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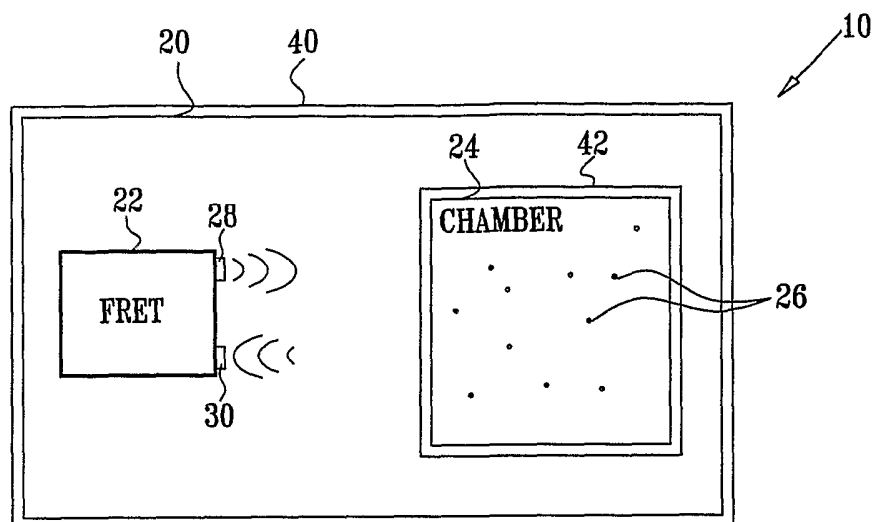
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(54) Title: **IMPLANTABLE POWER SOURCES AND SENSORS**

(57) Abstract: A protein is provided, including a glucose binding site, cyan fluorescent protein (CFP), and yellow fluorescent protein (YFP). The protein is configured such that binding of glucose to the glucose binding site causes a reduction in a distance between the CFP and the YFP. Substance monitoring apparatus (210) is also provided, including a semi-permeable barrier (212), adapted to be implanted in a body of a subject and to allow passage therethrough of a substance, while inhibiting passage therethrough of immune cells; and microorganisms (214), disposed within the semi-permeable barrier (212) so as to produce a measurable response to a level of the substance. A sensor (220) is adapted to measure the measurable response and not to measure a response of any mammalian cells that may be disposed within the semi-permeable barrier (212).

IMPLANTABLE POWER SOURCES AND SENSORS

CROSS-REFERENCES TO RELATED APPLICATIONS

The present application claims the benefit of: (i) US Provisional Patent Application 60/658,716, filed March 3, 2005, entitled, "Implantable power sources and sensors," and (ii) US Provisional Patent Application 60/588,211, filed July 14, 2004, entitled, "Implantable sensor." Both of these applications are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to implantable power sources and sensors, and specifically to implantable bio-fuel cells and methods and apparatus for sensing blood glucose concentrations.

BACKGROUND OF THE INVENTION

Fluorescence resonance energy transfer (FRET) is the transfer of photon energy from an excited fluorophore (the donor) to another fluorophore (the acceptor) without the emission of a photon, when the donor and acceptor molecules are in close proximity to each other. FRET enables the determination of the relative proximity of the molecules, for investigating, for example, molecular interactions between two protein partners, structural changes within one molecule, and ion concentrations. Fluorescent proteins (FPs) can be genetically fused to proteins of interest and expressed in cells. FP pairs useful for performing FRET measurements in living cells include cyan fluorescent protein (CFP) as the donor, and yellow fluorescent protein (YFP) as the acceptor, because the emission spectrum of CFP partially overlaps the excitation spectrum of YFP.

US Patent 3,837,339 to Aisenberg et al., which is incorporated herein by reference, describes techniques for monitoring blood glucose levels, including an implantable glucose diffusion-limited fuel cell. The output current of the fuel cell is proportional to the glucose concentration of the body fluid electrolyte and is therefore directly indicative of the blood glucose level. This information is telemetered to an external receiver which generates an alarm signal whenever the fuel cell output current exceeds or falls below a predetermined current magnitude which represents a normal

blood glucose level. Valve means are actuated in response to the telemetered information to supply glucose or insulin to the monitored living body.

US Patent 3,861,397 to Rao et al., which is incorporated herein by reference, describes an implantable fuel cell that uses an oxidizable body substance, preferably
5 glucose, as well as oxygen from the body fluids.

US Patent 4,140,963 to Rao et al., which is incorporated herein by reference, describes a device for measuring blood sugar levels, including an electrochemical glucose cell that produces an electrical signal corresponding to the sugar concentration. The glucose cell produces in conjunction with a sugar solution (as electrolyte) an electrical
10 signal which represents a measure of the present sugar concentration value. The cell can be operated, for example, by an outer source of current, a battery, or a fuel cell, for example a glucose-oxygen cell. The cell itself can also provide its own current; it may be constructed, for example, as a glucose-oxygen-fuel cell or as a glucose/silver/silver-chloride cell.

US Patent 3,837,922 to Ng et al., which is incorporated herein by reference, describes an implantable fuel cell power source for an artificial heart or pacemaker device which utilizes blood carbohydrates as the anode fuel. The cathode of the implantable fuel cell is an oxygen utilizing cathode, and may be air breathing, for example, following
15 being ventilated through a percutaneous airway by a balloon system. The anode is separated from the whole venous blood by a thin, porous membrane capable of passing a blood ultra-filtrate containing the oxidizable organics.
20

US Patent 3,774,243 to Ng et al., which is incorporated herein by reference, describes an implantable hybrid power system for artificial hearts or pacemakers, which includes a fuel cell assembly air-breathing cathode assembly. A storage battery is
25 combined with a fuel cell for peak power requirements and for more nearly steady-state fuel cell operation. The fuel cell may have either an external anode fuel source, such as hydrogen or hydrazine, or utilize blood carbohydrates, such as glucose. Electrical output from the power system is used to power any desired type of artificial heart or pacemaker device.

US Patent 6,294,281 and US Patent Application Publication 2002/0025469 to Heller, which are incorporated herein by reference, describe a fuel cell having an anode and a cathode, with an anode enzyme disposed on the anode and a cathode enzyme
30

disposed on the cathode. The fuel cell typically uses as fuel compounds available in a biological system. The fuel for the operation of the fuel cell may be provided by compounds in blood, sap, and other biological fluids or solids. Such compounds may include, for example, sugars, alcohols, carboxylic acids, carbohydrates, starches, 5 cellulose, and dissolved or complexed oxygen (e.g., oxygen complexed with a biomolecule such as hemoglobin or myoglobin). Examples of compounds for electroreduction or electrooxidation in the operation of a fuel cell in an animal include glucose or lactate at the anode and oxygen, dissolved as molecular oxygen or bound in hemoglobin or myoglobin, at the cathode.

10 US Patent Application Publication 2004/0091757 to Wang et al., which is incorporated herein by reference, describes an implantable fuel cell assembly containing a device for converting fat to glycerol and fatty acid, a device for converting glycerol to hydrogen, a device for converting fatty acid to hydrogen, a device for converting a bodily fluid to a gas selected from the group consisting of hydrogen, oxygen, and mixtures 15 thereof, and a fuel cell for producing electricity from hydrogen and oxygen.

US Patent 5,660,940 to Larsson et al., which is incorporated herein by reference, describes a method for producing electric energy in a biofuel-powered fuel cell, the metal in the first acid metallic salt solution forming a redox pair having a normal potential between -0.1 and 0.7 V and the metal in the second acid metallic salt solution forming a 20 redox pair having a normal potential between 0.7 and 1.3 V, both metals preferably being vanadium which forms the redox pairs vanadium(IV)/(III) and vanadium (V)/(IV), respectively.

US Patent 4,578,323 to Hertl et al., which is incorporated herein by reference, describes a fuel cell which produces electricity from the anaerobic oxidation of hydroxylic 25 compounds, e.g. alcohols and sugars, in the presence of a quinone. For applications in which the fuel used has a greater affinity for its electrons than the quinone compound in its ground state, the oxidation half cell mixture must be irradiated with light energy.

US Patents 5,368,028 and 5,101,814 to Palti, which are incorporated herein by reference, describe methods and apparatus for monitoring blood glucose levels by 30 implanting glucose sensitive living cells, which are enclosed in a membrane permeable to glucose but impermeable to immune system cells, inside a patient. Cells that produce detectable electrical activity in response to changes in blood glucose levels are used in the

apparatus along with sensors for detecting the electrical signals, as a means for detecting blood glucose levels. Human beta cells from the islets of Langerhans of the pancreas, sensor cells in taste buds, and alpha cells from the pancreas are discussed as appropriate glucose sensitive cells.

5 US Patents 6,091,974 and 5,529,066 to Palti, which are incorporated herein by reference, describe a capsule for encapsulating implantable cells for improving the detectability of electrical signals generated by the cells. The capsule includes a low-conductivity (high electrical resistance) membrane and a semi-permeable (low electrical resistance) membrane. The low-conductivity membrane seals around the circumference
10 of the cell mass between the electrical poles of the capsule, and further extends for increasing the electrical resistance between the poles. The semi-permeable membrane enables nutrients and waste materials to flow to and from the cell mass. The semi-permeable membrane encloses at least one of the poles of the cell mass, and cooperates with the low-conductivity membrane to completely enclose the cell mass. The low-
15 conductivity membrane may enclose one of the poles, if desired. Electrodes are used to detect the electrical signals from the cell mass.

US Patent Application 2002/0038083 to Houben and Larik, which is incorporated herein by reference, describes methods and apparatus for monitoring blood glucose levels by implanting glucose sensitive living cells, which are enclosed in a membrane permeable
20 to glucose but impermeable to immune system cells, inside a patient. The living cells come from the islets of Langerhans of the pancreas and have been genetically engineered so as to grow on a substrate containing interdigitated electrodes, which serves as a sensor of cellular electrical activity.

US Patent 6,605,039 to Houben and Larik, which is incorporated herein by
25 reference, describes methods and apparatus for monitoring blood glucose levels by implanting glucose sensitive living cells, which are enclosed in a membrane permeable to glucose but impermeable to immune system cells, inside a patient. The heat response of cells from the islets of Langerhans of the pancreas to glucose levels is proposed as a glucose sensor along with measurements of the membrane impedance of pancreatic B-
30 cells as a result of glucose exposure.

US Patent 6,650,919 to Edelberg and Christini, which is incorporated herein by reference, describes methods and apparatus for monitoring physiological or

pathophysiological variables in a living organism by implanting tissue or cells capable of carrying out physiological or pathophysiological functions. Particular applications involving the use of cardiac or neuronal tissue to monitor cardiac function and health are discussed.

5 US Patent 6,368,592 to Colton et al., which is incorporated herein by reference, describes techniques for supplying oxygen to cells in vitro or in vivo by generating oxygen with an oxygen generator that electrolyzes water to oxygen and hydrogen. The oxygen generator may be used to supply oxygen to cells contained in an encapsulating chamber for implanting in the body such as an immunoisolation chamber bounded by a
10 semipermeable barrier layer that allows selected components to enter and leave the chamber. A bioactive molecule may be present with the cells. US Patent Application Publication 2003/0087427 to Colton et al., which is incorporated herein by reference, describes similar techniques.

US Patent 5,443,508 to Giampapa, which is incorporated herein by reference,
15 describes an implantable biological agent delivery system. The system includes a pod adapted for subcutaneous implantation beneath the dermis of the skin. The pod includes a porous surface and has at least one internal chamber which is in fluid communication with the porous surface. The system includes a dome adapted to be detachably secured to the chamber. The dome includes interior chambers, each in fluid communication with the
20 interior of the pod. Prior to implantation, the chambers are loaded with bioactive agents, such as hormones, enzymes, biologic response modifiers, free radical scavengers, or genetically altered cell cultures. Time-release micropumps pump the agents into the interior chambers of the pod for transmission through the porous surfaces into a growth factor-stimulated capillary matrix and then to the bloodstream of the subject. The pod
25 may be removed, refilled, and resecured to the dome upon exhaustion of its contents or upon medical requirement for changes in medication, or may be percutaneously refilled in situ through injection into the dome. The surface of the pod may be treated with one or more vascular growth factors or related biologic molecules.

US Patent 5,614,378 to Yang et al., which is incorporated herein by reference,
30 describes a photobioreactor system for oxygen production for a closed ecological life support system. The photobioreactor is described, among other things, as being useful for converting carbon dioxide to oxygen in an artificial lung.

US Patent 4,721,677 to Clark, Jr., which is incorporated herein by reference, describes an implantable biosensor and method for sensing products, such as hydrogen peroxide, generated from an enzymatic reaction between an analyte, like glucose, and an enzyme in the presence of oxygen. The biosensor is equipped with an enclosed chamber
5 for containing oxygen and can be adapted for extracting oxygen from animal tissue adjacent the container. The biosensor is designed to optically or electrically sense products generated from the enzymatic reaction which serve as a function of the analyte.

US Patent 5,855,613 to Antanavich et al., which is incorporated herein by reference, describes embedding cells in a thin sheet of alginate gel that is then implanted
10 in a body.

US Patent 5,834,005 to Usala, which is incorporated herein by reference, describes immunoisolating cells by placing them in a chamber that is implanted inside the body. In the chamber, the cells are shielded from the immune system by means of a membrane permeable to small molecules such as glucose, oxygen, and the hormone secreted by the
15 cells, but impermeable to cells and antibodies.

US Patent 4,402,694 to Ash et al., which is incorporated herein by reference, describes a body cavity access device for supplying a hormone to a patient. The device includes an implantable housing placed in the body and having an impermeable extracorporeal segment and a semipermeable subcutaneous segment. A hormone source
20 such as live, hormone-producing cells, e.g., pancreatic islet cells, is then removably positioned in the housing to provide a hormone supply to the patient. A sensor can be located within the subcutaneous segment and operably associated with a dispenser to release medication into the housing and to the patient.

US Patent 5,011,472 to Aebischer et al., which is incorporated herein by reference,
25 describes techniques for providing hybrid, modular systems for the constitutive delivery of active factor to a subject and, in some instances, to specific anatomical regions of the subject. The systems include a cell reservoir containing living cells capable of secreting an active agent, which is preferably adapted for implantation within the body of the subject and further includes at least one semipermeable membrane, whereby the
30 transplanted cells can be nourished by nutrients transported across the membrane while at the same time protected from immunological, bacterial, and viral assault. The systems further include a pumping means, which can be implantable or extracorporeal, for

drawing a body fluid from the subject into the cell reservoir and for actively transporting the secreted biological factors from the cell reservoir to a selected region of the subject.

US Patent 5,116,494 to Chick et al., which is incorporated herein by reference, describes a device that serves as an artificial pancreas. The device comprises a hollow
5 fiber which is surrounded by islets of Langerhans enclosed in a housing. The islets are suspended in a temperature sensitive matrix which is sufficiently viscous to support islets at a temperature below about 45 degrees C and sufficiently fluid to enable removal of islet suspension at a temperature above about 45 degrees C. A warm (e.g., 48 degree to 50 degree C solution) may be flushed through the device to change the physical state of the
10 temperature sensitive matrix from a semi-solid state to a liquefied semi-gel state. The temperature sensitive supporting material is described as enabling long-term maintenance of islet cells in in vitro culture.

US Patent 5,741,334 to Mullon et al., which is incorporated herein by reference, describes an artificial pancreatic perfusion device comprising a hollow fiber having a
15 porosity ranging from about 25 Kd to about 200 Kd. The hollow fiber has one end connected to a blood vessel for receiving blood and a second end connected to a blood vessel for returning the blood. Islets of Langerhans surround the hollow fiber. The hollow fiber and islets are surrounded by a housing comprising a semipermeable membrane having a pore size small enough to offer protection to the islets and host from
20 immune reactive substances.

US Patent 5,702,444 to Struthers et al., which is incorporated herein by reference, describes an implantable artificial endocrine pancreas comprising a reactive body of soft, plastic, biocompatible, porous hydratable material supporting a multiplicity of endocrine pancreatic islets in isolated spaced relationship from each other, and a microporous barrier
25 membrane enveloping and supporting the body, in spaced relationship from the pancreatic islets therein and through which molecules having a molecular weight greater than 60,000 Daltons cannot penetrate.

US Patent 6,630,154 to Fraker et al., which is incorporated herein by reference, describes a composition including at least one glycosaminoglycan, e.g., CIS, at least one
30 perfluorinated substance and at least one alginate, e.g., sodium alginate.

US Patent Application Publication 2004/0109302 to Yoneda et al., which is incorporated herein by reference, describes a plant cultivation method, including

cultivating plants with irradiating pulsed light with a period of 2 microseconds to 1 millisecond and a duty ratio of 20% to 70%, using a light emitting diode that emits white light or light of two colors.

US Patent 5,381,075 to Jordan, which is incorporated herein by reference,
5 describes a method for driving an immersed flashing light system to enhance algae growth. The flashing light system includes a plurality of light source elements that are arranged to illuminate the algae. The light source elements are electrically connected to form banks of light source elements. Power is supplied to each bank of light sources in a predetermined sequence at regular intervals to substantially evenly supply each bank of
10 light source elements with a series of power pulses, while maintaining a substantially continuous load on the power supply. The power pulses are substantially half cycles of a square wave.

PCT Publication WO 03/011445 to Monzyk et al., which is incorporated herein by reference, describes a photolytic cell and a photolytic artificial lung incorporated the
15 photolytic cell.

PCT Publication WO 90/15526 to Kertz, which is incorporated herein by reference, describes an integument and related process for the culturing and growing of living organic material. The integument includes a cellule made of a gas-permeable, liquid- and contaminant-impermeable membrane for completely enclosing and sealing the
20 culture from biological contaminants in the ambient environment. The membrane allows gas exchange between the living organic material and the ambient environment to provide enhanced growth and the prevention of contamination.

PCT Publication WO 01/50983 to Vardi et al., and US Patent Application 10/466,069 in the national phase thereof, which are incorporated herein by reference,
25 describe an implantable device comprising a chamber for holding functional cells and an oxygen generator for providing oxygen to the functional cells. In one embodiment, the oxygen generator comprises photosynthetic cells that convert carbon dioxide to oxygen when illuminated. In another embodiment, the oxygen generator comprises electrodes that produce oxygen by electrolysis. In another embodiment, an implantable chamber is
30 used as part of a system for detecting or monitoring the level of a substance in body fluids. Such a system includes a detector adapted to monitor a property of the functional

cells that is correlated with the level of the substance in the medium surrounding the functional cells.

Wu H et al., in "In situ electrochemical oxygen generation with an immunoisolation device," Ann N Y Acad Sci 875:105-25 (1999), which is incorporated
5 herein by reference, describe an in situ electrochemical oxygen generator which decomposes water electrolytically to provide oxygen to the adjacent planar immunobarrier diffusion chamber. In vitro culture experiments were carried out with beta TC3 cells encapsulated in titanium ring devices. The growth and viability of cells with or without in situ oxygen generation was studied.

10 Methods for immunoprotection of biological materials by encapsulation are described, for example, in US Patents 4,352,883, 5,427,935, 5,879,709, 5,902,745, and 5,912,005, all of which are incorporated herein by reference. The encapsulating material is typically selected so as to be biocompatible and to allow diffusion of small molecules between the cells of the environment while shielding the cells from immunoglobulins and
15 cells of the immune system. Encapsulated beta cells, for example, can be injected into a vein (in which case they will eventually become lodged in the liver) or embedded under the skin, in the abdominal cavity, or in other locations. Fibrotic overgrowth around the implanted cells, however, gradually impairs substance exchange between the cells and their environment. Hypoxia of the cells typically leads to cell death.

20 PCT Patent Publication WO 01/50983 to Bloch et al., which is incorporated herein by reference, describes methods and apparatus for monitoring physiological variables in a living organism by implanting, inside a patient, functional tissue or cells, which are enclosed in a membrane permeable to glucose and other nutrients but impermeable to immune system cells. In order to maintain a sufficient oxygen supply for the functional
25 cells an oxygen generator comprising photosynthetic cells and a light source is placed inside the membrane. In an application described in the '983 publication, an implantable chamber is used as part of a system for detecting or monitoring the level of a substance in body fluids. Such a system includes a detector adapted to monitor a property of the functional cells that is correlated with the level of the substance in the medium
30 surrounding the functional cells.

PCT Publication WO 04/051774 to Minteer et al., which is incorporated herein by reference, describes bioanodes comprising a quaternary ammonium treated Nation(R).

polymer membrane and a dehydrogenase incorporated within the treated Nation(R) polymer. The dehydrogenase catalyzes the oxidation of an organic fuel and reduces an adenine dinucleotide. The ion conducting polymer membrane lies juxtaposed to a polymethylene green redox polymer membrane, which serves to electro-oxidize the
5 reduced adenine dinucleotide.

An article by Khamisi R, entitled, "Microbes Pass Valuable Gas," Wired News, May 20, 2003, describes the use of microorganisms to power fuel cells, such as by using baker's yeast (aerobic metabolism), algae (photosynthesis), and bacteria.

An article by Parikh et al., entitled, "Role of Spirulina in the control of glycemia
10 and lipidemia in type 2 diabetes mellitus," J Med Food 2001, Winter 4(4): 193-199, which is incorporated herein by reference, describes a study aimed to evaluate the hypoglycemic and hypolipidemic role of Spirulina. Twenty-five subjects with type 2 diabetes mellitus were randomly assigned to receive Spirulina (study group) or to form the control group. The efficacy of Spirulina supplementation (2 g/day for 2 months) was
15 determined using the preintervention and postintervention blood glucose levels, glycosylated hemoglobin (HbA(1c)) levels, and lipid profiles of the diabetic subjects. Two-month supplementation with Spirulina resulted in an appreciable lowering of fasting blood glucose and postprandial blood glucose levels.

The following references, which are incorporated herein by reference, may be of
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Diabetes is a disorder that affects many people and results from the inability of the body to properly utilize and metabolize carbohydrates, particularly glucose. Normally the
10 balance between glucose in the blood and glucose in body tissue cells is maintained by insulin, a hormone produced by the pancreas that controls the transfer of glucose from the blood into body tissue cells. Abnormal levels of glucose in the blood cause many complications and pathologies, leading to premature death in many cases.

Abnormally high levels of blood glucose can be controlled in many cases by the
15 injection of insulin into the body. The amount of insulin to be injected depends upon the level of glucose in the blood, leading to a demand for accurate blood glucose sensors. Since regular monitoring of blood glucose levels allows for better regulation via insulin injections, it is desirable to have a simple and convenient means for monitoring blood glucose levels. Historically, the most common method to determine blood glucose levels
20 was to obtain a small blood sample by piercing the finger and then placing the blood in an analyzer.

To avoid the regular piercing of a finger and to obtain more continuous monitoring of blood glucose levels, implantable glucose sensors have been described. In some cases, implantable sensors have been described that include cells such as transplanted pancreatic
25 cells. These pancreatic cells are described as responding in a manner proportional to blood glucose levels, such that by monitoring the cellular response a blood glucose level can be determined. Several patents and applications using these techniques are discussed hereinbelow.

SUMMARY OF THE INVENTION

30 In some embodiments of the present invention, a device for determining the level of a substance in the blood or in another body fluid of a patient comprises a semi-

permeable barrier such as a membrane, which is adapted to be implanted in the body of a patient and to enclose one or more types of microorganisms and a sensor. Examples of substances that are to be sensed include specific chemical compounds, blood glucose levels, lipids, electrolyte levels, and/or levels of various hormones. The microorganisms
5 respond to the specific compound in the blood by generating a measurable response that can be detected by the sensor. By way of example, if algae are exposed to glucose, the algae will perform aerobic respiration, consuming oxygen while breaking down the glucose by glycolysis into carbon dioxide and water. This in turn leads to measurable changes in carbon dioxide and oxygen levels within the device, which can be detected by
10 sensors. Thus, a difficult to measure substance (glucose) can be measured indirectly by measuring the level of an easy to measure substance (oxygen or carbon dioxide) that changes as the algae metabolize the glucose.

Typically, the membrane is adapted to allow the passage of nutrients, such as glucose, and other small molecules through the membrane, while inhibiting the passage of
15 immune systems cells through the membrane. Examples of suitable membrane materials include polysulfone and polyurethane, among others. Isolation of the microorganisms from the immune system of the patient prevents the immune system from destroying the microorganisms and also reduces the tendency of the microorganisms to trigger an immune response.

20 Alternatively or additionally, the semi-permeable barrier comprises a matrix, which serves to contain the microorganisms and to isolate the microorganisms from the immune system. Typically, the matrix comprises a polymer and/or alginate, though other materials could be used.

The semi-permeable barrier also serves to contain the microorganisms, such that
25 they cannot travel to other parts of the body. Additionally, the semi-permeable barrier provides a physical barrier limiting the number of microorganisms in the device due to the limited space inside the semi-permeable barrier. Further additionally, the semi-permeable barrier supports a gradient between the chemical concentrations inside the semi-permeable barrier and the body fluid outside the semi-permeable barrier.

30 Typically, the microorganisms comprise individuals from one or more of various species of algae. For example, spirulina and/or chlorella are species of algae that may be used in the device. Alternatively or additionally, various species of fungus, yeast, and

bacteria, or some combination thereof are used as the microorganisms. In order to facilitate operation of the sensor, the microorganisms typically exhibit a response to the level of the specific compound in the blood or other body fluid that is measurable by the sensor.

5 Measurable responses typically comprise physiological responses of the microorganisms to levels of the specific compound. For example, increased glucose levels typically lead to increased glycolysis activity by the microorganisms, which results in increased energy release by the microorganisms and a temperature increase in the device. Thus, temperature within the device is used in some embodiments to indicate
10 glucose levels. Additionally, optical changes induced by the response of the microorganisms to glucose levels facilitates the measurement of blood glucose levels, in some embodiments of the invention. For example, the scattering or absorption of light due to the microorganisms or the medium within which the cells reside typically changes in response to varying glucose levels. In addition, spectroscopy techniques provide
15 quantification of glucose changes, as well as the quantification of other blood components such as hemoglobin or hematocrit, for the detection of patient anemia.

 Alternatively or additionally, measurable responses comprise chemical responses of the microorganisms to levels of the specific compound. For example, as described hereinabove, increased glucose levels lead to increased microorganism respiratory
20 metabolism, which results in a decrease in oxygen and an increase in carbon dioxide levels. Thus, by monitoring oxygen and/or carbon dioxide levels, a measure of the glucose level is attained. Other chemical species that can be monitored to deduce the level of the specific compound include electrolytes, enzymes, carbohydrates, lipids, and amino acids, along with other chemical species produced or consumed by cellular
25 metabolism. Additionally, for some microorganisms, e.g., yeast, the level of glucose can be determined by monitoring the level of alcohol within the semi-permeable barrier, as yeast produces alcohol in the presence of glucose.

 Further alternatively or additionally, measurable responses comprise electrical responses of the microorganisms to levels of the specific compound. Typically, the
30 electrical conductivity across a portion of the device containing the microorganisms varies in response to the metabolic activity of the microorganisms, so by placing electrodes on opposing sides of the device the level of the specific compound can be inferred.

Alternatively or additionally, physiological electrical activity of the microorganisms is measured, and a determination of blood glucose level is made responsive thereto.

For some embodiments of the current invention, the microorganisms comprise photosynthetic organisms. In a configuration, the device does not comprise a light source.

5 Typically, however, the device comprises a light source, which is adapted to provide intermittent light to the photosynthetic organisms such that photosynthesis occurs. Typically, the device comprises a controller, which is coupled to the light source, such that the light source can be turned on and off. In a typical mode of operation, the controller pulses the light, such that when the light is on the photosynthetic organisms

10 produce glucose and oxygen, while when the light is off photosynthesis ceases and the organisms consume the glucose that had crossed the membrane from the body as well as the glucose generated by photosynthesis. Measurements are typically taken while the light source is off and the organisms are consuming the glucose within the device. Typically, the measurements comprise measurements of oxygen levels and/or carbon

15 dioxide levels, but other measurable quantities that characterize glucose metabolism may also be used, as discussed hereinabove. Once the measurements are complete, the light source is turned back on such that the photosynthetic organisms can replenish the oxygen level within the device, to maintain the health and proper function of the photosynthetic organisms. It is noted that for at least some of these embodiments, use of the light source

20 is not integrally related to the sensing functionality of the device, but is instead related to maintaining the photosynthetic organisms in good health.

For some other embodiments of the present invention, the microorganisms comprise both photosynthetic organisms and non-photosynthetic organisms. The photosynthetic organisms provide oxygen to the device by means of photosynthesis, while

25 the non-photosynthetic organisms consume the glucose within the device, and provide a measurable response to the glucose level.

For some embodiments of the present invention, the device is coupled to an insulin pump, which supplies insulin to the body in response to the glucose level determined by the device.

30 For some embodiments of the present invention, the device comprises a transmitter, which is adapted to transmit the measurements from the device to an external receiver.

For some embodiments of the present invention, the device comprises two sensors, one sensor inside the semi-permeable barrier and one sensor outside the semi-permeable barrier, so as to facilitate the measurement of blood glucose levels. The two sensors measure the same quantity for some applications, while they measure different quantities
5 for other applications. For example, both sensors could measure oxygen levels, or one sensor could measure the oxygen level while the other sensor measures the temperature.

In another embodiment of the present invention, a device for controlling blood glucose levels comprises a large mass of algae or other photosynthesizing cells, a light source, and a blood glucose sensor as described hereinabove. When the glucose sensor
10 detects high glucose levels the light source is turned off, such that the cells metabolize the blood glucose, resulting in decreasing blood glucose levels. When the blood glucose level is low, the light source is turned to a high level such that the cells produce glucose, which can permeate through the semi-permeable barrier into the blood, alleviating the hypoglycemia. During normoglycemia, the light is maintained at an intermediate level, so
15 as not to affect the blood glucose level. Typically, a level of the light source is controlled to maintain glucose homeostasis. As appropriate, the level may be a duty cycle of the light and/or an amplitude of the light. For some applications, these techniques are applied to treat (a) only hypoglycemia, (b) only hyperglycemia, or (c) in the same patient, hypoglycemia and hyperglycemia.

For some embodiments of the current invention, the device is placed into a body space (e.g., the abdomen), whereby the surrounding body fluids provide the glucose, lipids, electrolytes, or various hormones and chemicals that the device is adapted to detect. For some other embodiments of the present invention, the device comprises optional graft tubes, which are adapted to be anastomosed to the vascular system such that
25 blood flows through the device due to the natural pressure gradient in the vascular system. For some applications, the graft tubes are anastomosed in line with or in parallel with a single vein (e.g., the radial vein of the arm), resulting in a relatively small pressure gradient across the device. For some other applications, one of the graft tubes is anastomosed to a vein, while the other graft tube is anastomosed to an artery, resulting in
30 a relatively large pressure gradient across the device.

There is therefore provided, in accordance with an embodiment of the present invention, substance monitoring apparatus, including:

a semi-permeable barrier, adapted to be implanted in a body of a subject and to

allow passage therethrough of a substance, while inhibiting passage therethrough of immune cells;

microorganisms, disposed within the semi-permeable barrier so as to produce a measurable response to a level of the substance; and

5 a sensor, adapted to measure the measurable response and not to measure a response of any mammalian cells that may be disposed within the semi-permeable barrier.

In an embodiment, the microorganisms include fungus, yeast, algae, and/or bacteria.

10 In an embodiment, the semi-permeable barrier is adapted to be implanted in fluid communication with blood.

In an embodiment, the semi-permeable barrier is adapted to be implanted in fluid communication with interstitial fluid.

15 In an embodiment, the semi-permeable barrier includes a membrane shaped to define an outer surface of a chamber, and wherein the microorganisms are disposed with the chamber.

In an embodiment, the semi-permeable barrier includes a matrix, and wherein the microorganisms are disposed within the matrix.

In an embodiment, the sensor is adapted to measure an oxygen level within the semi-permeable barrier associated with metabolism by the microorganisms.

20 In an embodiment, the sensor is adapted to measure a carbon dioxide level within the semi-permeable barrier associated with metabolism by the microorganisms.

In an embodiment, the sensor is adapted to measure a property of light within the semi-permeable barrier responsive to metabolism by the microorganisms.

25 In an embodiment, the semi-permeable barrier is adapted to allow passage therethrough of glucose, whereby the microorganisms produce the measurable response responsive to a level of the glucose.

In an embodiment, the semi-permeable barrier is adapted to allow passage therethrough of hemoglobin, whereby the microorganisms produce the measurable response responsive to a level of the hemoglobin.

30 In an embodiment, the microorganisms include two different types of

microorganisms.

In an embodiment, the apparatus includes a transmitter, adapted to convey data responsive to the sensor measurement to a site external to the apparatus.

There is also provided, in accordance with an embodiment of the present invention, a protein including:

- a glucose binding site;
- cyan fluorescent protein (CFP); and
- yellow fluorescent protein (YFP),

wherein the protein is configured such that binding of glucose to the glucose binding site causes a reduction in a distance between the CFP and the YFP.

In an embodiment, the protein is encoded by an isolated nucleic acid fragment having a nucleotide sequence represented by Sequence No. 1.

There is further provided, in accordance with an embodiment of the present invention, apparatus for detecting a concentration of a substance in a subject, the apparatus including a housing adapted to be implanted in the subject, the housing including:

- a fluorescence resonance energy transfer (FRET) measurement device; and
- cells genetically engineered to produce, *in situ*, a FRET protein having a FRET complex including a fluorescent protein donor, a fluorescent protein acceptor, and a binding site for the substance.

There is further provided, in accordance with an embodiment of the present invention, apparatus including a biofuel cell, adapted to be implanted in a body of a subject in fluid communication with blood of the subject, the biofuel cell including:

- an electrolyte membrane;
- an anode, coupled to the membrane;
- photosynthetic cells that photosynthetically generate oxygen using water present in the blood;
- a light source, adapted to illuminate the photosynthetic cells; and
- an oxygen cathode, coupled to the membrane, and adapted to use the oxygen as a reagent.

In an embodiment, the photosynthetic cells include algae. For some applications, the photosynthetic cells are loaded into the oxygen cathode.

In an embodiment, the apparatus is adapted to power the light source using a portion of energy generated by the biofuel cell.

5 In an embodiment, the anode is adapted to use a substance in the blood as a reagent, and the apparatus is adapted to determine a concentration of the substance in the blood responsively to a level of power output by the biofuel cell.

In an embodiment, the apparatus includes fuel-generating cells that biosynthetically generate a fuel, using a constituent of the blood as an input, and the
10 anode is adapted to use the fuel as a reagent.

There is yet further provided, in accordance with an embodiment of the present invention, apparatus including a biofuel cell, adapted to be implanted in a body of a subject in fluid communication with blood of the subject, the biofuel cell including:

an electrolyte membrane;
15 a cathode, coupled to the membrane;
cells that biosynthetically generate a fuel, using a constituent of the blood as an input; and
an anode, coupled to the membrane, and adapted to use the fuel as a reagent.

In an embodiment, the cells include algae. For some applications, the cells are
20 loaded into the anode.

For some applications, the fuel includes ethanol, and the cells generate the ethanol. For some applications, the constituent includes glucose, and the cells generate the fuel using the glucose as the input.

In an embodiment, the apparatus is adapted to determine a concentration of the
25 constituent in the blood responsively to a level of power output by the biofuel cell.

There is still further provided, in accordance with an embodiment of the present invention, a cell genetically engineered to express glucose oxidase (GOx) *in situ*.

There is also provided, in accordance with an embodiment of the present invention, a method including:
30 implanting cells in a subject; and

subsequently administering, to the subject, a drug capable of killing the cells.

There is additionally provided, in accordance with an embodiment of the present invention, a method including:

- implanting cells in a subject;
- 5 administering, to the subject, a promoter that regulates protein expression of the cells.

There is further provided, in accordance with an embodiment of the present invention, a method including implanting a glucose sensor in cerebral spinal fluid (CSF) of a spinal cord of a subject.

- 10 There is yet further provided, in accordance with an embodiment of the present invention, a method including:

- implanting an active medical device inside bone of a subject; and
 - detecting or affecting a property of blood in fluid communication with the medical device.

- 15 There is still further provided, in accordance with an embodiment of the present invention, apparatus including a sensor, adapted to be implanted in a subject, the sensor including an electrical circuit that includes a material that has binding sites for a substance, such that binding of the substance to the material changes an electrical property of the material, the sensor adapted to determine a concentration of the substance
- 20 responsively to the electrical property of the material.

In an embodiment, the material includes a polymer. For some applications, the substance includes blood glucose. For some applications, the electrical property includes electrical conductivity of the material.

- 25 There is also provided, in accordance with an embodiment of the present invention, a method including:

- implanting, in a subject, cells that are genetically engineered to express a promoter that is inducible by a substance; and
 - administering the substance to the subject.

- 30 The present invention will be more fully understood from the following detailed description of embodiments thereof, taken together with the drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of an implantable device for detecting a concentration of a substance in a subject, in accordance with an embodiment of the present invention;

5 Fig. 2 is a schematic illustration of an implantable biofuel cell, in accordance with an embodiment of the present invention; and

Fig. 3 is a schematic illustration of apparatus for monitoring blood glucose levels, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

10 Fig. 1 is a schematic illustration of an implantable device 10 for detecting a concentration of a substance in a subject, such as a blood constituent or other body fluid constituent of the subject, in accordance with an embodiment of the present invention. Device 10 comprises an implantable housing 20 that holds a fluorescence resonance energy transfer (FRET) measurement device 22 and cells 26. FRET measurement device
15 22 comprises a light source 28, such as a laser, and a FRET detector 30. Cells 26 are genetically engineered to produce, *in situ*, a FRET protein having a FRET complex comprising a fluorescent protein donor, a fluorescent protein acceptor, and a binding site for the substance. The FRET complex is configured such that binding of the substance to the binding site changes the configuration of the complex, and thus the distance between
20 the donor and the acceptor. FRET detector 30 detects this change in distance to determine the quantity of the FRET complex in each of the two configurations, thereby enabling a calculation of the concentration of the substance. Typically, cells 26 comprise slowly-dividing cells, such as, for example, beta cells, neuronal cells, or liver cells.

For some applications, the substance includes glucose, and the binding site is a
25 glucose binding site. For some applications, the concentration of the substance is calculated by calculating a ratio of an emission level of the donor at a first wavelength to an emission level of the acceptor at a second wavelength.

For some applications, the fluorescent protein donor includes cyan fluorescent protein (CFP), and the fluorescent protein acceptor includes yellow fluorescent protein
30 (YFP). Alternatively or additionally, the protein comprises another donor/acceptor pair, such as blue fluorescent protein (BFP)/green fluorescent protein (GFP), GFP/Rhodamine,

FITC/Cy3, FITC/Rhodamine, or another pair in which the donor emission spectrum overlaps the excitation spectrum of the acceptor. For some applications, the FRET complex includes one or more flexible hinge regions that enable the winding of large molecules, so as to enable energy transfer between the donor and the acceptor.

5 In an embodiment of the present invention, the FRET protein is encoded by an isolated nucleic acid fragment having a nucleotide sequence represented by Sequence No. 1. For some applications, the FRET protein further comprises a leading peptide that directs the protein to the cell membrane, such as represented by Sequence No. 2.

For some applications, implantable device 10 comprises a chamber 24, which
10 holds cells 26. Alternatively, the cells are held directly in housing 20. For some applications, the cells are placed in a matrix, while for other applications, the cells are placed in suspension.

In an embodiment of the present invention, implantable device 10 comprises a first membrane 40, placed around housing 20, such that the membrane separates the housing
15 from the body of the subject. For some applications, first membrane 40 is configured to prevent passage therethrough of cells, such as white blood cells, while allowing passage of the FRET protein out of housing 20, typically into blood surrounding the housing, where the protein breaks down. For example, the first membrane may be configured to allow passage only of molecules smaller than about 50 kilodalton. Such a membrane is
20 typically used for applications in which the FRET protein is engineered to have a high affinity for the substance, such that the substance generally remains irreversibly bound to the protein. In order to maintain the accuracy of the concentration determination even as the concentration of the substance in the body drops, the FRET protein is allowed to exit housing 20. In these applications, cells 26 are typically configured to continuously
25 generate quantities of the FRET protein sufficient to replace the protein that escapes.

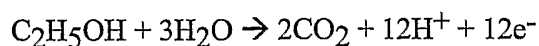
In an embodiment of the present invention, first membrane 40 is configured to additionally prevent passage therethrough of the FRET protein, while allowing fragments of the protein to exit housing 20 as the protein is naturally broken down. Such a membrane is typically used for applications in which the FRET protein is engineered to
30 have a medium affinity for the substance, such that the substance reversibly binds to the protein at high concentrations of the substance, and detaches from the protein at lower concentrations of the substance (similar to the reversible concentration-dependent binding

of oxygen to hemoglobin). In this embodiment, cells 26 are typically configured to produce lower quantities of the FRET protein than in embodiments in which first membrane 40 is configured to allow passage of FRET protein therethrough.

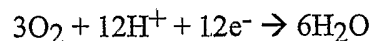
For some applications in which implantable device 10 comprises chamber 24, chamber 24 is surrounded by a second membrane 42, which is typically configured to prevent passage of cells 26 therethrough, but allow passage of FRET protein and/or fragments thereof, as appropriate for the application. For some applications, FRET measurements are made when the protein is outside of chamber 24 in housing 20. For other applications, the FRET protein remains within chamber 24 while FRET measurements are made thereof. For example, cells 26 and the FRET protein may be configured such that the FRET protein remains contained within cells 26 in chamber 24. Alternatively or additionally, cells 26 and the FRET protein may be configured such that the FRET protein becomes positioned on the cell membrane of the cells.

Reference is now made to Fig. 2, which is a schematic illustration of an implantable biofuel cell 100, in accordance with an embodiment of the present invention. Biofuel cell 100 is adapted to be implanted in a body of a subject, such as in, or in fluid communication with, a blood vessel, peritoneum, or other body chamber. Biofuel cell 100 is similar in some respects to a conventional fuel cell, such as a conventional direct ethanol fuel cell. However, unlike a conventional fuel cell, biofuel cell 100 generates one or both of the reactants (oxygen and the fuel) using at least one biological process that has as a reagent a substance available in blood serum or in another body fluid. Biofuel cell 100 typically comprises an oxygen cathode 110, an ethanol anode 112, and an electrolyte membrane 114. Alternatively, for some applications, anode 112 uses another fuel, such as glucose, or an alcohol other than ethanol, e.g., methanol.

In embodiments in which anode 112 uses ethanol as its fuel, the following reaction occurs at the anode:



The electrons are conducted through a circuit 116 to cathode 110, while the hydrogen ions are transported across membrane 114 to cathode 110. At cathode 110, the follow reaction occurs:



Each of the electrodes typically comprises three layers: a current collector plate 117, an intermediary layer 118, and a porous active layer 119.

In an embodiment of the present invention, biofuel cell 100 comprises photosynthetic cells 120 that photosynthetically generate the oxygen used by cathode 110. Photosynthetic cells 120 typically comprise algae. Typically, photosynthetic cells 120 are loaded into cathode 110 (either in active layer 119 and/or in collector plate 117). Alternatively, the photosynthetic cells are held in a separate chamber in a vicinity of the cathode (configuration not shown). Biofuel cell 100 comprises a light source 122 that is adapted to provide light for the photosynthetic cells, such as via at least one optical fiber 123. The photosynthetic cells typically use water present in blood serum for photosynthesis. Alternatively, for some applications, biofuel cell 100 uses electrolysis for generating oxygen (for example, using techniques described in the above-mentioned '592 patent and/or '427 patent application publication to Colton et al.). Optionally, the electrolysis is powered by a portion of the energy generated by the biofuel cell.

For some applications, light source 122 is powered by a portion of the energy generated by biofuel cell 100. Alternatively, the biofuel cell comprises a power source 124, such as a battery, a rechargeable battery, a capacitor, or a coil adapted to be inductively coupled to an external coil. For some applications, power source 124 provides power to the light source during the entire time the light source operates. For other applications, power source 124 provides power to the light source only during an initial activation period of the fuel cell, and thereafter, once the fuel cell generates sufficient power, the fuel cell powers the light source. For these applications, the fuel cell optionally recharges the power source.

In an embodiment of the present invention, biofuel cell 100 comprises cells 130 that biosynthetically generate the ethanol used by anode 112. Cells 130 typically comprise algae or yeast. For some applications, cells 130 comprises the same type of algae as photosynthetic cells 120. Typically, cells 130 are loaded into anode 112 (either in active layer 119 and/or in collector plate 117). Alternatively, the cells are held in a separate chamber in a vicinity of the anode (configuration not shown). Cells 130 typically use glucose present in blood serum as an input for their biosynthesis of ethanol. For some applications, anode 112 comprises one or more elements selected from the list consisting of: platinum, ruthenium, and carbon. For some applications, cells 130 are separated from blood serum by a membrane that limits the rate of passage of glucose from the serum to

the cells. For example, the membrane may surround anode 112. For some applications, anode 112 or the chamber holding the cells, as appropriate, additionally comprise one or more enzymes to catalyze the reactions.

5 In an embodiment of the present invention, to remove CO₂ that may coat the electrodes of biofuel cell 100 over time, the biofuel cell intermittently illuminates cells 130, e.g., once per second, per hour, or per day. The cells generate O₂, which cleans the CO₂ from the electrodes.

For some applications, blood serum that enters the electrode compartments of cathode 110 and anode 112 by diffusion, natural flow, and/or convection is sufficient to
10 maintain reagent concentrations necessary for operating the fuel cell at the desired power output level. For some applications in which greater reagent concentrations are desired, the fuel cell is configured to actively drive blood serum into the electrode compartments, such as with a pump.

For some applications, biofuel cell 100 achieves a greater than 5:1 ratio (e.g., an
15 approximately 10:1 ratio) of power generated to power consumed by light source 112. For some applications, biofuel cell 100 produces between about 10 and about 20 mA per cm² of electrode surface area, while light source 122 consumes only about 1 mA per cm². It is estimated that to produce 1 mA (excluding the power consumption of the light source), cathode 110 consumes 5 micrograms of oxygen per minute, and anode 112
20 consumes 2.4 micrograms of ethanol per minute.

In an embodiment of the present invention, biofuel cell 100 is configured to function as a glucose sensor. The electrical current generated by the cell is related, e.g., linearly related within a range, to the glucose concentration in the blood serum. The cell comprises an analog or digital processor that measures the current, and, for some
25 applications, calculates the glucose concentration responsively thereto. For some applications, the cell measures concentrations of blood components other than glucose.

For some applications, the biofuel cell transmits (typically wirelessly) the collected data to a portable electronic device, such as a cell phone or PDA, which is configured to present the data on a screen of the device. For some applications, the
30 biofuel cell transmits raw data to the device, and the device is programmed (in hardware or software) to perform all or a portion of the processing necessary to translate the raw data into concentration data. For some applications, the device is configured to transmit

the raw data or concentration data over a public wireless or wired communication network.

In an embodiment of the present invention, biofuel cell 100 is implanted in order to consume blood glucose of a subject, thereby reducing the blood glucose level. This
5 technique may be used, for example, to treat subjects suffering from diabetes or hyperglycemia.

In an embodiment of the present invention, cells are genetically engineered to express glucose oxidase (GOx) *in situ*. Some implantable glucose sensors use GOx to convert blood glucose into gluconic acid. The gluconic acid is converted into oxygen, and
10 the oxygen concentration is measured to determine the glucose concentration. The genetically engineered cells of this embodiment typically generate sufficient GOx to maintain an implantable blood glucose sensor for weeks or months. Alternatively, the cells are engineered to express another enzyme used to convert glucose into gluconic acid.

In an embodiment of the present invention, a method comprises administering to a
15 patient a drug to kill cells implanted in the patient. For example, the implanted cells may eventually cease to function for their intended purpose, and so may need to be replaced. (In addition, some implanted cells may, under certain circumstances, escape from a chamber containing them, and therefore need to be eliminated.) For some applications, the drug is administered to the patient when the patient is asymptomatic with respect to
20 the implanted cells. For some applications, the drug is administered to kill the cells while they are in an implanted chamber. For some applications, the method further comprises implanting the cells in the patient prior to administering the drug. For some applications, the drug is administered in conjunction with removing an implanted chamber from the patient's body (for example, to kill any cells that may escape during or prior to the
25 removal procedure). Optionally, a new chamber is subsequently implanted. Alternatively, the implanted chamber is not removed from the patient's body, and the method comprises administering the drug to kill the cells in the chamber while it remains in the patient's body. For some applications, the drug includes a promoter, e.g., to control the expression of a gene. For some applications, the drug includes tetracycline. In an
30 embodiment, the drug is administered systemically (e.g., intramuscularly, or intravenously), and travels to a site where the cells are located. Alternatively, the drug is administered directly to a site where the cells are located.

In an embodiment of the present invention, a method comprises administering, to a subject, a promoter that regulates protein expression of cells implanted in the subject. For some applications, the cells are implanted for sensing a concentration of a blood constituent. For some applications, a level of expression of the FRET protein described
5 hereinabove is regulated, such as to optimize the FRET measurement. For some applications, the promoter is selected to reduce protein expression, for example, if the subject has a reaction to the protein.

In an embodiment of the present invention, a glucose sensor is adapted to be implanted in cerebral spinal fluid (CSF) of the spinal cord. Because the constituents of
10 CSF are more tightly controlled than those of blood, there is generally less background noise in CSF that might reduce the accuracy of the sensor. For some applications, the techniques of this embodiment are practiced in conjunction with the glucose sensing techniques described herein, *mutatis mutandis*. Alternatively, these techniques are practiced in conjunction with implantable glucose sensors known in the art, *mutatis*
15 *mutandis*.

In an embodiment of the present invention, a method comprises implanting an active medical device inside bone, and detecting or affecting a property of blood or another body fluid in fluid communication with the medical device. The lack of fibrosis inside bone generally results in good fluid communication between the medical device
20 and the blood. For some applications, the medical device comprises a glucose sensor. For some applications, the bone includes bone of a tooth or bone of a long bone.

In an embodiment of the present invention, an implantable sensor is provided for sensing a concentration of a substance, the sensor comprising an electrical circuit that comprises a material that has binding sites for the substance, such that binding of the
25 substance to the material changes an electrical conductivity or other electrical property of the material. The sensor measures the concentration of the substance by detecting the conductivity of the material in the circuit. For some applications, the material comprises a polymer. For some applications, the substance includes blood glucose. Typically, the modification of the material is reversible, such that the binding sites bind and unbind the
30 substance depending on the level of the substance in contact with the material, e.g., in blood in contact with the material.

In an embodiment of the present invention, one or both opposing plates of a capacitor are coated with the material, such that the binding of the substance to the material changes the capacitance of the capacitor. This change is detectable, for example, by assessing changes in a discharge time of the capacitor, or by applying the equation $Q = CV$. Alternatively, the material is integrated into a resistor, such that the binding of the substance to the material changes a resistance of the resistor.

In an embodiment of the present invention, the material comprises a polymer produced by preparing a polymer mixture including the substance (e.g., glucose), and subsequently allowing the substance to dissolve out of the mixture. The sites of the polymer from which the substance dissolved preferentially bind the substance.

In an embodiment of the present invention, an internal surface of an implantable chamber comprises a material that has binding sites for a substance, such as glucose. The chamber is adapted to open, so as to allow blood to enter the chamber, thereby allowing the substance in the blood to bind to the material. The chamber is then closed, and cleansed of constituents other than the substance, which constituents do not bind to the material. This cleansing serves to reduce noise. For some applications, the material is integrated into an electrical circuit, as described hereinabove, and the concentration of the substance is measured by the circuit. Alternatively, this technique is used to generate the substance, e.g., glucose, for example, as fuel for a fuel cell, which is adapted to either measure the concentration of the substance, or to generate energy using the substance as fuel.

In an embodiment of the present invention, implantable cells are genetically engineered to express a promoter that is inducible by a substance administered to a body of a subject in which the cells are implanted. For some applications, the inducing substance includes an antibiotic. Typically, the promoter is capable of activating and/or deactivating one or more genes of interest.

Fig. 3 is a schematic illustration of a glucose sensing device 210, which is adapted to be implanted in the body of a patient, in accordance with an embodiment of the present invention. Device 210 comprises a semi-permeable barrier 212, such as a membrane, which is adapted to be implanted in the body of the patient and to contain one or more types of microorganisms 214 and a sensor 220. For example, when semi-permeable barrier 212 comprises a membrane, the membrane typically defines an outer surface of

device 210, and microorganisms 214 are disposed within a space defined by the membrane. Typically, semi-permeable barrier 212 is adapted to allow the passage therethrough of nutrients, such as glucose, while inhibiting the passage therethrough of immune systems cells. Examples of suitable membrane materials include polysulfone and polyurethane, among others. Isolation of the microorganisms from the immune system of the patient prevents the immune system from destroying the microorganisms and also reduces the tendency of the microorganisms to trigger an immune system response.

Alternatively or additionally, semi-permeable barrier 212 comprises a matrix, in which the microorganisms are disposed, and which isolates the microorganisms from the immune system. Typically, the matrix comprises a polymer and/or alginate, though other materials could be used.

In an embodiment, microorganisms 214 comprise individuals from one or more of various species of algae. For example, spirulina and chlorella are species of algae that may be used in device 210. Alternatively or additionally, various species of fungus, yeast, and bacteria, or some combination thereof are used as the microorganisms. Microorganisms 214 typically exhibit a measurable response to blood glucose level, as discussed hereinabove.

In an embodiment, sensor 220 is adapted to determine the oxygen level within the device, since the oxygen level varies with glucose metabolism by microorganisms 214. Thus, as the blood glucose diffuses across semi-permeable barrier 212, the microorganisms metabolize the glucose, resulting in a decrease in the oxygen level in the device. The greater the level of glucose within the device, the more the oxygen level will decrease. Similarly, when blood glucose levels are lower, glucose levels within device 210 are also lower, and oxygen levels within device 210 are detected by sensor 220 to be higher. Alternatively or additionally, other parameters are measured by sensor 220, as described hereinabove.

For some applications, device 210 additionally comprises a light source 216, which is coupled to a controller 218. The sensor is also coupled to controller 218, and controller 218 is programmed such that if the oxygen level in the device becomes low enough to threaten the health of the microorganisms, the controller turns on the light source, initiating photosynthesis which results in the production of oxygen and rising oxygen levels in the device. Once the oxygen level is sufficiently high, the light source is

turned off. Alternatively or additionally, the controller regulates the light source as described hereinabove.

For some embodiments of the current invention, device 210 is placed into a body space (e.g., the abdomen), whereby the surrounding body fluids provide the glucose that the device is adapted to detect. For some other embodiments of the present invention, device 210 comprises optional graft tubes 222, which are adapted to be anastomosed to the vascular system such that blood flows through the device due to the natural pressure gradient in the vascular system. For some applications, graft tubes 222 are anastomosed in line with or in parallel with a single vein (e.g., the radial vein of the arm), resulting in a relatively small pressure gradient across the device. For some other applications, one of graft tubes 222 is anastomosed to a vein, while the other one of graft tubes 222 is anastomosed to an artery, resulting in a relatively large pressure gradient across the device.

It will be appreciated by persons skilled in the art that the present invention is not limited to detecting blood glucose, but that blood glucose is used by way of example. The scope of the present invention includes determining and/or monitoring levels of other substances in the body.

It will be appreciated by persons skilled in the art that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof that are not in the prior art, which would occur to persons skilled in the art upon reading the foregoing description.

CLAIMS

1. A protein comprising:
a glucose binding site;
cyan fluorescent protein (CFP); and
5 yellow fluorescent protein (YFP),
wherein the protein is configured such that binding of glucose to the glucose binding site causes a reduction in a distance between the CFP and the YFP.
2. The protein of claim 1, wherein the protein is encoded by an isolated nucleic acid fragment having a nucleotide sequence represented by Sequence No. 1.
- 10 3. Apparatus for detecting a concentration of a substance in a subject, the apparatus comprising a housing adapted to be implanted in the subject, the housing comprising:
a fluorescence resonance energy transfer (FRET) measurement device; and
cells genetically engineered to produce, *in situ*, a FRET protein having a FRET complex comprising a fluorescent protein donor, a fluorescent protein acceptor, and a
15 binding site for the substance.
4. Apparatus comprising a biofuel cell, adapted to be implanted in a body of a subject in fluid communication with blood of the subject, the biofuel cell comprising:
an electrolyte membrane;
an anode, coupled to the membrane;
20 photosynthetic cells that photosynthetically generate oxygen using water present in the blood;
a light source, adapted to illuminate the photosynthetic cells; and
an oxygen cathode, coupled to the membrane, and adapted to use the oxygen as a reagent.
- 25 5. The apparatus according to claim 4, wherein the photosynthetic cells comprise algae.
6. The apparatus according to claim 4, wherein the photosynthetic cells are loaded into the oxygen cathode.
7. The apparatus according to claim 4, wherein the apparatus is adapted to power the
30 light source using a portion of energy generated by the biofuel cell.

8. The apparatus according to claim 4, wherein the anode is adapted to use a substance in the blood as a reagent, and wherein the apparatus is adapted to determine a concentration of the substance in the blood responsively to a level of power output by the biofuel cell.
- 5 9. The apparatus according to claim 4, comprising fuel-generating cells that biosynthetically generate a fuel, using a constituent of the blood as an input, wherein the anode is adapted to use the fuel as a reagent.
- 10 10. Apparatus comprising a biofuel cell, adapted to be implanted in a body of a subject in fluid communication with blood of the subject, the biofuel cell comprising:
- 10 an electrolyte membrane;
- a cathode, coupled to the membrane;
- cells that biosynthetically generate a fuel, using a constituent of the blood as an input; and
- an anode, coupled to the membrane, and adapted to use the fuel as a reagent.
- 15 11. The apparatus according to claim 10, wherein the cells comprise algae.
12. The apparatus according to claim 10, wherein the cells are loaded into the anode.
13. The apparatus according to claim 10, wherein the fuel includes ethanol, and the cells generate the ethanol.
14. The apparatus according to claim 10, wherein the constituent includes glucose,
- 20 and wherein the cells generate the fuel using the glucose as the input.
15. The apparatus according to claim 10, wherein the apparatus is adapted to determine a concentration of the constituent in the blood responsively to a level of power output by the biofuel cell.
16. A cell genetically engineered to express glucose oxidase (GOx) *in situ*.
- 25 17. A method comprising:
- implanting cells in a subject; and
- subsequently administering, to the subject, a drug capable of killing the cells.
18. A method comprising:
- implanting cells in a subject;

administering, to the subject, a promoter that regulates protein expression of the cells.

19. A method comprising implanting a glucose sensor in cerebral spinal fluid (CSF) of a spinal cord of a subject.

5 20. A method comprising:
implanting an active medical device inside bone of a subject; and
detecting or affecting a property of blood in fluid communication with the medical device.

21. Apparatus comprising a sensor, adapted to be implanted in a subject, the sensor
10 comprising an electrical circuit that comprises a material that has binding sites for a substance, such that binding of the substance to the material changes an electrical property of the material, the sensor adapted to determine a concentration of the substance responsively to the electrical property of the material.

22. The apparatus according to claim 21, wherein the material comprises a polymer.

15 23. The apparatus according to claim 21, wherein the substance includes blood glucose.

24. The apparatus according to claim 21, wherein the electrical property includes electrical conductivity of the material.

25. A method comprising:
20 implanting, in a subject, cells that are genetically engineered to express a promoter that is inducible by a substance; and
administering the substance to the subject.

26. Substance monitoring apparatus, comprising:
a semi-permeable barrier, adapted to be implanted in a body of a subject and to
25 allow passage therethrough of a substance, while inhibiting passage therethrough of immune cells;

microorganisms, disposed within the semi-permeable barrier so as to produce a measurable response to a level of the substance; and

a sensor, adapted to measure the measurable response and not to measure a
30 response of any mammalian cells that may be disposed within the semi-permeable barrier.

27. The apparatus according to claim 26, wherein the microorganisms comprise fungus.
28. The apparatus according to claim 26, wherein the microorganisms comprise yeast.
29. The apparatus according to claim 26, wherein the microorganisms comprise algae.
- 5 30. The apparatus according to claim 26, wherein the microorganisms comprise bacteria.
31. The apparatus according to claim 26, wherein the semi-permeable barrier is adapted to be implanted in fluid communication with blood.
32. The apparatus according to claim 26, wherein the semi-permeable barrier is
10 adapted to be implanted in fluid communication with interstitial fluid.
33. The apparatus according to claim 26, wherein the semi-permeable barrier comprises a membrane shaped to define an outer surface of a chamber, and wherein the microorganisms are disposed with the chamber.
34. The apparatus according to claim 26, wherein the semi-permeable barrier
15 comprises a matrix, and wherein the microorganisms are disposed within the matrix.
35. The apparatus according to claim 26, wherein the sensor is adapted to measure an oxygen level within the semi-permeable barrier associated with metabolism by the microorganisms.
36. The apparatus according to claim 26, wherein the sensor is adapted to measure a
20 carbon dioxide level within the semi-permeable barrier associated with metabolism by the microorganisms.
37. The apparatus according to claim 26, wherein the sensor is adapted to measure a property of light within the semi-permeable barrier responsive to metabolism by the microorganisms.
- 25 38. The apparatus according to claim 26, wherein the semi-permeable barrier is adapted to allow passage therethrough of glucose, whereby the microorganisms produce the measurable response responsive to a level of the glucose.
39. The apparatus according to claim 26, wherein the semi-permeable barrier is adapted to allow passage therethrough of hemoglobin, whereby the microorganisms
30 produce the measurable response responsive to a level of the hemoglobin.

40. The apparatus according to claim 26, wherein the microorganisms comprise two different types of microorganisms.
41. The apparatus according to claim 26, comprising a transmitter, adapted to convey data responsive to the sensor measurement to a site external to the apparatus.

1/2

FIG. 1

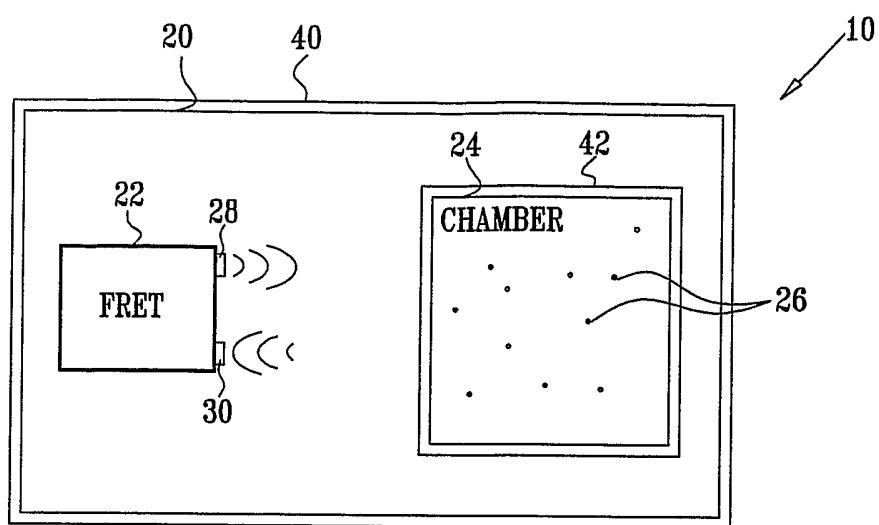
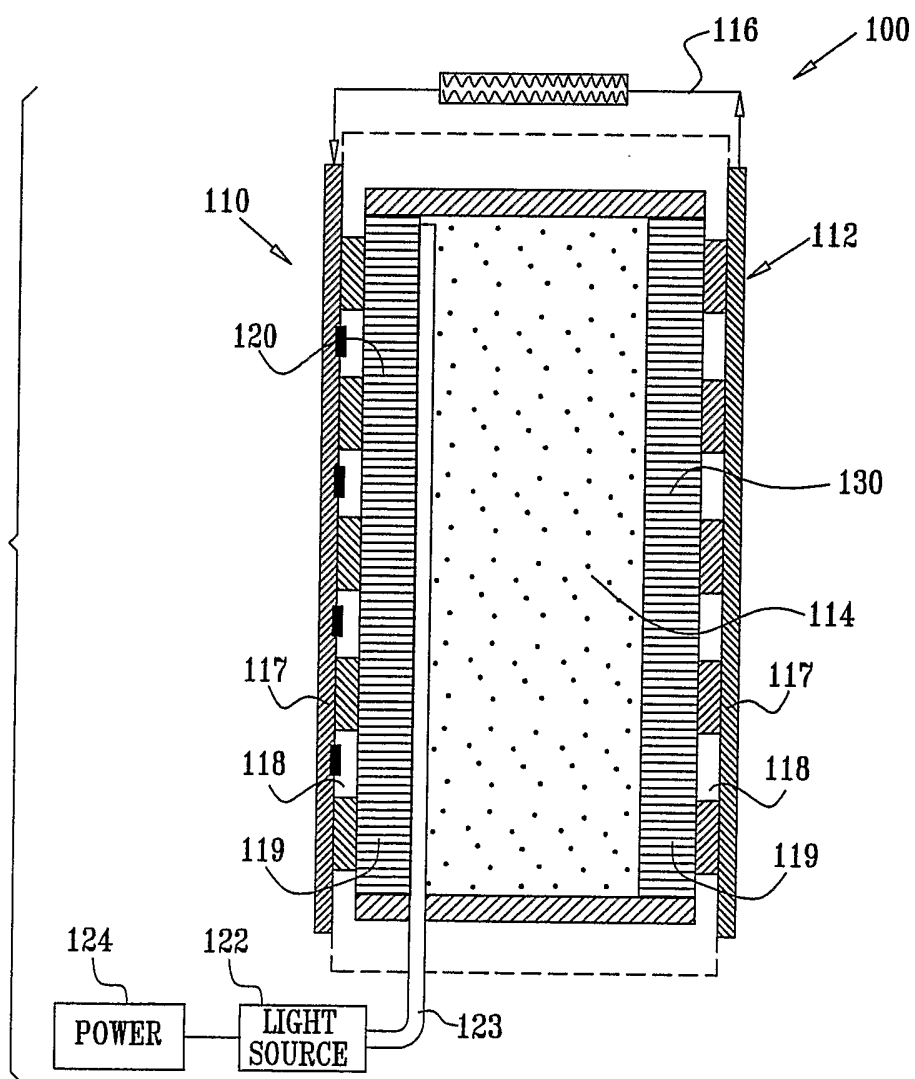
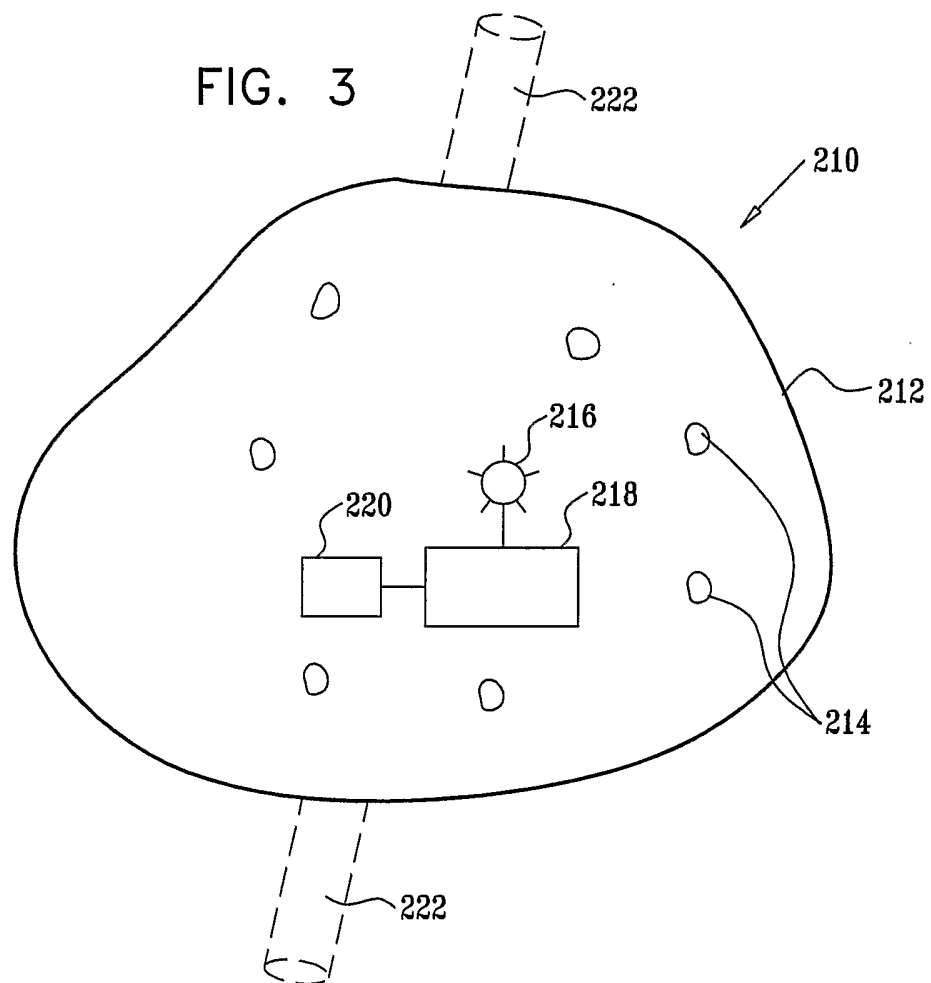


FIG. 2



2/2



SEQUENCE LISTING

Sequence No. 1

Type: DNA

Sequence:

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GGGCGATGCCACCTACGGCAAGCTGACCCTGAAGTTCATCTGCACCACCGGC
AAGCTGCCCCGTGCCCTGGCCCCACCCTCGTGACCACCCTGACCTGGGGCGTGCA
GTGCTTCAGCCGCTACCCCGACCACATGAAGCAGCACGACTTCTTCAAGTCCG
10 CCATGCCCCGAAGGCTACGTCCAGGAGCGCACCATCTTCTTCAAGGACGACGG
CAACTACAAGACCCGCGCCGAGGTGAAGTTCGAGGGCGACACCCTGGTGAAC
CGCATCGAGCTGAAGGGCATCGACTTCAAGGAGGACGGCAACATCCTGGGGC
ACAAGCTGGAGTACAACATCAGCCACAACGTCTATATACCCGCCGACAA
GCAGAAGAACGGCATCAAGGCCAACTTCAAGATCCGCCACAACATCGAGGAC
15 GGCAGCGTGCAGCTCGCCGACCACTACCAGCAGAACACCCCCATCGGCGACG
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GAT ACT CGC ATT GGT GTA ACA ATC TAT AAG TAC GAC GAT AAC TTT
20 ATG TCT GTA GTG CGC AAG GCT ATT GAG CAA GAT GCG AAA GCC GCG
CCA GAT GTT CAG CTG CTG ATG AAT GAT TCT CAG AAT GAC CAG TCC
AAG CAG AAC GAT CAG ATC GAC GTA TTG CTG GCG AAA GGG GTG AAG
GCA CTG GCA ATC AAC CTG GTT GAC CCG GCA GCT GCG GGT ACG GTG
ATT GAG AAA GCG CGT GGG CAA AAC GTG CCG GTG GTT TTC TTC AAC
25 AAA GAA CCG TCT CGT AAG GCG CTG GAT AGC TAC GAC AAA GCC TAC
TAC GTT GGC ACT GAC TCC AAA GAG TCC GGC ATT ATT CAA GGC GAT
TTG ATT GCT AAA CAC TGG GCG GCG AAT CAG GGT TGG GAT CTG AAC
AAA GAC GGT CAG ATT CAG TTC GTA CTG CTG AAA GGT GAA CCG GGC
CAT CCG GAT GCA GAA GCA CGT ACC ACT TAC GTG ATT AAA GAA TTG
30 AAC GAT AAA GGC ATC AAA ACT GAA CAG TTA CAG TTA GAT ACC GCA
ATG TGG GAC ACC GCT CAG GCG AAA GAT AAG ATG GAC GCC TGG CTG
TCT GGC CCG AAC GCC AAC AAA ATC GAA GTG GTT ATC GCC AAC AAC

GAT GCG ATG GCA ATG GGC GCG GTT GAA GCG CTG AAA GCA CAC AAC
AAG TCC AGC ATT CCG GTG TTT GGC GTC GAT GCG CTG CCA GAA GCG
CTG GCG CTG GTG AAA TCC GGT GCA CTG GCG GGC ACC GTA CTG AAC
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5 CTG GCC GAT GGT AAA GGT GCG GCT GAT GGC ACC AAC TGG AAA ATC
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10 CTGAAGTTCA TCTGCACCAC CGGCAAGCTG CCCGTGCCCT GGCCACCCCT
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ACATGAAGCA GCACGACTTC

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15 ACACCCTGGT GAACCGCATC

GAGCTGAAGG GCATCGACTT CAAGGAGGAC GGCAACATCC TGGGGCACAA
GCTGGAGTACAACTACAACA GCCACAACGT CTATATCATG GCCGACAAGC
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20 CCACTACCAGCAGAACACCC CCATCGGCGA CGGCCCCGTG CTGCTGCCCCG
ACAACCACTA CCTGAGCTAC

CAGTCCGCCC TGAGCAAAGA CCCCAACGAG AAGCGCGATC ACATGGTCCT
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ACAAGTAA

25 Sequence No. 2

Type: DNA

Sequence:

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30 TGCCCATCCTGGTCGAGCTGGACGGCGACGTAAACGGCCACAAGTTCAGCGT
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GACCTGGGGCGTGTCAGTGCTTCAGCCGCTACCCCGACCACATGAAGCAGCAC
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CTTCAAGGACGACGGCAACTACAAGACCCGCGCCGAGGTGAAGTTCGAGGGC
5 GACACCCTGGTGAACCGCATCGAGCTGAAGGGCATCGACTTCAAGGAGGACG
GCAACATCCTGGGGCACAAGCTGGAGTACA ACTACATCAGCCACAACGTCTA
TATCACCGCCGACAAGCAGAAGAACGGCATCAAGGCCAACTTCAAGATCCGC
CACAACATCGAGGACGGCAGCGTG CAGCTCGCCGACCACTACCAGCAGAACA
CCCCCATCGGCGACGGCCCCGTGCTGCTGCCCGACAACCACTACCTGAGCAC
10 CCAGTCCGCCCTGAGCAAAGACCCCAACGAGAAGCGCGATCACATGGTCCTG
CTGGAGTTCGTGACCGCCGCGGGGATCACTCTCGGCATGGACGAGCTGTACA
AG GGT GGT GGT GCT GAT ACT CGC ATT GGT GTA ACA ATC TAT AAG TAC
GAC GAT AAC TTT ATG TCT GTA GTG CGC AAG GCT ATT GAG CAA GAT
GCG AAA GCC GCG CCA GAT GTT CAG CTG CTG ATG AAT GAT TCT CAG
15 AAT GAC CAG TCC AAG CAG AAC GAT CAG ATC GAC GTA TTG CTG GCG
AAA GGG GTG AAG GCA CTG GCA ATC AAC CTG GTT GAC CCG GCA GCT
GCG GGT ACG GTG ATT GAG AAA GCG CGT GGG CAA AAC GTG CCG GTG
GTT TTC TTC AAC AAA GAA CCG TCT CGT AAG GCG CTG GAT AGC TAC
GAC AAA GCC TAC TAC GTT GGC ACT GAC TCC AAA GAG TCC GGC ATT
20 ATT CAA GGC GAT TTG ATT GCT AAA CAC TGG GCG GCG AAT CAG GGT
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25 GAC GCC TGG CTG TCT GGC CCG AAC GCC AAC AAA ATC GAA GTG GTT
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30 CTG GCG AAA AAC CTG GCC GAT GGT AAA GGT GCG GCT GAT GGC ACC
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