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[Continued on next page]

(54) Title: MAGNETIC RESONANCE SAFE CABLE FOR BIOPOTENTIAL MEASUREMENTS

(57) Abstract: A cable for use in biopotential measurements in a magnetic resonance (MR) environment comprises a flexible plastic or polymer sheet (32, 40) extending as a single unitary structure from a first end to an opposite second end, and an electrically conductive trace (38, 58) disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end. The electrically conductive trace has sheet resistance of one ohm/square or higher, and may have a hatching or checkerboard pattern. The cable may further include an electrically insulating protective layer (50, 70) disposed on the substrate and covering the electrically conductive trace, an electrode (30) disposed on the electrically conductive trace at the second end, an edge connector (74) at the first end, or various combinations of such features.

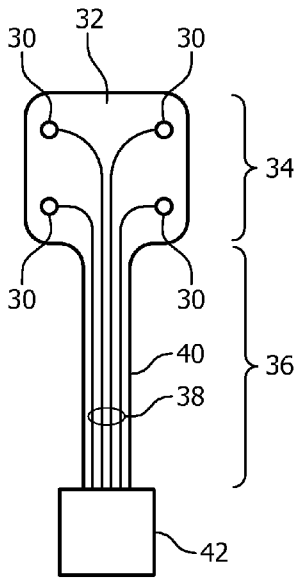

FIG. 2

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Magnetic Resonance Safe Cable For Biopotential Measurements

DESCRIPTION

The following relates to the sensor arts, measurement arts, magnetic resonance arts, safety arts, biopotential measurement arts including electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG) electroretinography (ERG), and so forth, gated MR imaging arts employing cardiac gating or the like, and so forth.

In conventional biopotential measurements such as electrocardiograph (ECG), electroencephalograph (EEG), and similar measurements, electrical potentials are measured by electrodes placed on the skin. Conventionally, cabling with high electrical conductivity, e.g. using copper wires, is employed to connect the electrodes with the monitoring electronics.

When biopotential measurements are performed while the subject is disposed in a magnetic resonance (MR) scanner, the conventional high conductivity cabling is replaced by high resistance cabling. This is in deference to numerous problems that can arise in placing high conductivity cabling in the MR environment, including problems such as heating caused by RF pulses and/or magnetic field gradients, radio frequency interference issues, and so forth. Use of ECG or other biopotential measurement instruments in an MR setting has numerous applications. For example, ECG signals can be used to monitor the condition of the patient, and/or can be used to trigger or gate certain events such as imaging data acquisition. Cardiac gating performed in this way can reduce motion artifacts due to the beating heart.

In the MR room due to the RF heating effects and burn hazards associated with the MRI environment, a distributed or discrete high-resistance cable is used to connect the electrode to the MRI patient monitor with ECG functionality. These high resistance cables are expensive and can still be susceptible to heating and consequent risk of burns to the patient. They are cumbersome to manufacture, can suffer from inductive pickup, are susceptible to triboelectric effects, can suffer from parasitic capacitance, and are sensitive to patient movement. Routing of discrete lead wires can lead to inconsistency and inaccuracies in ECG performance.

Radio frequency (RF) fields produced by the MR scanner can generate currents in the cable, or "hot-spots" that may increase surface temperatures enough to exceed those allowed by regulatory standards and pose discomfort or a burn hazard to the patient. MR magnetic field gradients can cause interference and can also induce currents on the ECG cables and connections points, producing an additive interference waveform components that potentially give false heart rate readings, obscure ECG R-wave detection schemes, or otherwise degrade the ECG analysis. Cables employing a plated snap connector at each electrode location also introduce a time-consuming manual task of connecting each disposable electrode to a re-usable cable consisting of discrete wires and connectors.

Tuccillo et al., U.S. Pub. No. 2006/0247509 A1 discloses an a cable for use in an MRI, which is adapted to resist motion in response to magnetic fields generated by the MR scanner. The cable of Tuccillo et al. is constructed of a flexible Kapton substrate on which a plurality of conductive traces are drawn using a conductive carbon ink. In the disclosed embodiment, the carbon ink has a resistance of 10 ohm/sq while the cable is six feet in length and has a distributed impedance of about 330 ohms/cm. The ends of the cable include expanded regions with copper pads for connection to an ECG electrode at one end and an ECG monitor at the opposite end.

Electrodes for biopotential measurements also pose difficulties in an MR environment. A known electrode is a silver-silver chloride (Ag-AgCl) electrode. This type of electrode is also used in the construction of MR-compatible ECG electrodes in efforts to reduce DC offset voltage created by the half-cell potential of the electrode and to minimize contact impedance. Either a paste or gel is used as the electrolyte interface to the patient. Van Genderingen et al., "Carbon-Fiber Electrodes and Leads for Electrocardiography during MR Imaging", Radiology vol. 171 no. 3 page 872 (1989) discloses replacing conventional Ag-AgCl ECG electrodes with braided metal leads with ECG electrodes made of carbon fiber with plastic reinforced carbon fiber leads (Carbo Cone RE-I, Sundstroem, Sweden). They report that the carbon fiber electrodes did not degrade the images as compared with the conventional Ag-AgCl electrode/braided metal leads, and the plastic reinforcement made the carbon fiber leads less susceptible to bending as compared with similar leads made of graphite.

The following contemplates improved apparatuses and methods that overcome the aforementioned limitations and others.

According to one aspect, a cable for use in biopotential measurements in a magnetic resonance (MR) environment is disclosed. The cable comprises: a flexible plastic or polymer sheet extending as a single unitary structure from a first end to an opposite second end; an electrically conductive trace disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive trace having sheet resistance of one ohm/square or higher; and an electrode disposed on the electrically conductive trace at the second end. The electrode includes: a layer of electrically conductive material disposed on the electrically conductive trace at the second end that is more electrically conductive than the material comprising the electrically conductive trace; and an attachment layer disposed on the layer of electrically conductive material and configured to attach the electrode to human skin.

According to another aspect, a cable for use in biopotential measurements in a magnetic resonance (MR) environment is disclosed. The cable comprises: a flexible plastic or polymer sheet extending as a single unitary structure from a first end to an opposite second end; an electrically conductive trace disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive trace having sheet resistance of one ohm/square or higher; an electrically insulating protective layer disposed on the substrate and covering the electrically conductive trace; and an edge connector at the first end comprising a layer or layer stack of electrically conductive material disposed on the electrically conductive trace at the first end that is more electrically conductive than the material comprising the electrically conductive trace, the electrically insulating protective layer not covering the layer or layer stack of electrically conductive material.

According to another aspect, a cable for use in biopotential measurements in a magnetic resonance (MR) environment is disclosed. The cable comprises: a flexible plastic or polymer sheet extending as a single unitary structure from a first end to an opposite second end; and an electrically conductive trace disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive trace having sheet resistance of one ohm/square or higher, the electrically conductive trace having a hatching or checkerboard pattern.

According to another aspect, a biopotential measurement apparatus comprises: an electrode configured for attachment to skin of a human or animal; a monitor or receiver unit configured to receive biopotential measurements; and a cable as set forth in any of the three immediately preceding paragraphs connecting the electrode with the monitor or receiver unit.

One advantage resides in providing a magnetic resonance-compatible cable for ECG or other biopotential measurements with reduced susceptibility to eddy currents.

Another advantage resides in providing a magnetic resonance-compatible cable for ECG or other biopotential measurements that is robust against interference.

Another advantage resides in providing a magnetic resonance-compatible cable for ECG or other biopotential measurements that simplifies acquisition setup.

Numerous additional advantages and benefits will become apparent to those of ordinary skill in the art upon reading the following detailed description.

The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 diagrammatically shows a magnetic resonance (MR) system with an electrocardiograph (ECG) operating inside the MR scanner.

FIGURE 2 diagrammatically shows the ECG acquisition system.

FIGURE 3 diagrammatically shows an electrode and proximate portion of cable as disclosed herein.

FIGURE 4 diagrammatically shows an electrode patch with uniformly distributed high resistance printed circuitry.

FIGURE 5 diagrammatically shows an electrode patch with non-uniformly distributed high resistance printed circuitry.

FIGURES 6-8 show ECG results acquired using conventional electrode patches with ECG results acquired using electrode patches as disclosed herein.

With reference to FIGURE 1, a magnetic resonance environment includes a magnetic resonance (MR) scanner **10** disposed in a radio frequency isolation room **12**

(diagrammatically indicated by a dashed box surrounding the MR scanner **10**), for example, comprising a wire mesh or other radio frequency screening structures embedded in or disposed on the walls, ceiling, and floor of the MR room containing the MR scanner **10**. The MR scanner **10** is shown in diagrammatic side-sectional view in FIGURE 1, and includes a housing **14** containing a main magnet windings **16** (typically superconducting and contained in suitable cryogenic containment, not shown, although a resistive magnet windings are also contemplated) that generate a static (B_0) magnetic field in a bore **18** or other examination region. The housing **14** also contains magnetic field gradient coils **20** for superimposing magnetic field gradients on the static (B_0) magnetic field. Such gradients have numerous applications as is known in the art, such as spatially encoding magnetic resonance, spoiling magnetic resonance, and so forth. An imaging subject, such as an illustrative patient **22**, or an animal (for veterinary imaging applications), or so forth is loaded into the examination region (inside the bore **18** in the illustrative case) via a suitable couch **24** or other patient support/transport apparatus. The MR scanner may include numerous additional components known in the art which are not shown for simplicity, such as optional steel shims, optional whole body radio frequency (RF) coil disposed in the housing **14**, and so forth. The MR scanner also typically includes numerous auxiliary or ancillary components again not shown for simplicity, such as power supplies for the main magnet **16** and the magnetic field gradient coils **20**, optional local RF coils (e.g. surface coils, a head coil or limb coil, or so forth), RF transmitter and RF reception hardware, and various control and image reconstruction systems, by way of some examples. Moreover, it is to be understood that the illustrative MR scanner **10**, which is a horizontal-bore type scanner, is merely an illustrative example and that more generally the disclosed MR safe cables and electrodes are suitably employed in conjunction with any type of MR scanner (e.g., a vertical bore scanner, open-bore scanner, or so forth).

In operation, the main magnet **16** operates to generate a static B_0 magnetic field in the examination region **18**. RF pulses are generated by the RF system (including for example a transmitter and one or more RF coils disposed in the bore or a whole-body RF coil in the housing **14**) at the Larmor frequency (i.e., magnetic resonance frequency) for the species to be excited (usually protons, although other species may be excited, e.g. in MR spectroscopy or multinuclear MR imaging applications). These pulses excite nuclear magnetic resonance (NMR) in the target species (e.g., protons) in the subject **22** which are

detected by a suitable RF detection system (e.g., a magnetic resonance coil or coils and suitable receiver electronics). Magnetic field gradients are optionally applied by the gradient coils **20** before or during excitation, during a delay period (e.g., time to echo or TE) period prior to readout, and/or during readout in order to spatially encode the NMR signals. An image reconstruction processor applies a suitable reconstruction algorithm comporting with the chosen spatial encoding in order to generate a magnetic resonance image which may then be displayed, rendered, fused or contrasted with other MR images and/or images from other modalities, or otherwise utilized.

With continuing reference to FIGURE 1 and with further reference to FIGURE 2, as part of the MR procedure, biopotential measurements are acquired using electrodes **30** disposed on an appropriate portion of the patient (e.g., on chest skin and optionally also on limb skin in the case of ECG, or on the scalp in the case of EEG, or so forth). In illustrative FIGURE 1 four electrodes are disposed on a common substrate **32** to form an electrodes patch **34**. The common substrate **32** provides defined spacing and a supporting substrate for the (illustrative four) electrodes. The number, arrangement, and location of electrodes are chosen for the particular application. In the case of ECG some common electrode configurations include EASI configurations and variants thereof, which typically include about five electrodes, and so-called 12-lead ECG which employs ten electrodes disposed on the chest and limbs in a standard 12-lead ECG configuration. In some embodiments the electrodes may be discrete, rather than being disposed on a common patch as in the illustrative example.

A cable **36** includes conductors in the form of electrically conductive traces **38** disposed on a substrate **40**. Although electrically conductive, the traces **38** are highly resistive compared with conventional printed circuitry such as copper traces. For example, in some embodiments the traces **38** have sheet resistance R_S of one ohm/sq or higher. (By comparison, a copper trace in typical printed circuitry has sheet resistance of about 0.05 ohm/sq or lower). More generally, the material resistivity ρ together with the thickness t and width W of the trace are chosen to provide the desired conductor resistance. As is known in the art, sheet resistance R_S is given by the bulk resistivity ρ of the material forming the layer divided by the layer thickness t, i.e. $R_S=\rho/t$. Then the resistance R of a trace (i.e., conductor) of thickness t having length L and width W is given as $R=R_S\times(L/W)$.

In some embodiments the conductive traces **38** are formed from a mixture of conductive particles disposed in a solvent matrix, which is applied to the substrate **40**. Upon curing the solvent dissipates leaving the conductive particles bonded to the substrate **40** by residue of the curing. In some embodiments the conductive traces **38** are formed of graphite, nanotubes, buckyballs, or other carbon-based particles disposed on the substrate **40** by screen printing or another deposition process to form the conductive traces **38**. Instead of carbon-based particles, particles of other materials of suitable (bulk) resistivity and mechanical and thermal properties can be chosen, such as a doped semiconductor material, silicone particles, metal oxide materials, or so forth. Instead of screen printing, other processes can be used to form the traces **38** on the substrate **40**, such as depositing a bulk layer and etching away to define the traces, depositing the traces by a vacuum evaporation process, or so forth. The material forming the traces **38** should also be non-ferromagnetic to avoid interference with the MR scanner.

The substrate **40** can be any substrate capable of supporting the conductors **38** in suitable electrical isolation. Some suitable substrates include a plastic or polymer substrate such as a Melinex® sheet or film (available from DuPont Teijin Films, Chester, VA), a polyimide sheet or film, or so forth. The substrate should be electrically insulating as compared with the conductivity of the material of the traces **38**; alternatively the substrate can be electrically conductive but including an electrically insulating layer on which the traces are disposed, where the electrically insulating layer is insulating as compared with the conductivity of the material of the traces **38**. In some embodiments, the substrate **40** advantageously has some flexibility (as is the case for a Melinex® sheet or film) to enable the cable **36** to be somewhat flexible.

The cable **36** runs from the electrodes **30** to a receiver unit **42**. In the illustrative example the receiver unit **42** is a wireless ECG module that receives the measured potential signals and transmits them via a wireless channel **44** (diagrammatically indicated in FIGURE 1 by a dashed double-headed curved line) to an ECG monitor **46** located outside (or optionally inside) the MR room **12**. The wireless ECG module **42** can be located inside the bore **18** (as illustrated) or outside (for example, by running the cable through a passageway through the MR housing **14** or out the open end of the bore **18**). Moreover, it is contemplated to omit the wireless ECG module and instead run the cable directly to the ECG monitor (in which case the ECG monitor is the receiver unit), although this will

generally require a substantially longer cable. The ECG monitor **46** is configured to process and display the acquired biopotential measurements. For example, in the illustrative case of the ECG monitor **46**, the ECG data may be displayed as ECG traces, and may optionally be processed to detect R-wave occurrences or other ECG events for use in gating of the MR imaging or so forth. In some embodiments the acquired ECG (or other biopotential) data are stored on a non-transitory storage medium such as a hard disk drive, flash drive, or so forth, and/or are printed on paper (e.g., as ECG traces).

With reference to FIGURE 3, a suitable configuration for the cable **34** and electrodes **30** is shown in side sectional view so as to show the conductor or trace **38** disposed on the substrate **40**. Optionally, a protective layer **50** covers the traces **38** to provide electrical insulation and protection against damage by abrasion or the like. The protective layer **50** should be electrically insulating as compared with the material of the traces **38**, and should be non-ferromagnetic and MR compatible. Some suitable embodiments of the protective layer **50** include a polymer or polymide sheet applied on top of the substrate **40** after depositing or otherwise forming the traces **38**, or depositing an insulating plastic, polymer, or other material on top of the substrate **40** and traces **38** to form the protective layer **50**. The protective layer **50** may also be a foam thermal insulating layer to provide patient comfort.

With continuing reference to FIGURE 3, the electrode patch **34** can be formed similarly, with the common substrate **32** being a Melinex® sheet or film or other suitable substrate with appropriate electrically insulating and MR compatible properties, and with flexibility as desired. The common substrate **32** of the electrodes can be the same material as the substrate **40** of the cable **36** (as in illustrative FIGURE 3), or can be different materials. The electrode **30** is disposed on a trace **58** formed on the substrate **32**. The trace **58** can be of the same material and deposition technique as the traces **38** of the cable **36**, e.g. a carbon-based printed trace. The traces **38** of the cable **36** and the traces **58** connecting and supporting the electrodes **30** can be of the same material (as illustrated), or can be different materials. The electrode **30** is formed on the trace **58** using a suitable layer or layer stack to facilitate electrical contact with skin **60** of the patient or other subject **22**. In one suitable embodiment, the electrodes **30** include a silver layer **62** disposed on the carbon-based trace **58**, and a silver chloride-based electrolyte layer **64** disposed on the silver layer **62**. The electrolyte layer **64** can serve as an adhesive, or an additional adhesive

layer can be provided (not shown). The electrode patch **34** preferably includes a protective layer **70** which may be the same material as the protective layer **50** of the cable **36**. However, the protective layer **70** should include openings for the electrodes **30** to enable the electrodes **30** to contact the skin **60**. It is contemplated to include a pull-off tab or other covering (not shown) disposed over the electrode **30** which is pulled off or otherwise removed just before the electrode is applied to the skin **60**.

With continuing reference to FIGURE 3, electrical connection between the electrode patch **34** and the cable **36** (or, between individual electrodes and the cable **36** in embodiments employing individual electrodes rather than a patch), and electrical connection between the cable **36** and the receiver unit **42** can take various forms. In the illustrative example of FIGURE 3, at the end of the cable **36** distal from the electrodes patch **34** each conductor or trace **38** is coated with a layer or layer stack **72** of a suitably electrically conductive material (that is, more electrically conductive than the conductors or traces **38**). In the illustrative example, layer **72** is a silver layer comparable to the silver layer **62** of the electrodes **30**, but omitting the silver chloride coating **64**. In other embodiments, the layer **72** may be silver, copper, or another material having higher conductivity than the material forming the trace **38**. In some embodiments the layer 72 is an added piece of metal foil. The protective layer **50** does not cover these layers **72**. The effect is to form an edge connector **74** that can plug into a mating socket of the receiver unit **42**. Unless the distal end of the cable extends outside of the MR scanner, the layer or layers **72** should be made of an MR compatible material, e.g. a non-ferromagnetic material. Although not shown in FIGURE 3, the connection between the electrodes patch **34** and the cable **36** can employ a similar arrangement except with a mating connector attached to one of the components **34**, **36**.

By manufacturing the cable **36** and the electrodes patch **34** as separate elements, the cable can be reused while the patch would typically be a disposable consumable item that is used once for a patient and then discarded. Alternatively, in some embodiments the electrodes patch **34** and the cable **36** are formed as a single unitary structure on a single-piece substrate that embodies both substrates **32**, **40**, and with the traces **38**, **58** forming single continuous traces. This approach simplifies patient workflow as the single-piece ECG patch/cable is utilized by plugging the edge connector **74** into the mating socket of the receiver unit **42** (or alternatively into the mating socket of the ECG monitor), applying

the electrodes **30** to the patient, and running the ECG. The step of connecting the cable with the ECG electrodes is eliminated. Because the cable and patch are fabricated as a single unitary structure, the additional cost of discarding the cable is reduced.

In various embodiments, the traces **38**, **58** are suitably formed of carbon-based ink with specific electrical resistance applied to the planar flexible substrate **32**, **40**, such as polymer resin-based film, by any reproductive method, such as by screen printing. The printed trace **38**, **58** may be solid or may contain features such as hatching to reduce eddy current generation in the trace or to vary resistance with identical geometry. The cable may have any number of conductors from 1 to 12 (or more, if appropriate for the application). For example, in a 12-lead ECG setup the cable may include 12 conductors **38**, while in an EASI ECG setup only 5 conductors may be included. All conductors may be on a single substrate or may be on different substrates to accommodate various patient body shapes and/or to simplify cable routing.

In other contemplated aspects, the resistance of the conductors **38**, **58** may be evenly or unevenly distributed along the trace **38**, **58**. Uneven distribution can be achieved, for example, by varying the trace width and/or thickness, or by using a "checkerboard" pattern or other nonuniform printing pattern for the trace. It is also contemplated to add electrical components to the cable **36** and/or to the electrode patch **34**. For example, a discrete resistance component may be added, or a small region of higher-resistance material may be interposed along the trace to form a localized resistance. The cable **36** and/or electrode patch **34** is optionally surrounded by a protective shield (e.g., Faraday cage) to minimize electrical interference. Notch filters or low pass filters, integrated circuit components, antenna circuits, power supplies, sensors (e.g., piezo sensors or MEMS accelerometers), or optical elements are optionally be incorporated into the cable **36** and/or electrode patch **34** by adhering or otherwise attaching such components to the substrate **32**, **40** and connecting to various traces **38**, **58** as appropriate.

With reference to FIGURES 4 and 5, some illustrative configurations for the electrodes patch **34** are shown. In these embodiments, the patch **34** includes a connector **80** that may, for example, accept an edge connector (not shown) of the cable **36** that is similar to the edge connector **74** shown in FIGURE 3, except located at the end of the cable **36** proximate to the electrodes patch **34**. In the patch embodiment of FIGURE 4, the traces **58** are continuous traces. In the patch embodiment of FIGURE 5, traces **58C** have the same

layout as the traces **58**, but are deposited in a "checkerboard" pattern with only 50% coverage (see inset of FIGURE 5). By reducing the area coverage of the traces the sheet resistance R_S is effectively increased (e.g., typically by a factor of about two for 50% area coverage).

By printing the electrode and lead connections, repeatability and reproducibility of the lead-wire routing is assured between cases and for the same patient. Patient movement is less likely to induce voltages or introduce noise to the biopotential measurement, because such motion does not change the relative spacing of the electrodes or the leads (i.e., conductors **38**, **58**). If the substrates **32**, **40** have some flexibility then some motion related voltage induction and noise may result, but the amount of motion (and hence the introduced noise) is substantially reduced versus the case for individual wires. Moreover, a tradeoff between patient comfort and preparation convenience (facilitated by making the substrates flexible) and noise (suppressed by making the substrates rigid) can be achieved by appropriate design of the substrate flexibility (controlled, for example, by the thickness of the substrate, as a thicker substrate is generally less flexible).

The materials for the electrodes and the cable are selected so that proton emissions do not obscure the MR image, and to minimize contact impedance, and to minimize offset voltages. The disclosed cables and electrodes are readily constructed to be "MR Safe" rather than merely "MR Conditional". (The distinction is that for "MR safe" there should be no condition under which the component poses a risk to the patient or introduces functional limitations in the MRI).

Although in the disclosed embodiments the electrodes **30** are attached by adhesive, alternatively a mechanical mechanism can be used to attach the patch rather than adhesive. Moreover, materials other than silver-silver chloride may be used to create the electrode tissue interface circuit. For example, gel soaked sponge or paste may be used to create the electrode tissue interface circuit. As with protective layer **50**, the protective layer **70** of the electrode patch **34** may advantageously be a foam thermal insulating layer.

With reference to FIGURES 6-8, test ECG results are shown for a prototype of the electrodes patch **34**. The tests were performed in a Philips 3.0T Achieva™ MRI Scanner. Several high dB/dT scan sequences were evaluated using an existing commercial electrode patch (i.e. "current electrode") versus the electrodes patch **34** (i.e., "Disclosed electrode"). Criteria used to evaluate performance include the R-wave to T-wave amplitude ratio

(where the bigger the ratio, the better because it prevents the T-wave from being detected as an R-wave creating false triggering/synchronization to the MRI) and the variation (or RMS noise) in the baseline (where lower is the better because it prevents the R-wave from being obscured during R-wave detection). FIGURE 6 shows results for a diffusion-weighted imaging (DWI) scan. FIGURE 7 shows results for a field-echo, echo planar imaging (FE-EPI) scan. FIGURE 8 shows results for a survey scan.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

Having described the preferred embodiments, the invention is now claimed to be:

1. A cable for use in biopotential measurements in a magnetic resonance (MR) environment, the cable comprising:

a flexible plastic or polymer sheet (32, 40) extending as a single unitary structure from a first end to an opposite second end;

an electrically conductive trace (38, 58) disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive trace having sheet resistance of one ohm/square or higher; and

an electrode (30) disposed on the electrically conductive trace at the second end, the electrode including:

a layer (62) of electrically conductive material disposed on the electrically conductive trace at the second end that is more electrically conductive than the material comprising the electrically conductive trace, and

an attachment layer (64) disposed on the layer (62) of electrically conductive material and configured to attach the electrode to human skin.

2. The cable of claim **1**, wherein the layer (62) of electrically conductive material of the electrode (30) comprises a silver layer.

3. The cable of any one of claims **1-2**, wherein the attachment layer comprises an electrolyte layer (64).

4. The cable of claim **3**, wherein the electrolyte layer (64) comprises silver chloride.

5. The cable of any one of claims **1-4**, wherein the attachment layer (64) adheres to human skin to effect attachment of the electrode (30) to human skin.

6. The cable of any one of claims **1-5**, further comprising:

a connector (74) disposed at the first end and configured to connect with a monitor or receiver unit (42), the electrically conductive trace conducting biopotential measurements from the electrode (30) to the connector (74).

7. The cable of any one of claims **1-6**, wherein the electrically conductive trace is an electrically conductive carbon trace.

8. The cable of any one of claims **1-7**, further comprising:

an electrically insulating protective layer (50, 70) disposed on the substrate and covering the electrically conductive trace but not the electrode.

9. A cable for use in biopotential measurements in a magnetic resonance (MR) environment, the cable comprising:

a flexible plastic or polymer sheet (32, 40) extending as a single unitary structure from a first end to an opposite second end;

an electrically conductive trace (38, 58) disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive trace having sheet resistance of one ohm/square or higher;

an electrically insulating protective layer (50, 70) disposed on the substrate and covering the electrically conductive trace; and

an edge connector (74) at the first end comprising a layer or layer stack (72) of electrically conductive material disposed on the electrically conductive trace at the first end that is more electrically conductive than the material comprising the electrically conductive trace, the electrically insulating protective layer not covering the layer or layer stack (72) of electrically conductive material.

10. The cable of claim **9**, wherein the material comprising the electrically conductive trace includes carbon and the layer or layer stack (72) of electrically conductive material includes a silver layer.

11. The cable of claim **9**, wherein the material comprising the electrically conductive trace is a metal oxide.

12. The cable of claim **9**, wherein the material comprising the electrically conductive trace is a doped semiconductor.

13. The cable of any one of claims **9-12**, wherein the electrically conductive trace has a hatching or checkerboard pattern.

14. The cable of any one of claims **9-13**, further comprising:

an electrode (30) disposed on the electrically conductive trace at the second end, the electrode configured for attachment to human skin, the electrically conductive trace electrically connecting the edge connector and the electrode, the electrically insulating protective layer (50, 70) not covering the electrode.

15. The cable of claim **14**, wherein the electrode (30) comprises a layer (62) of electrically conductive material disposed on the electrically conductive trace at the second end that is more electrically conductive than the material comprising the electrically conductive trace.

16. The cable of claim **14**, wherein the electrode (30) comprises:

a silver layer (62) disposed on the electrically conductive trace at the second end; and

a silver chloride-based electrolyte layer (64) disposed on the silver layer (62).

17. A cable for use in biopotential measurements in a magnetic resonance (MR) environment, the cable comprising:

a flexible plastic or polymer sheet (32, 40) extending as a single unitary structure from a first end to an opposite second end; and

an electrically conductive trace (38, 58) disposed on the flexible plastic or polymer sheet and running from the first end to the opposite second end, the electrically conductive

trace having sheet resistance of one ohm/square or higher, the electrically conductive trace having a hatching or checkerboard pattern.

18. The cable of claim **17**, further comprising:

an electrode (30) disposed on the electrically conductive trace at the second end, the electrode configured for attachment to human skin.

19. A biopotential measurement apparatus comprising:

an electrode (30) configured for attachment to skin of a human or animal;

a monitor or receiver unit (42) configured to receive biopotential measurements; and

a cable (36, 34) as set forth in any one of claims **1-19** connecting the electrode with the monitor or receiver unit.

20. The biopotential measurement apparatus of claim **19**, wherein the monitor or receiver unit (42) comprises an electrocardiography (ECG) instrument.

21. The biopotential measurement apparatus of claim **19**, wherein the biopotential measurements are one of electrocardiography (ECG) measurements, electromyography (EMG) measurements, electroencephalography (EEG) measurements, and electroretinography (ERG) measurements.

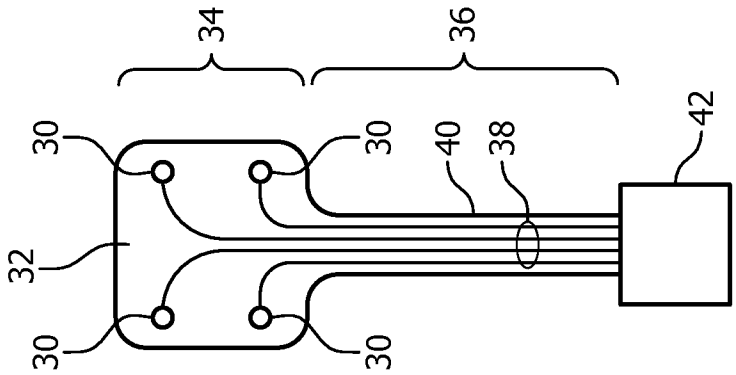

FIG. 2

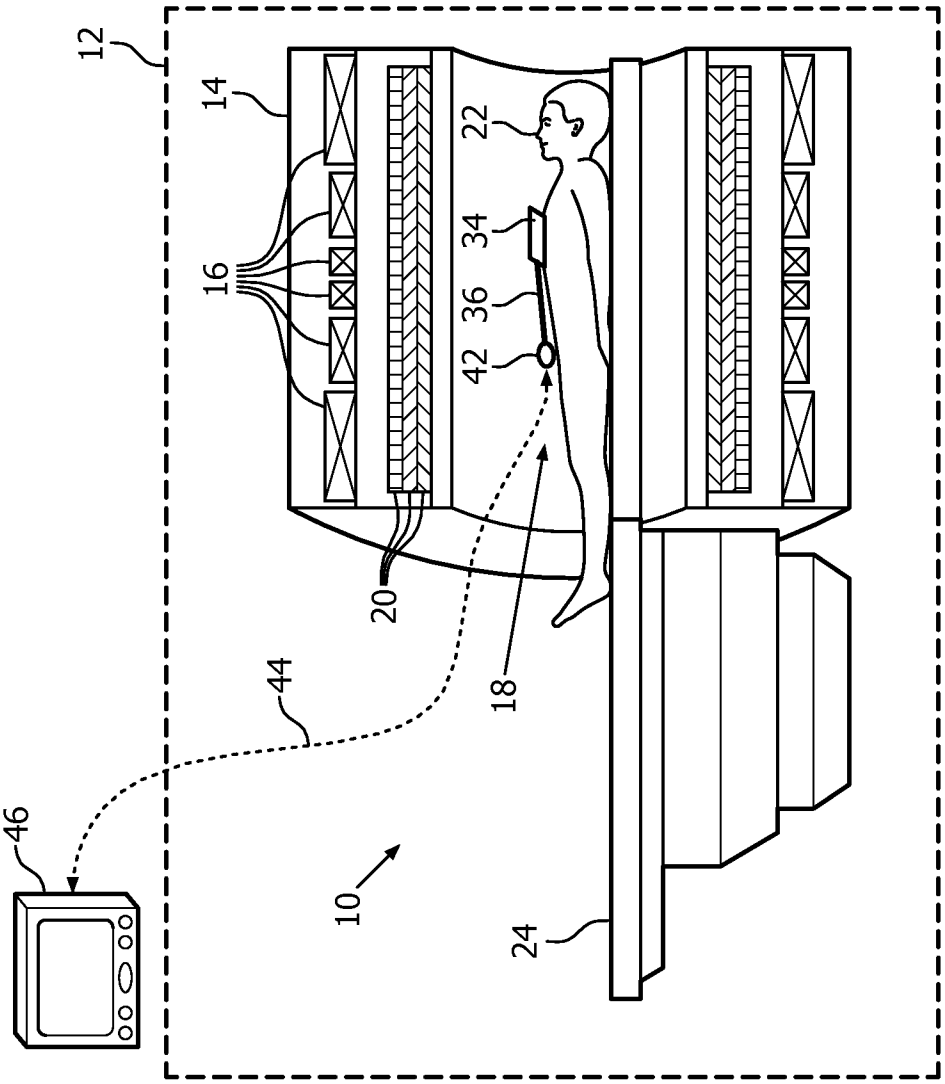

FIG. 1

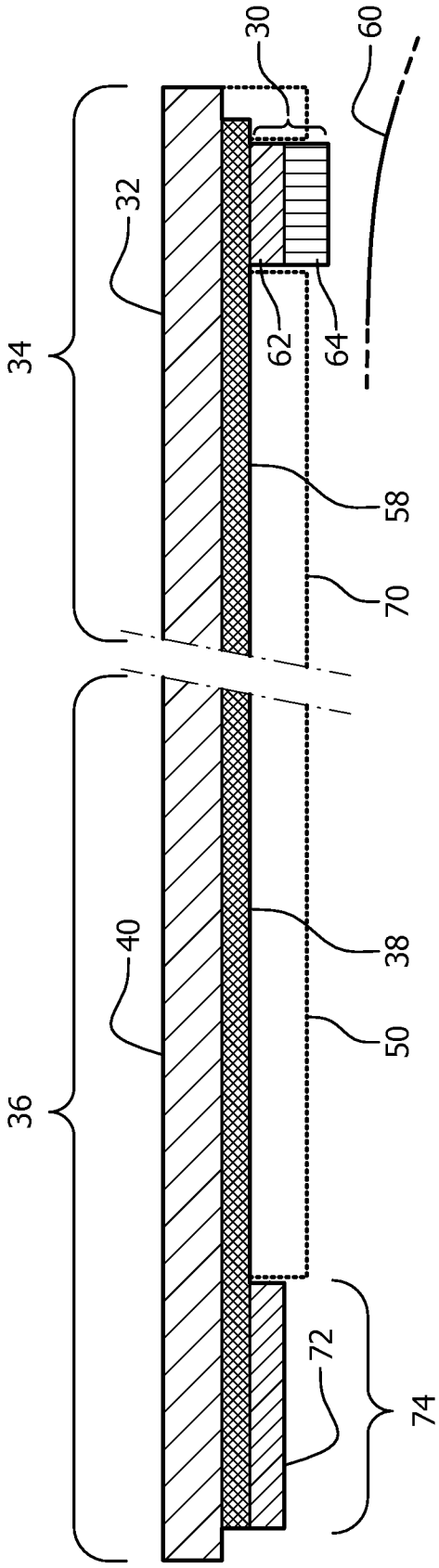

FIG. 3

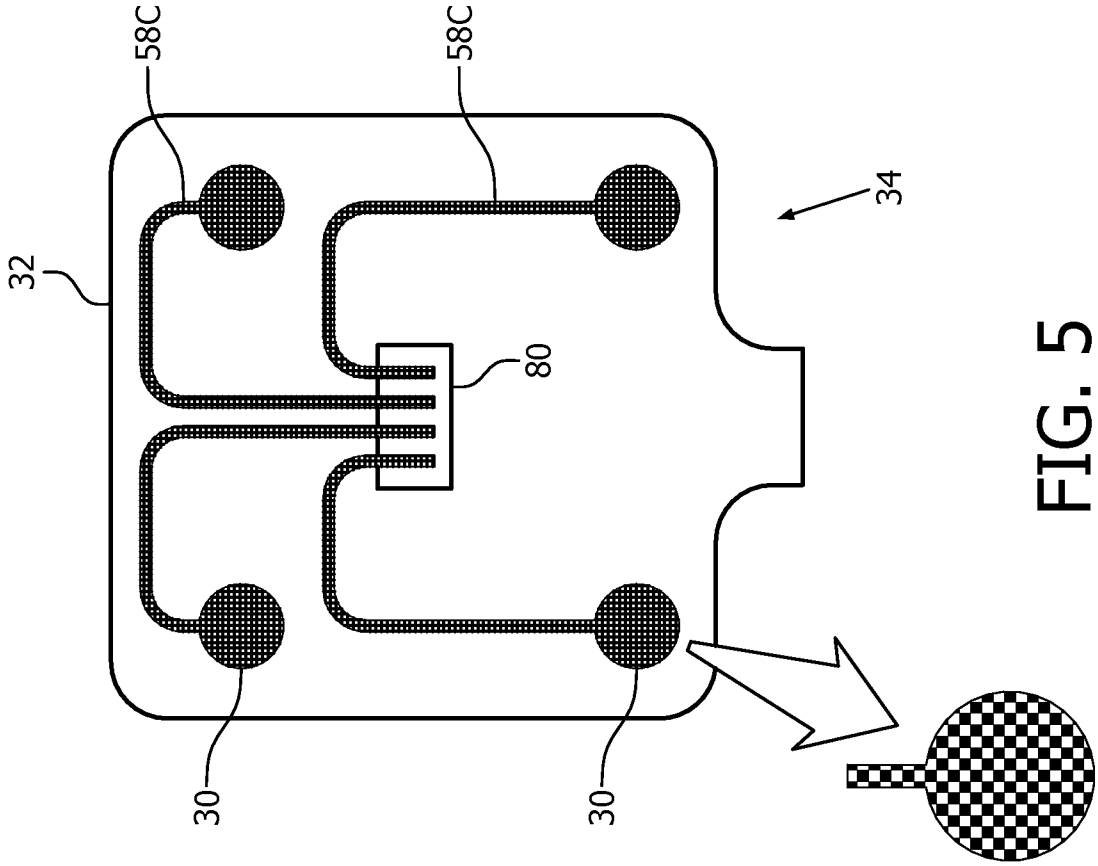

FIG. 5

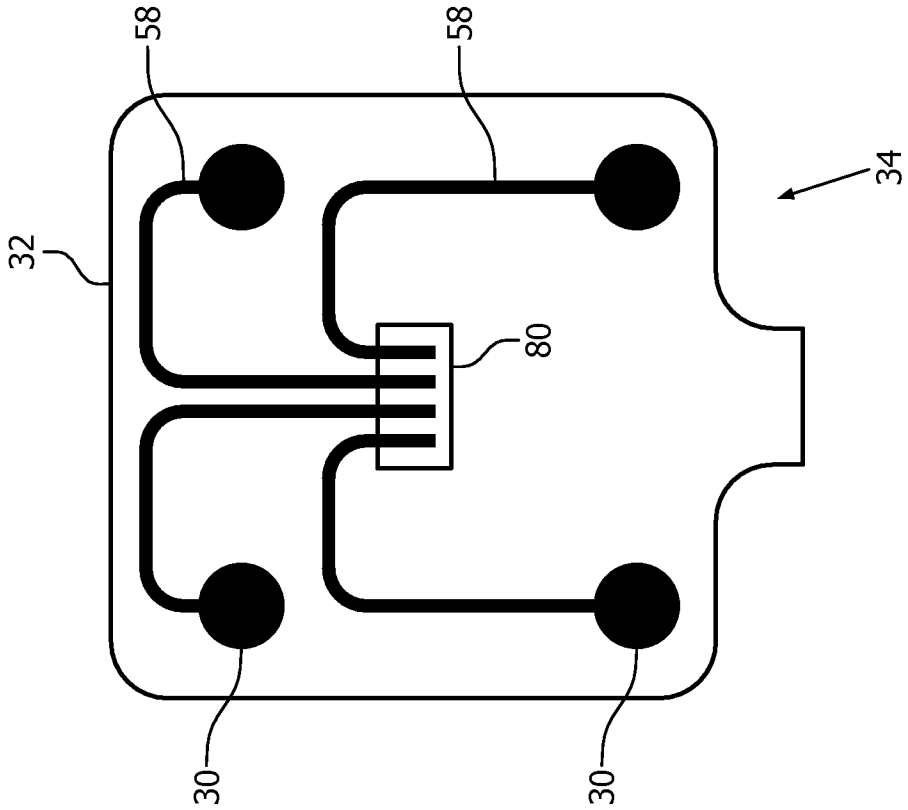

FIG. 4

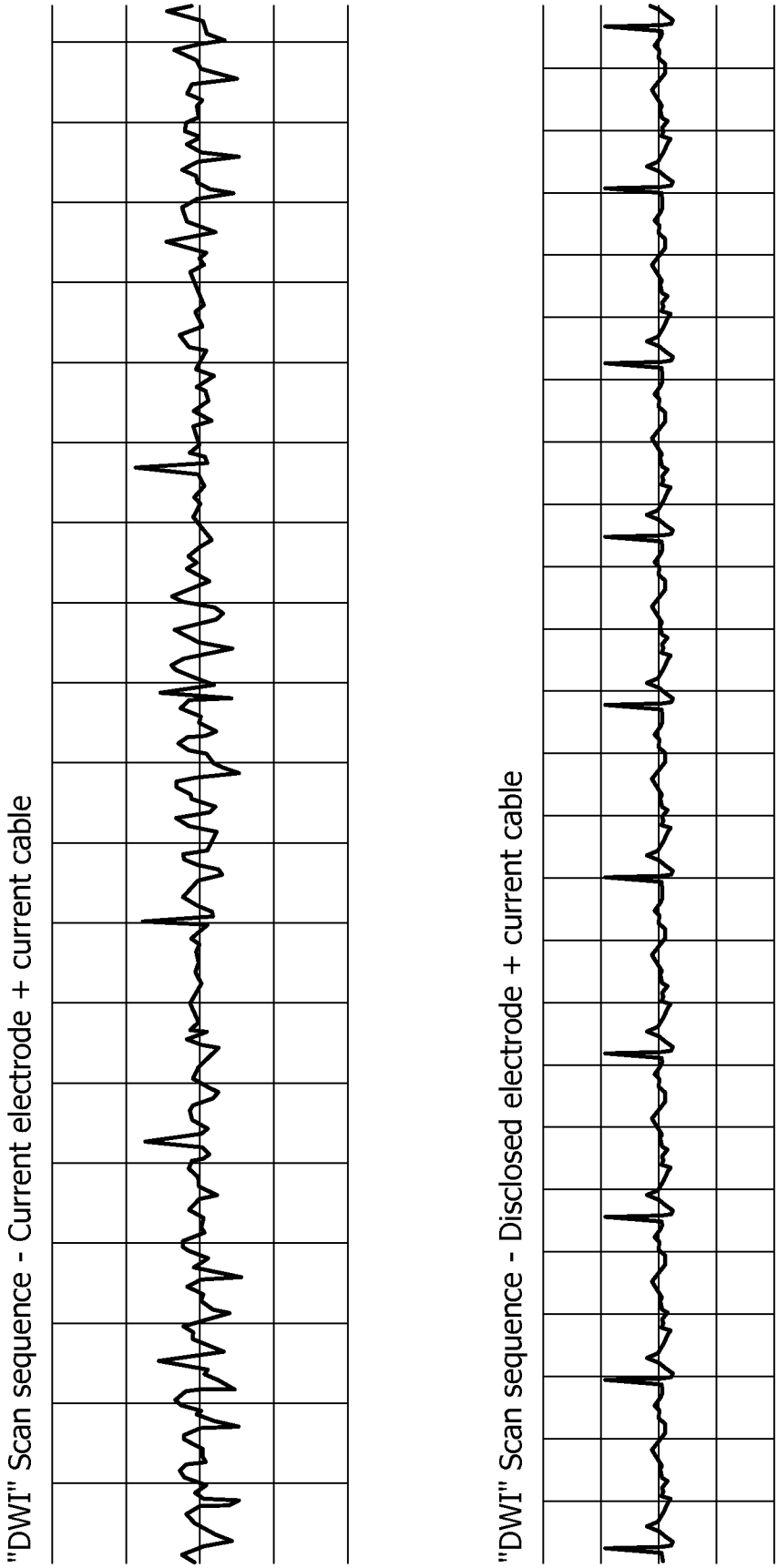
"DWI" Scan sequence - Current electrode + current cable
"DWI" Scan sequence - Disclosed electrode + current cable

FIG. 6

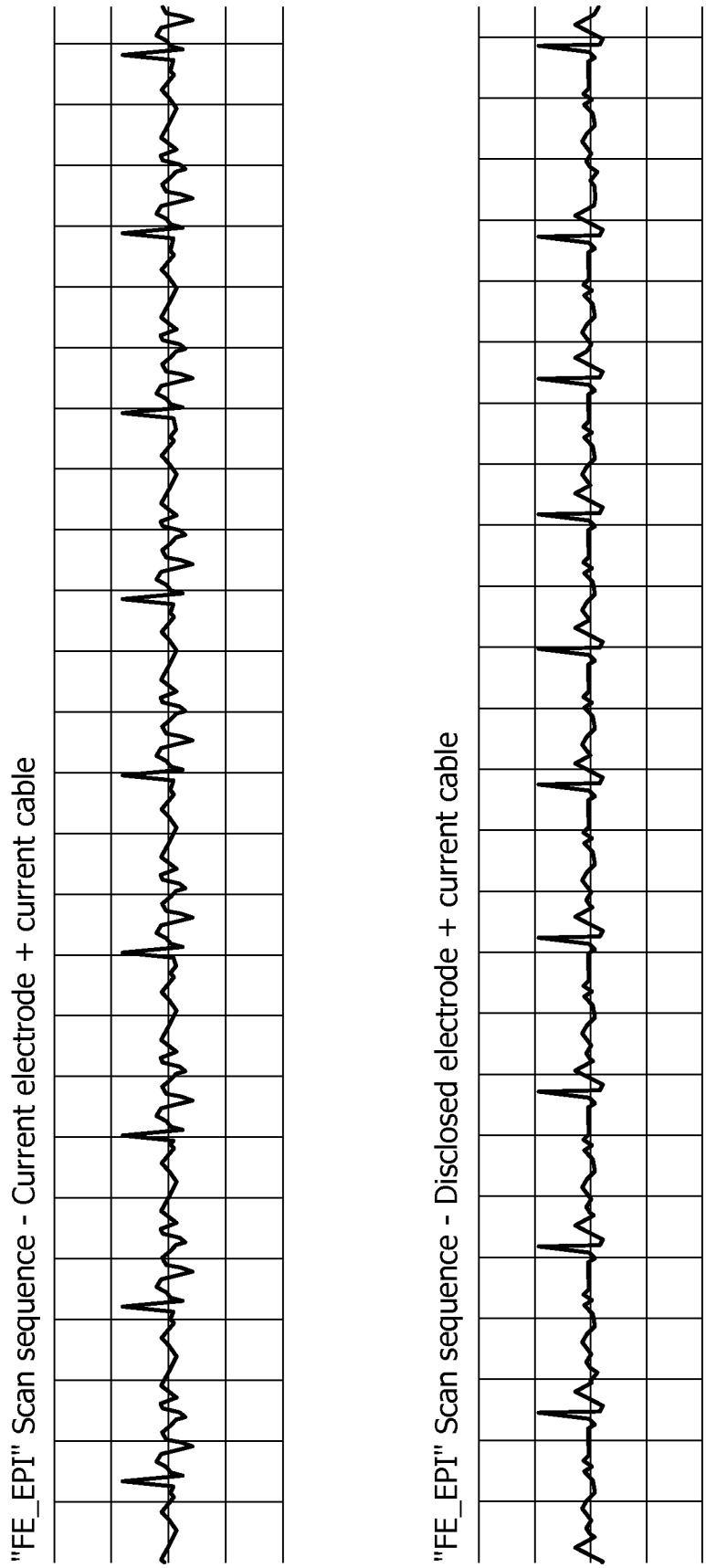
"FE_EPI" Scan sequence - Current electrode + current cable
"FE_EPI" Scan sequence - Disclosed electrode + current cable

FIG. 7

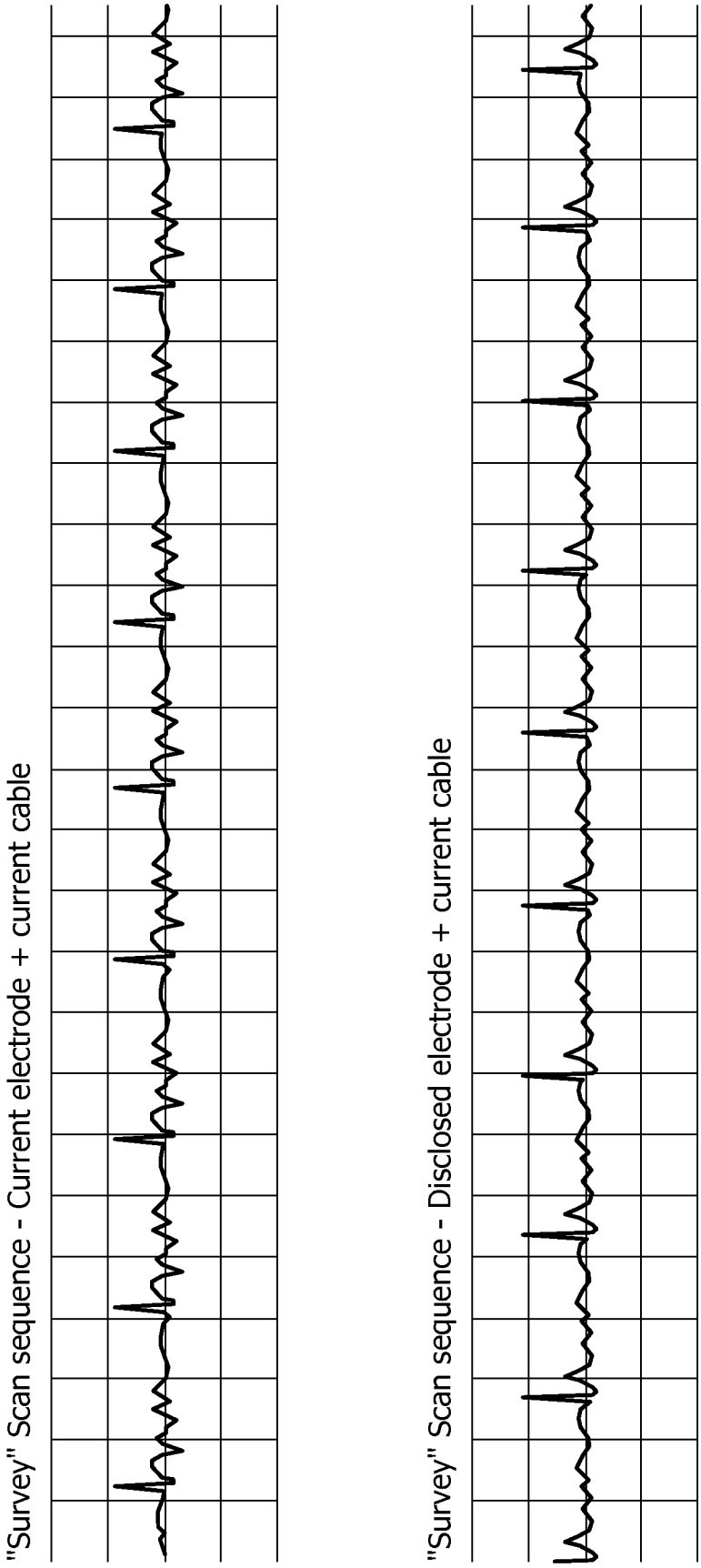
"Survey" Scan sequence - Current electrode + current cable
"Survey" Scan sequence - Disclosed electrode + current cable

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/054353

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61B5/0428 A61B5/055
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B A61N

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2006/121469 A1 (GEN HOSPITAL CORP [US]; BONMASSAR GIORGIO [US]; PURDON PATRICK L [US]) 16 November 2006 (2006-11-16)	1-8, 17-21
Y	figures 1, 7, 8A, 8B, 13-17 claims 14, 44, 45, 47 page 1, lines 12, 13 page 5, lines 27-30 page 6, lines 13-15 page 7, lines 7-9 page 10, lines 30-32 page 12, lines 14-16, 25 page 16, lines 25-27 page 17, lines 22-31 page 18, lines 4-12, 21-27 page 20, lines 4-7, 31-33	9-16

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 2013	04/11/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Almeida, Mariana

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/054353

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2006/116677 A2 (IVY BIOMEDICAL SYSTEMS INC [US]; TUCCILLO MARK JOSEPH [US]; BLANK ELLI) 2 November 2006 (2006-11-02)	17-21
Y	figure 1	9-16
A	claims 2, 6 paragraphs [0009] - [0011], [0013], [0014] -----	1-8

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2013/054353

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		US 2008306397 A1	11-12-2008
		WO 2006121469 A1	16-11-2006
WO 2006116677 A2	02-11-2006	EP 1874182 A2	09-01-2008
		JP 2008539041 A	13-11-2008
		US 2006247509 A1	02-11-2006
		WO 2006116677 A2	02-11-2006