant peak was tracked. FIG. 4 shows that the resonant frequency of the FPW device **104** decreases as the magnetic particles **146**, **147** and **148** accumulate on the surface. Once the magnet **150** is removed and some of the magnetic particles are washed away, the frequency of the device **104**



increases. Eventually, the system establishes a final baseline that can be compared to the initial baseline taken at the start of the test, or to that of a control.

[0148] FIG. 5 is a summary plot showing the final signal change detected as a function of original analyte concentration.

[0149] Other detection protocols may be used with the system 100 described above. Individual steps can be eliminated or added depending on the requirements of a specific application or analyte. For example, FIG. 6 shows a time evolution plot for a detection protocol, similar to the one shown in FIG. 4. FIG. 6, however, depicts a detection protocol for a PSA assay, which demonstrates the capability of the system 100 for detecting proteins. Also, the flow direction can be reversed during the protocol. For example, reversing the flow direction may be useful for washing nonspecifically bound material from the device, or for making more efficient use of the available sample.

[0150] Another variation in the detection protocol includes alternating between wash steps and binding steps. This can allow better use of the dynamic range of the device. In some cases, a large fraction of the particles do not have bound analyte, especially at low analyte concentrations. By repeatedly binding and washing away particles, it is possible to accumulate more analyte-particle complexes 146 and, hence, improve the sensitivity of the measurement.

[0151] Changing or manipulating the magnetic field distribution at the sensor surface 143 during the transport step 212 can enhance the probability that the analyte attached to a particular particle encounters the sensor surface 143. For example, if the spatial distribution of the field is alternated during binding, it is possible to cause the paramagnetic particles at the sensor surface 143 to roll. In some embodiments, by controlling the spatial distribution of the field, an operator or the instrument/control electronics 126 can be used to control the rolling of the paramagnetic particles along the sensor surface 143.

[0152] As described above, introducing a second magnetic field (i.e., a second source of magnetic flux) in the system 100 can improve the control of the assay conditions and enhance the specificity of the assay. For example, during the binding or wash steps of the protocol as described above, applying a secondary magnetic field to the sensor surface 143 can act to pull off weakly bound magnetic particles. The strength of the secondary field can be tailored to generate a force on the analyte-particle complexes 146 at the sensor surface 143 that is below the binding force of the specifically bound analyte but above the typical binding force for nonspecifically bound material. This sequence of steps can be repeated multiple times during the assay to further increase the specificity of the test.

[0153] The relative binding strength of the various analyte-particle complexes 146 on the sensor surface 143 can be determined by increasing (continuously or discretely) this magnetic pull-off force during the wash step, while monitoring the response of the FPW device 104. Information on the relative binding strength can be used to distinguish between different analytes in the sample 108.

[0154] The particular way the sample interfaces with the device 104 can be different in other embodiments. In the above-described embodiments, the system 100 flows the

sample through a channel to establish contact between the analyte-particle complexes 146 and the sensor surface 143. In an alternative variation of the system 100, the FPW device 104 is mounted on a probe and at least partially immersed into a test solution containing magnetic particles bound to an analyte. For this embodiment, the immersion is sufficient to place the bound magnetic particles in proximity to the sensor surface 143 so that the particles are attracted toward the sensor surface 143 and subsequently detected, as described herein. To obtain a baseline signal, the device 104 (or cartridge 103) is immersed in a reference test solution. In some embodiments, a portion of the device 104 (e.g., the membrane 134) is mounted to a probe. Further, only part of the sensor surface 143 of the membrane 134 is placed in contact with the solution containing magnetic particles bound to an analyte. In these embodiments, immersion or controlled movement of the probe in the fluid is sufficient to place the bound magnetic particles in proximity to the sensor surface 143 so that the particles are attracted toward the sensor surface 143 and subsequently detected.

[0155] Another alternative embodiment of the system 100 involves mounting the device 104 inside of a tube that can be partially immersed into a well holding the sample 108, and then retracted. A pump applies suction to draw sample into the tube and over the sensor surface 143 (or cartridge 103) when the sample is immersed. The sample is then ejected back into the well by reversing the pump or simply by venting the tube. This cycle of drawing and releasing the sample can be repeated to improve the collection efficiency and, therefore, the performance of the assay.

[0156] The following examples illustrate, for one embodiment of the system 100 described herein, steps for preparing and utilizing the system 100 for detecting an analyte.

## EXAMPLES

### Example I

#### Generalized Method for Capture Agent Functionalization of a Surface of a Flexural Plate Wave Device

[0157] 1. Deposit gold onto the surface (e.g., sensor surface 143) of the flexural plate wave device 104 and clean the gold surface 143 with, for example, oxygen plasma.

[0158] 2. An ideal surface chemistry for the surface 143 of the gold is one that provides 1) non-specific binding resistance and 2) reactive groups located on the surface for covalent attachment of capture agents. An exemplary surface chemistry for the surface 143 of the gold is a self-assembled monolayer (SAM) of alkane thiols. The SAM can be formed from a mixture of two alkane thiols; one terminated with a reactive group for subsequent covalent attachment of capture agents, and one terminated with a non-reactive group. By way of example, a mixture of EG<sub>3</sub>-OH (EG3) and EG<sub>6</sub>-OCH<sub>2</sub>COOH (EG6) terminated C<sub>11</sub>-alkane thiols may be used for this purpose. In one embodiment, the flexural plate wave device 104 (particularly the surface 143 of the device 104) is placed in contact with the alkane thiol solution and allowed to incubate at room temperature for, for example, about 16 hours. The surface 143 of the flexural plate wave device 104 is then rinsed with ethanol and blown dry with nitrogen.

[0159] 3. The next step involves covalent attachment of capture agent or analyte to the surface **143** of the flexural plate wave device **104**. A number of methods may be used for covalent attachment of capture agent or analyte. An exemplary method involves covalently linking a biotin linker moiety to the SAM, then binding a biotinylated antibody or analyte to the flexural plate wave device surface **143** via a streptavidin linking layer.

#### Example II

Detecting *E. coli* O157:H7 In Ground Beef Using, for Example, the Method of FIG. 3 (FIG. 5 Contains Data Representative of Various Concentrations of *E. coli*).

[0160] 1. Prepare an analyte sample containing *E. coli* O157:H7 with a concentration greater than about 100 cfu/mL.

[0161] 2. Concentrate the analyte sample in solution by performing an immunomagnetic separation. A variety of commercial instruments (e.g., Pathatrix by Matrix Microsciences and Bead Retriever by Dynal Biotech) or manual methods may be used to perform the immunomagnetic separation. An exemplary manual method involves:

[0162] a. Resuspend magnetic beads coated with *E. coli* antibody (e.g., Dynabeads anti-*E. coli* O157, available from Dynal Biotech) until the magnetic bead pellet in the bottom of the tube disappears. Place a microcentrifuge tube in the rack (e.g., a Dynal MPC-S) of a magnetic plate. Pipette 1-20  $\mu$ L of magnetic bead stock solution into the tube (the volume of magnetic bead stock selected is based on desired final bead concentration).

[0163] b. Add 1 mL of the analyte sample to the tube in the rack of the magnetic plate and close the tube.

[0164] c. Invert the rack a few times. Incubate the solution in the tube at room temperature for 10 to 60 minutes with gentle continuous agitation to prevent magnetic beads from settling.

[0165] d. Invert the rack several times to concentrate the magnetic beads into a pellet on the side of the tube. Allow about 3 minutes for proper recovery.

[0166] e. Open the tube and carefully aspirate and discard the sample supernatant as well as the remaining liquid in the tube's cap.

[0167] f. Remove the magnetic plate.

[0168] g. Add 1 mL of wash buffer (PBS-Tween) to the tube. Close the cap of the tube and invert the rack a few times to resuspend the beads.

[0169] h. Repeat steps d-g twice.

[0170] i. Mix the contents of the tube briefly using a vortex mixer.

[0171] 3. Detection of *E. coli* O157:H7

[0172] a. Functionalize (similarly as described by the steps in A.3 and A.4) the surface **143** of a flexural plate wave device **104** with *E. coli* O157:H7 antibody.

[0173] b. Place a first inlet hose into a tube containing standard wash buffer (1 $\times$  PBS with 0.05% Tween 20) and a

second inlet hose into the tube containing the magnetic beads bound with *E. coli* O157:H7 (prepared in B.2). The first inlet hose and second inlet hose are joined by a t-joint so the two hoses are in fluid communication and fluid from either the first inlet hose or from the second inlet hose is directed to an inlet of the fluid chamber **160**. Each of the two hoses has a valve that is capable of permitting or limiting the flow of fluid through respective hoses.

[0174] c. Place a first outlet hose in fluid communication with an outlet of the fluid chamber **160**. Fluid from the first outlet hose is collected in a waste collection bottle.

[0175] d. A baseline output signal is obtained using the flexural plate wave device. The baseline signal is measured with standard wash buffer flowing into the fluid chamber **160** and out of the fluid chamber **160** for about 5 minutes at a standard pump speed (e.g., 200  $\mu$ L/min).

[0176] e. The first source of magnetic flux **150** is engaged, and then fluid from the tube containing the analyte is directed into the inlet of the fluid chamber **160**. Fluid is directed into the inlet of the fluid chamber **160** to accumulate magnetic beads bound with *E. coli* O157:H7 on the at least one surface **143** of the flexural plate wave device **160** until a desired amount is attached to the at least one surface **143**. In one embodiment, the desired amount is achieved when, for example, there is a frequency shift in the output of the flexural plate wave device **104** of about 4000 ppm.

[0177] f. The flow of fluid from the tube containing the analyte is then discontinued. Fluid from the wash buffer tube is then directed into the fluid chamber **160** to wash away nonspecifically bound material (i.e., materials other than 1) magnetic beads and 2) magnetic beads with bound analyte).

[0178] g. The first source of magnetic flux **150** is then disengaged.

[0179] h. Initiate automatic wash protocol to remove any magnetic beads or matrix components.

[0180] i. The final signal output by the flexural wave plate device **104** is then measured. The baseline signal is compared with the final signal to determine the concentration of *E. coli* O157:H7 in the analyte sample.

#### Example III

Detecting Prostate Specific Antigen (PSA) in Human Blood Serum Using, for Example, the Method Steps of FIG. 3.

[0181] 1. Prepare an analyte sample containing human serum obtained by centrifugation from a human blood sample.

[0182] 2. Concentrate the analyte sample in solution by performing an immunomagnetic separation. A variety of commercial instruments (e.g., Pathatrix by Matrix Microsciences and Bead Retriever by Dynal Biotech) or manual methods may be used to perform the immunomagnetic separation. An exemplary manual method involves:

[0183] a. Resuspend magnetic beads coated with PSA antibody (e.g., Dynabeads anti-PSA, available from Dynal Biotech) until the magnetic bead pellet in the bottom of the tube disappears. Place a microcentrifuge tube in the rack (e.g., a Dynal MPC-S) of a magnetic plate. Pipette 1-20  $\mu$ L

of magnetic bead stock solution into the tube (the volume of magnetic bead stock selected is based on desired final bead concentration).

[0184] b. Add 1 mL of the analyte sample to the tube in the rack of the magnetic plate and close the tube.

[0185] c. Invert the rack a few times. Incubate the solution in the tube at room temperature for 10 to 60 minutes with gentle continuous agitation to prevent magnetic beads from settling.

[0186] d. Invert the rack several times to concentrate the magnetic beads into a pellet on the side of the tube. Allow about 3 minutes for proper recovery.

[0187] e. Open the tube and carefully aspirate and discard the sample supernatant as well as the remaining liquid in the tube's cap.

[0188] f. Remove the magnetic plate.

[0189] g. Add 1 mL of wash buffer (PBS-Tween) to the tube. Close the cap of the tube and invert the rack a few times to resuspend the beads.

[0190] h. Repeat steps d-g twice.

[0191] i. Mix the contents of the tube briefly using a vortex mixer.

[0192] 3. Detection of PSA

[0193] a. Functionalize (similarly as described by the steps in A.3 and A.4) the surface 143 of a flexural plate wave device 104 with PSA antibody.

[0194] b. Place a first inlet hose into a tube containing standard wash buffer (1× PBS with 0.05% Tween 20) and a second inlet hose into the tube containing the magnetic beads bound with PSA (prepared in B.2). The first inlet hose and second inlet hose are joined by a t-joint so the two hoses are in fluid communication and fluid from either the first inlet hose or from the second inlet hose is directed to an inlet of the fluid chamber 160. Each of the two hoses has a valve that is capable of permitting or limiting the flow of fluid through respective hoses.

[0195] c. Place a first outlet hose in fluid communication with an outlet of the fluid chamber 160. Fluid from the first outlet hose is collected in a waste collection bottle.

[0196] d. A baseline output signal is obtained using the flexural plate wave device 104. The baseline signal is measured with standard wash buffer flowing into the fluid chamber 160 and out of the fluid chamber 160 for about 5 minutes at a standard pump speed (e.g., 200  $\mu$ L/min).

[0197] e. The first source of magnetic flux 150 is engaged, and then fluid from the tube containing the analyte is directed into the inlet of the fluid chamber 160. Fluid is directed into the inlet of the fluid chamber 160 to accumulate magnetic beads bound with PSA on the at least one surface 143 of the flexural plate wave device 104 until a desired amount is attached to the at least one surface 143. In one embodiment, the desired amount is achieved when, for example, there is a frequency shift in the output of the flexural plate wave device 104 of about 4000 ppm.

[0198] f. The flow of fluid from the tube containing the analyte is then discontinued. Fluid from the wash buffer tube is then directed into the fluid chamber 160 to wash away

nonspecifically bound material (i.e., materials other than 1) magnetic beads and 2) magnetic beads with bound analyte).

[0199] g. The first source of magnetic flux 150 is then disengaged.

[0200] h. Initiate automatic wash protocol to remove any magnetic beads or matrix components.

[0201] i. The final signal output by the flexural wave plate device 104 is then measured. The baseline signal is compared with the final signal to determine the concentration of PSA in the analyte sample.

#### Example IV

##### PSA in Calibrator I

[0202] By way of illustration, an experiment was conducted in which data was acquired using the system 100 of FIG. 1A, according to principles of the present invention. Dynal tosyl-activated super paramagnetic beads, functionalized with anti-Prostate Specific Antigen (PSA) capture antibody (PN 90205, Scripps Laboratories Inc. with offices in San Diego, Calif.) were exposed to samples. The samples comprised 1× PBS (Phosphate Buffered Saline) and 1% Bovine Serum Albumin (BSA), spiked with approximately 0 pg/mL, 10 pg/mL, 100 pg/mL and 500 pg/mL of free PSA [Fitzgerald Industries International, Inc. with offices in Concord, Mass.]. A bead concentration on the order of approximately  $2 \times 10^4$  beads/mL with respect to sample was used in the experiment. Spiked samples were incubated with beads with gentle continuous agitation for 1 hour.

[0203] Eight of the Flexural Plate Wave (FPW) devices 104 of FIG. 2 provided on a single chip in a cartridge (not shown) were functionalized with complimentary anti-PSA antibodies (PN 90197, Scripps Laboratories Inc. with offices in San Diego, Calif.) after being first primed with 1× PBS containing 0.05% Tween 20 (polyethylene glycol sorbitan monolaurate) [Sigma-Aldrich Co. with offices in St. Louis, Mo.].

[0204] Data was acquired and analyzed as described for example, in the U.S. patent application entitled "Methods and Apparatus for Assay Measurements" by Masters et al. filed on May 2, 2006 (Attorney Docket Number BIO-008). A baseline measurement (similarly as described previously herein) of eight individual frequencies, each corresponding to tracked sensor phases, each with respect to reference signals, was made at about 17800 seconds. Tracking phases are initially selected for each device to be within a resonance band of the device, near a frequency where the magnitude of response is near a peak value and where the phase response has significant linear range with respect to frequency change. When tracking the sensor phases, at each time point, individual device tracking frequencies are found by 1) sweeping each device over a range of frequencies and recording the phase of response at each excitation frequency with respect to a reference signal, 2) fitting a function relating excitation frequencies to measured phase for each device, and 3) using that function to compute the tracking frequency corresponding to the previously determined tracking phase.

[0205] In this embodiment, the devices are operated near 20 MHz and the sweep range is approximately 20 kHz. Over this range, the phase characteristic is substantially linear

allowing the fit function to be linear. The reference signal for each device comprises the output of a network of passive electrical components, resistors and capacitors, simultaneously driven by the excitation. The reference network is selected to match the attenuation and provide a preferred phase shift for the devices near resonance. Baseline frequencies are referenced to, and normalized by, the tracked frequency and are shown as parts per million (ppm) at a selected point in time.

[0206] The sensing surface **143** of each device **104** was functionalized with capture agent. Gold coated chips were cleaned using an oxygen plasma source in which typical processing conditions were about 50 W for about 2 minutes. The chips were subsequently immersed in pure ethanol for 30 minutes. Next, the chips were transferred to a 0.5 mM solution of biotin PEG disulfide solution (Cat No. 41151-0895, Polypure AS with offices in Oslo, Norway) in ethanol and allowed to incubate overnight. The chips were transferred back into a pure ethanol solution for 30 minutes. The chips received a brief, final ethanol rinse and were blown dry using a nitrogen stream. Variations on preparation conditions can be made with similar results achieved.

[0207] The resultant biotinylated surface of the devices **104** was coated with Neutravidin (PN 31000, Pierce Biotechnology, Inc. with offices in Rockford, Ill.) by flowing a 10 µg/ml solution of neutravidin over the biotinylated surface for 1 hour. Antibody was biotinylated according to the manufacturer's instructions (PN F-6347, Invitrogen Corporation with offices in Carlsbad, Calif.) and then coupled to the neutravidinated surface, by flowing 5 µg/ml solution of the biotinylated antibody (diluted into 1× PBS 0.1% BSA buffer), over the neutravidin coated surface for 1 hour.

[0208] PSA sample was introduced and simultaneously a magnetic field was generated near the sensor surfaces **143** from about 17900 to about 18200 seconds. Samples of approximately 0 pg/mL, 10 pg/mL, 100 pg/mL and 500 pg/mL of free PSA were each provided to two different devices **104** (total of eight devices). The samples were flowed over the sensors at approximately 100 µL/min for a total sample run/volume of 500 µL flowing over the sensors. In this manner, Dynal tosyl-activated super paramagnetic beads coated with free PSA were bound to a substantial surface (surface **143**) of the devices **104**. Each bead was bound to the surface **143** of the devices **104** by a plurality of bonds. Each plurality of bonds giving rise to the discriminatory force with which each binds to the surface of the device. The characteristic of association and dissociation of an ensemble of beads for each sample determines the concentration of analyte in that sample.

[0209] At approximately 18200 seconds the sample was replaced with priming buffer (1× PBS, 0.05% Tween 20 (polyethylene glycol sorbitan monolaurate)). As shown in FIG. 11, a change (see location **30**) in each of the signals was observed from 18200 seconds to 18400 seconds and represents the change in bulk fluid properties associated with switching from the sample fluids back to the buffer fluid. At approximately 18400 seconds the magnetic field was disengaged. The flow speed of the buffer fluid (1× PBS containing 0.05% Tween 20) was approximately 50 µL/minute between about 18200 seconds and 18400 seconds (corresponding to a flow speed of approximately 1.5 mm/second at the sensor surface **143**).

[0210] The flow speed was increased over the next 450 seconds (from about 18400 seconds to about 18850) from approximately 50 µL/min to approximately 300 µL/min in linear increments (the flow speed was increased by about 17 µL/min every 30 seconds for 450 seconds then the flow speed was reduced to approximately 50 µL/min). In this manner, a controlled external influence (i.e., the flow speed in this embodiment) was applied to the beads by increasing the flow speed between about 18400 and about 18850 seconds). The portion of curves between about 18400 and about 18850 seconds represents a signal that is indicative of the change in the amount of beads (and other non-specific material) bound to the sensor surfaces **143** over that time period.

[0211] FIG. 11 is a graphical illustration of a plot of the data acquired versus time. The Y-Axis of the plot is the change in relative magnitude of the signal output by the device **104** (in parts per million) at a tracked sensor phase near the resonance of the device **104**. The X-Axis of the plot is time in units of seconds. The plot is the change in tracked frequency referenced to and normalized by a tracked frequency at a selected point in time.

[0212] The data for each curve shown in parts per million of tracked frequency, was further normalized by the value of that curve at about 18350 seconds and referenced to the baseline frequency that was measured before introduction of the sample fluid. Each data curve was thereby scaled to a value of 100% at about 18350 seconds compared to when sample is introduced. The data associated with each of the normalized curves was then integrated with respect to time over the 450 seconds (from about 18400 seconds to about 18850 seconds) after the magnetic field was removed at about 18400 seconds.

[0213] The integration was performed by accumulating respective device signal levels, each interval level multiplied by the respective interval time periods, and dividing the final sum by the period over which the sum was performed. This provides the time normalized amount of material elements (beads) bound to the surfaces **143** of the devices, and these values are shown here to be a measure of concentration of analyte associated with each sample. In this manner, the concentration of analyte is determined based on the change in the amount of material elements bound to the surfaces **143** of each device **104** during the period of time between about 18400 seconds to about 18850 seconds. As shown in FIG. 11, approximately 10 pg/mL of free PSA was detected within less than about 9 minutes of introducing the sample into the system.

[0214] In some embodiments, data points are omitted that are, for example, outside the normal variation observed in the curves. For example, spurious data points that vary by more than an order of magnitude in value relative to adjacent data points may be omitted from subsequent analysis. The data points may be removed from the data by, for example an operator or by a computer program.

#### Example V

##### Competitive Assay for Estradiol in Serum

[0215] A sheep monoclonal antibody specific for free estradiol was coupled to Dynal M280-tosyl activated beads using standard methods.

[0216] A sensor surface was constructed by coupling disulphide-PEG-biotin to the gold sensor surface, then cou-

pling Neutravidin (Pierce PN 31000) and then biotinylated antibody was performed as described above.

[0217] BSA coupled Estradiol, E2-6-CMO-BSA (Sigma PN E5630) was then coupled to the antibody surface by flowing 10 ug/ml BSA coupled estradiol diluted in 1x PBS buffer over the antibody surface for 1 hour. Since the estradiol is coupled to multiple amine sites on the BSA (30 mols of estradiol per mol of BSA) the aforementioned approach provides for a moderately dense small molecule surface presented to solution.

[0218] Sample solutions comprising 70% charcoal striped human serum (Texas Biologicals), 30% 1x PBS 0.05% Tween 20 (polyethylene glycol sorbitan monolaurate), were made with free estradiol (Sigma) spiked in at 0 pg/ml, 10 pg/ml, 30 pg/ml, 200 pg/ml. Beads, in concentration  $\sim 2^4$ /ml were incubated with sample for 2 hrs. The beads were then flowed over the FPW using typical protocol and results obtained in approx 0.5 hrs.

[0219] In some samples danazol was also added as an decomplexing antagonist, to remove any interfering molecules such as Sex Hormone Binding Protein from the estradiol. Approximately 10-100 ng/ml levels were added.

[0220] Sample was flowed over the FPW at approximately 70  $\mu$ L/min with magnetic field engaged and beads were accumulated on the sensor surfaces. A wash protocol beginning at 50  $\mu$ L/min, ending at 500  $\mu$ L/min, with 50  $\mu$ L/min intervals every 30 seconds was used to wash the bound beads off the sensor surfaces. FPW signals were normalized by exposure levels giving normalized signals, and these signals were integrated over the wash period. As shown in FIG. 12, less than 10 pg/mL can be detected in the presence of the antagonist additive 36, and less than 50 pg/mL can be detected in the absence of the antagonist additive 34.

[0221] As shown in FIG. 12, estradiol concentrations ranging from 1,000 pg/mL to 10 pg/mL were detected.

#### Example VI

##### Competitive Assay for FK-506

[0222] 1. FK-506 was added to 2 ml of buffer (0.05% 1x PBS Tween 20 containing 1% BSA) to produce analyte samples with FK-506 concentrations of 0, 0.5, 2.0, and 20 ng/ml.

[0223] 2. Eight  $\mu$ L of  $1 \times 10^7$ /ml anti-FK-506 IgM coated beads prepared as described above were added to each sample and incubated for 30-60 min. at room temperature. The beads are prepared by coupling anti-FK-506 IgM (Fitzgerald Industries Intl) to paramagnetic beads according to the manufacturer's instructions (Invitrogen Corporation). The analyte samples were concentrated in solution as described above.

[0224] 3. Five hundred  $\mu$ L of a solution comprising carrier (HRP) labeled with FK-506 (Diasorin Inc.) were added to the sample and incubated for 60 min. at room temperature.

[0225] 4. The samples were analyzed using an FPW device where the sensor was functionalized with capture agent (anti-FK-506 IgM). Referring to FIG. 10, the sensor 12 was functionalized with neutravidin 30 as described above, and anti-FK-506 IgM was biotinylated 32 using standard biotinylation methods. As shown in panel B of FIG.

10, analyte 10 (in this instance FK-506) was mixed with competitor molecule 24 and particles 16 labeled with capture agent 14 (in this instance anti-FK-506 antibody). For this example, the competitor molecule 24 comprised the carrier HRP labeled with the analyte FK-506). As shown in panels C and D, a lower level of FK-506 in the sample is expected to allow the particles to bind to the competitor molecule and thereby to bind to the sensor surface. A higher level of FK-506 is expected to result in fewer particles binding to the sensing surface because more of the particles will be bound to FK-506 from the sample. As shown in FIGS. 13 and 14, FK-506 concentrations ranging from 0.5 ng/ml to 20 ng/ml were detected in as little as 15 min from introducing the sample into the device.

#### Example VII

##### Competitive Assay for FK-506 in Processed Human Whole Blood Matrix

[0226] 1. Four samples each of one 100  $\mu$ L of blood was spiked with 0, 3, 10, or 30 ng/ml FK-506. The drug was extracted from the blood matrix by performing a protein digestion protocol according to the manufacturer's instructions (Diasorin Inc.).

[0227] 2. Six hundred microliters of protein digestion reagent was added to each sample.

[0228] 3. The sample was mixed by vortexing, and incubated for 15 min. at room temperature (about 23° C.), producing a semi-transparent mixture.

[0229] 4. The digestion reaction was stopped by incubating the samples at 75° C. for 35 min, producing a dark brown mixture.

[0230] 5. The sample was mixed by vortexing and centrifuged at 1800 g for 10 min, producing 500-600  $\mu$ L of supernatant.

[0231] 6. Five hundred microliters of supernatant was transferred into a new tube, the four samples the same concentration of FK-506 were combined in one tube, producing 2 ml of supernatant for each concentration of FK-506.

[0232] 7. The samples were analyzed as described above. As shown in FIGS. 15 and 16, FK-506 concentrations ranging from 0.5 ng/ml to 20 ng/ml were detected in as little as 8 min from introducing the sample into the device.

[0233] The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are therefore to be considered in respects as illustrative and not restrictive, the scope of the invention being indicated the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of the equivalency of the claims are therefore intended to be embraced herein.

1. A method for detecting estradiol in a sample, the method comprising the steps of:

a) introducing a plurality of particles coated with a capture agent capable of binding estradiol into a fluid

chamber, wherein at least one surface of the fluid chamber comprises an acoustic device having estradiol bound thereto, and

b) monitoring signal output by said acoustic device, thereby detecting estradiol in the sample.

2. The method of claim 1, wherein the acoustic device is a flexural plate wave device.

3. The method of claim 1, wherein an increased level of estradiol compared to a reference is indicative of the individual having an increased likelihood of developing breast cancer.

4. The method of claim 1, wherein prior to being introduced into the fluid chamber, said plurality of particles has been exposed to the sample.

5. The method of claim 1, wherein the sample has been introduced into the fluid chamber prior to introducing the plurality of particles.

6. The method of claim 1, wherein the particles are magnetic and further comprising creating a magnetic flux in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward the at least one surface.

7. The method of claim 6, wherein the magnetic flux is removed prior to step b).

8. The method of claim 1, wherein the estradiol is present in the sample at a concentration of about 10 pg/ml.

9. The method of claim 1, wherein the estradiol is selected from the group consisting of free estradiol, sex hormone-binding globulin (SHBG)-bound estradiol, estrone-3-glucuronide, and estradiol-3-glucuronide.

10. The method of claim 1, wherein the sample is selected from the group consisting of blood, serum, plasma, urine, saliva, and biopsy material.

11. The method of claim 1, further comprising comparing the signal output of b) to a control signal.

12. The method of claim 11, wherein the control signal is a standard curve.

13. The method of claim 11, wherein the control signal is obtained in the absence of sample.

14. The method of claim 1, wherein the estradiol is indirectly bound to said surface.

15. The method of claim 14, wherein said surface is coated with a first member of a binding pair, and the estradiol is bound to a second member of the binding pair.

16. The method of claim 15, wherein the binding pair is selected from the group consisting of biotin/avidin, biotin/streptavidin, and biotin/neutravidin.

17. The method of claim 1, wherein the capture agent is an antibody.

18. A method for detecting estradiol in a sample, the method comprising the steps of:

a) introducing a plurality of particles and a competitor molecule into a fluid chamber, said particles being coated with a first capture agent capable of binding estradiol, wherein at least one surface of the fluid chamber comprises an acoustic device that has been coated with a second capture agent capable of binding to the competitor molecule, and

b) monitoring signal output by said acoustic device, thereby detecting estradiol.

19. The method of claim 18, wherein the acoustic device is a flexural plate wave device.

20. The method of claim 18, an increased level of estradiol compared to a reference is indicative of the individual having an increased likelihood of developing breast cancer.

21. The method of claim 18, wherein prior to being introduced into the fluid chamber, said plurality of particles has been exposed to the sample and to the competitor molecule.

22. The method of claim 21, wherein the competitor molecule comprises estradiol bound to a tag and the second capture agent is capable of binding to the tag.

23. The method of claim 22, wherein the tag is biotin.

24. The method of claim 19, wherein the competitor molecule comprises two or more estradiol molecules bound to a carrier, and the second capture agent is capable of binding estradiol.

25. The method of claim 24, wherein the carrier is a selected from the group consisting of horseradish peroxidase and albumin.

26. The method of claim 18, wherein the particles are magnetic and further comprising creating a magnetic flux in proximity to the acoustic device to attract at least one of the plurality of magnetic particles toward the at least one surface.

27. The method of claim 26, wherein the magnetic flux is removed prior to step b).

28. The method of claim 18, wherein the estradiol is present in the sample at a concentration of about 10 pg/ml.

29. The method of claim 18, wherein the estradiol is selected from the group consisting of free estradiol, sex hormone-binding globulin (SHBG)-bound estradiol, estrone-3-glucuronide, and estradiol-3-glucuronide.

30. The method of claim 18, wherein the sample is selected from the group consisting of blood, serum, plasma, urine, saliva, and biopsy material.

31. The method of claim 18, further comprising comparing the signal output of b) to a control signal.

32. The method of claim 31, wherein the control signal is generated in the absence of sample.

33. The method of claim 31, wherein the control signal is a standard curve.

34. The method of claim 18, wherein the capture agent is indirectly bound to the at least one surface of the fluid chamber.

35. The method of claim 34, wherein the at least one surface is coated with a first member of a binding pair, and the capture agent is bound to a second member of the binding pair.

36. The method of claim 35, wherein the binding pair is selected from the group consisting of biotin/avidin, biotin/streptavidin, and biotin/neutravidin.

专利名称(译)	使用声学装置检测雌二醇及其代谢物的方法和装置		
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# 摘要(译)

提供了检测样品中雌二醇及其代谢物的方法。将多个颗粒（每个颗粒涂覆有对雌二醇具有亲和力的捕获剂）与样品组合以形成多个雌二醇 - 颗粒复合物。该系统还包括用于将样品和/或颗粒输送到传感器表面的输送装置，以及可选的磁场诱导结构，其构造和布置成在传感器表面处和附近建立磁场。共振传感器产生对应于与传感器表面结合的雌二醇 - 颗粒复合物的量的信号。

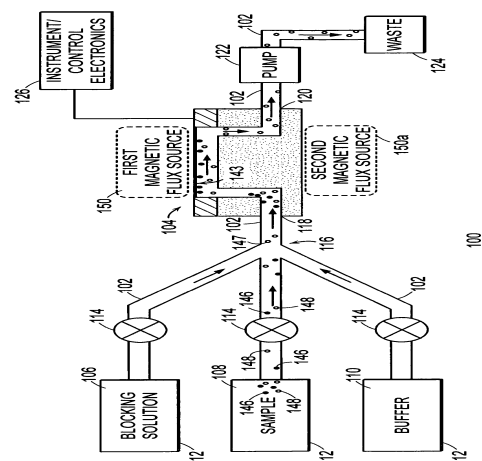


FIG. 1A