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### BRUSH ELECTRODE

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#### Abstract

A brush electrode includes an electrode base that is connectable to an external device that is configured to generate an electrical signal or receive an electrical signal. A plurality of strand electrodes extend outward from the electrode base. A distal end of each strand electrode is configured to contact a skin surface. The strand electrodes are configured to hold an electrolyte to facilitate ionic conduction of the electrical signal to or from the skin surface.

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## Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS [0001] The present application is a continuation application of U.S. patent application Ser. No. 18/120,427, filed Mar. 13, 2023, now U.S. Pat. No. 12,257,058, which is a Continuation of U.S. patent application Ser. No. 16/469,207, filed Jun. 13, 2019, now U.S. Pat. No. 11,647,937, which is a national phase application of PCT/IL2017/050934, filed Aug. 22, 2017, claiming benefit from U.S. Provisional Patent Application No. 62/434,954, filed Dec. 15, 2016, all of which are incorporated herein by reference in their entirety.

### FIELD OF THE INVENTION

[0002] The present invention relates to electrodes for contact with a body. More particularly, the present invention relates to a brush electrode.

### BACKGROUND OF THE INVENTION

[0003] Various medical applications or other applications benefit from electrodes that are noninvasive and sensitive to various electrical signals that are produced by the body of a human, animal, other form of living being. For example, various noninvasive medical diagnostic, therapeutic, or research procedures may utilize such electrodes that are placed on the skin. Such procedures include, for example, electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG) and other diagnostic techniques. A diagnostic or therapeutic technique may include electrical brain stimulation, muscle stimulation, neuronal stimulation, or other types of stimulation.

[0004] In some cases, such electrodes may be utilized in a gaming system, in lie detection, in monitoring of a vehicle or machine operator, or in various other situations, in or out of the laboratory.

[0005] Typically, an electrode for conducting electrical signals between the skin and an external device is placed or pressed onto the skin at one or more appropriate locations (e.g., near an organ or tissue that produces an electrical signal or that is affected by an externally applied electrical signal). Typically, the interface between the skin and the electrode is not an efficient conductor of electrical signals. Among other reasons, an electronic component operates via conduction of electrical charges in the form of electrons and holes, while electrical signals in physiological organs, tissues, and cells typically involve movement of electrical charges in the form of positive and negative ions. Conduction of an electrical signal into the body may require a charge conversion by an electrochemical process.

[0006] In order to facilitate electrical conduction at the interface between the skin and the electrode, a conductive medium is placed at the interface. For example, the conductive medium may include saline solution (e.g., permeating a sponge or other absorbent material), a conductive gel, or another wet medium. The conductive medium may be placed onto the skin, onto the electrode, or both. For example, some disposable electrodes are pre-embedded in a pad that may include a conductive medium, an adhesive, or both.

### SUMMARY OF THE INVENTION

[0007] There is thus provided, in accordance with an embodiment of the present invention, a brush electrode including: an electrode base that is connectable to an external device that is configured to

generate an electrical signal or receive an electrical signal; and a plurality of strand electrodes that extend outward from the electrode base, a distal end of each strand electrode configured to contact a skin surface, the plurality of strand electrodes configured to hold an electrolyte to facilitate ionic conduction of the electrical signal to or from the skin surface.

[0008] Furthermore, in accordance with an embodiment of the present invention, the strand electrodes are clustered into a plurality of clusters of strand electrodes, neighboring clusters of the plurality of clusters being separated from one another by gaps without any strand electrodes.

[0009] Furthermore, in accordance with an embodiment of the present invention, a cluster of the plurality of clusters is held to the base by a staple or a ferrule.

[0010] Furthermore, in accordance with an embodiment of the present invention, the plurality of clusters are electrically connected to a single external connector for connecting to the external device.

[0011] Furthermore, in accordance with an embodiment of the present invention, at least two clusters of the plurality of clusters are connected to different external connectors for connecting separately to the external device.

[0012] Furthermore, in accordance with an embodiment of the present invention, the brush electrode includes an isolating barrier for electrically isolating two clusters of the plurality of clusters from one another.

[0013] Furthermore, in accordance with an embodiment of the present invention, a distal face of the electrode base includes a plurality of openings, each opening configured to enable the strand electrodes of each cluster of the plurality of clusters to extend distally outward.

[0014] Furthermore, in accordance with an embodiment of the present invention, the plurality of openings are arranged in a rectangular array.

[0015] Furthermore, in accordance with an embodiment of the present invention, the plurality of strand electrodes are configured to hold the electrolyte by capillary forces.

[0016] Furthermore, in accordance with an embodiment of the present invention, a strand electrode of the plurality of strand electrodes includes a hollow core that is configured to be filled with the electrolyte, or is configured to absorb or adsorb the electrolyte.

[0017] Furthermore, in accordance with an embodiment of the present invention, a strand electrode of the plurality of strand electrodes is electrically resistive or ionically conducting.

[0018] Furthermore, in accordance with an embodiment of the present invention, a proximal segment of a strand electrode of the plurality of strand electrodes is electronically conducting, and a distal segment of that strand electrode is electrically resistive or ionically conducting.

[0019] Furthermore, in accordance with an embodiment of the present invention, the brush electrode includes an electrolyte reservoir.

[0020] Furthermore, in accordance with an embodiment of the present invention, the plurality of strand electrodes includes strand electrodes of different lengths.

[0021] Furthermore, in accordance with an embodiment of the present invention, the electrode base is curved.

[0022] Furthermore, in accordance with an embodiment of the present invention, the strand electrodes extend substantially perpendicularly outward from the electrode base.

[0023] Furthermore, in accordance with an embodiment of the present invention, the strand electrodes extend outward from the electrode base at an oblique angle to the electrode base.

[0024] Furthermore, in accordance with an embodiment of the present invention, the strand electrodes are tilted laterally outward.

[0025] Furthermore, in accordance with an embodiment of the present invention, a plurality of neighboring strand electrodes of the plurality of strand electrodes terminate in a single ion-conducting tip.

[0026] Furthermore, in accordance with an embodiment of the present invention, a plurality of strand electrodes are fully or partially covered by a sleeve.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0027] In order for the present invention to be better understood and for its practical applications to be appreciated, the following Figures are provided and referenced hereafter. It should be noted that the Figures are given as examples only and in no way limit the scope of the invention. Like components are denoted by like reference numerals.

[0028] FIG. 1 schematically illustrates a cross section of a brush electrode, in accordance with an embodiment of the present invention.

[0029] FIG. 2 schematically illustrates a cross section of a brush electrode having strand electrodes arranged in clusters in the form of tufts held in place by staples.

[0030] FIG. 3 schematically illustrates a cross section of a brush electrode having clusters of strand electrodes that are held in place by ferrules.

[0031] FIG. 4 schematically illustrates a cross section of a brush electrode as shown in FIG. 3, with an electrolyte solution adhering to the clusters of conductive strand electrodes.

[0032] FIG. 5A schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. 4, with segmented strand electrodes that are partially electrically conductive and partially nonconductive.

[0033] FIG. 5B schematically illustrates a segmented strand electrode of the brush electrode shown in FIG. 5A.

[0034] FIG. 6 schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. 4, where each electrode cluster includes different types of strand electrodes.

[0035] FIG. 7 schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. 4, where electrolysis is configured to occur at a proximal end of each strand electrode.

[0036] FIG. 8 schematically illustrates an example of a cross section of a brush electrode that includes an electrolyte reservoir within the electrode casing.

[0037] FIG. 9 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, with strand electrodes having different lengths.

[0038] FIG. 10 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, having a curved electrode base.

[0039] FIG. 11 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, having tilted strand electrodes.

[0040] FIG. 12 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 11, having strand electrodes that are tilted laterally outward.

[0041] FIG. 13 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, configured to separately connect each electrode cluster to an external device.

[0042] FIG. 14 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, with isolating barriers.

[0043] FIG. 15 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 13, having isolating barriers between electrode clusters.

[0044] FIG. 16 schematically illustrates a variant of the cross section of a brush electrode shown in FIG. 3, where the distal ends of groups of strand electrodes within a single electrode cluster terminate in an ion-conducting tip.

[0045] FIG. 17 schematically a variant of the cross section of a brush electrode shown in FIG. 3, where all strand electrodes in an electrode cluster terminate in a single ion-conducting tip.

[0046] FIG. 18 schematically illustrates variants of electrode clusters of the cross section of a brush electrode shown in FIG. 17.

[0047] FIG. 19 schematically illustrates variants in the forms of longitudinal cross sections strand electrodes for a brush electrode as shown in FIG. 1.

[0048] FIG. 20 schematically illustrates variants of a transverse cross-sectional shape of a strand electrode for a brush electrode as shown in FIG. 1.

[0049] FIG. 21 schematically illustrates a face of an electrode base of a brush electrode as shown in cross section in FIG. 3.

[0050] FIG. 22 schematically illustrates a system that includes a plurality of brush electrodes, in accordance with an embodiment of the present invention.

[0051] FIG. 23 schematically illustrates a brush electrode with hollow strand electrodes, in accordance with an embodiment of the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

[0052] In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the invention. However, it will be understood by those of ordinary skill in the art that the invention may be practiced without these specific details. In other instances, well-known methods, procedures, components, modules, units and/or circuits have not been described in detail so as not to obscure the invention.

[0053] Although embodiments of the invention are not limited in this regard, discussions utilizing terms such as, for example, “processing,” “computing,” “calculating,” “determining,” “establishing,” “analyzing,” “checking,” or the like, may refer to operation(s) and/or process(es) of a computer, a computing platform, a computing system, or other electronic computing device, that manipulates and/or transforms data represented as physical (e.g., electronic) quantities within the computer's registers and/or memories into other data similarly represented as physical quantities within the computer's registers and/or memories or other information non-transitory storage medium (e.g., a memory) that may store instructions to perform operations and/or processes. Although embodiments of the invention are not limited in this regard, the terms “plurality” and “a plurality” as used herein may include, for example, “multiple” or “two or more”. The terms “plurality” or “a plurality” may be used throughout the specification to describe two or more components, devices, elements, units, parameters, or the like. Unless explicitly stated, the method embodiments described herein are not constrained to a particular order or sequence. Additionally, some of the described method embodiments or elements thereof can occur or be performed simultaneously, at the same point in time, or concurrently. Unless otherwise indicated, the conjunction “or” as used herein is to be understood as inclusive (any or all of the stated options).

[0054] In accordance with an embodiment of the present invention, an electrode for detecting via skin an electrical signal that is generated by a body (e.g., human, animal, or other living body), or for applying an electrical signal to the body via the skin, is in the form of strand electrodes (having a form suggestive of bristles of a brush). An electrode that includes such strand electrodes is referred to herein as a brush electrode.

[0055] A distal end of a strand electrode is configured to be placed against a skin surface of the body and to enable conduction of an electrical signal between the body and an external device. For example, physical properties of the strand electrode (e.g., elasticity, plasticity, or other physical properties) may enable the strand electrode to bend or otherwise accommodate contours of the skin surface while the distal end remains in physical contact with the skin surface. The strand electrode is configured to enable ionic conduction at least at the point of contact. For example, the strand electrode may be made of, covered by (e.g., coated with, e.g., due to hydrophilicity of the strand electrode), or filled with (e.g., absorb or have a hollow core filled with) an ionically conducting material. Alternatively or in addition, the distal end of a strand electrode, or of a group of neighboring strand electrodes, may terminate in an ionically conducting pad or tip. Alternatively or in addition, strand electrodes and the separation distance between the strand electrodes may be configured to hold an ionically conducting substance by capillary forces or otherwise (e.g., hydrophilicity).

[0056] A proximal end of each strand electrode may be connected to an electrode base. The electrode base may be connected to an external device. The external device may include a signal

generator or other source of an electrical signal that is to be applied to the skin surface or a sensor or detector that is configured to sense or detect a signal that is produced by the body. An electrical signal may thus be conducted by each strand electrode between the external device and the skin surface.

[0057] For example, one or more brush electrodes may be configured to facilitate transcranial electric brain stimulation, such as, transcranial direct current stimulation (tDCS), random noise stimulation (RNS), transcranial alternating current stimulation (tACS), or other transcranial stimulation. As another example, one or more brush electrodes may be configured to be used in EEG for sensing neural activity of the brain. In some cases, the brush electrodes may be configured to transmit electric stimulation signals at some times and to sense electric signals at other times, or to concurrently transmit and sense, e.g., using different frequencies or frequency ranges.

[0058] A brush electrode as described herein may be advantageous over other types of electrodes. For example, other types of electrodes may require spreading a conductive substance, e.g., in the form of a conductive electrolyte solution or gel, over an entire area of the electrode, or over an equivalent area of the skin. Thus, extensive cleanup of the skin, and any hair covering the skin, may be required after use of the electrode. In particular, when the electrode is to be used on a hairy region of skin, such as the head, attaining contact between the electrode and the skin may require shaving that region of the skin. In addition, moving such an electrode about on the skin surface may wet the skin with the conductive substance and effectively increase the area of contact between the electrode and the skin, e.g., reducing precision of a measurement or application of the electric signal.

[0059] A brush electrode as described herein may be used on hair-covered regions without shaving the hair. The distal ends of each electrode strand may reach the skin between hairs. A conductive substance may be held on the strand electrodes, e.g., by capillary forces in the narrow space between adjacent strand electrodes, capillary forces within (e.g., within a hollow core or between braids of) a strand electrode, absorption within a strand electrode, adsorption to the surface of the strand electrode (e.g., by hydrophilicity of the strand electrode), or otherwise. Thus, it may not be necessary to spread the conductive substance over the skin. Thus, wetting of the skin may be reduced in comparison with use of other types of electrodes.

[0060] Some or all of the strand electrodes may be conducting, e.g., constructed of a conductive polymer, metal, or other conductive material, or coated with a conducting material. In some cases, the distal end of a strand electrode may be configured to penetrate into the skin, e.g., e.g., a stratum corneum layer, to facilitate electrical conduction between the body and the external device.

[0061] A thickness of each strand electrode may be selected for a particular application or type of application. Increasing the thickness of a strand electrode may increase its rigidity. Such increased rigidity may be advantageous where the strand electrode is to be used to penetrate hair, clothing, bandaging, skin, or in other situations where increased rigidity may be advantageous. On the other hand, decreasing the thickness of a strand electrode may increase its flexibility. Increased flexibility may enable the strand electrode to bend in order to increase its area of contact with smooth skin, or may enable accommodating various protrusions, depressions, or openings on the skin surface.

[0062] Similarly, a size of a cluster of strand electrodes, a number of strand electrodes in each cluster, or selection of a structure or technique for holding a plurality of adjacent strand electrodes in the form of a cluster, may be configured for a particular application or type of application.

[0063] FIG. 1 schematically illustrates a cross section of a brush electrode, in accordance with an embodiment of the present invention.

[0064] Brush electrode **10** includes a plurality of strand electrodes **12**. Although the cross sectional view of FIG. 1 shows a uniform linear array of strand electrodes **12** for convenience, it should be understood that strand electrodes **12** of a typical brush electrode **10** may be arranged in a two dimensional pattern (e.g., rectangular, circular, polygonal, oval, or other two-dimensional arrangement). A pattern of strand electrodes **12** may include rows, circles, or other arrangements.

Strand electrodes **12** may be irregularly or non-uniformly distributed on brush electrode **10**.

[0065] A distal end of each strand electrode **12** is configured to be placed against a skin surface **11**.

[0066] Strand electrodes **12** may be configured to adhere to, to absorb, to adsorb, or to otherwise hold a conductive substance, e.g., in the form of an electrolyte solution for conducting ion charges through the electrolyte solution to skin surface **11**. In some cases, each strand electrode **12** may be at least partially electrically conductive. Strand electrodes **12** may be configured to facilitate an electrolysis interface with the conductive substance.

[0067] Brush electrode **10** includes electrode casing **15**. For example, electrode casing **15** may be configured to isolate all parts of strand electrodes **12**, e.g., except for exposed distal ends of strand electrodes **12**, from contact with any other objects. Electrode casing **15** may be configured to partially or fully isolate strand electrodes **12** e.g., except for exposed distal ends of strand electrodes **12**, as well as other internal components of brush electrode **10** from contact with an ambient atmosphere. Thus, electrode casing **15** may function to prevent contact with external objects or with components of the atmosphere (e.g., moisture, suspended particles, or other components of the ambient atmosphere) from interfering with operation of brush electrode **10**.

[0068] Dimensions of electrode casing **15** may range from having a length of up to 5 mm, a width of up to 5 mm, and a thickness of up to 1 mm, to having a length of up to 100 mm, a width of up to 100 mm, and a thickness of up to 40 mm (or other ratios between length, width and thickness).

[0069] Strand electrodes **12** of brush electrode **10** may be held in place, e.g., in a particular arrangement, by electrode base **16**. Electrode base **16** may be incorporated into, or attachable to, electrode casing **15**. For example, electrode base **16** may include an arrangement of openings through which each strand electrode **12** may extend distally. In some cases, electrode base **16** may be configured to hold clusters of strand electrodes **12** in a particular arrangement of clusters.

[0070] Electrode base **16** may be elastic, rigid, or pliable. In some cases, electrode base **16** may be electrically conductive, for example, made of aluminum or another metal, conductive plastic or silicone, or another conductive material. In some cases, electrode base **16** may be made of a nonconductive plastic, silicone, or other nonconductive material. In some cases, electrode base **16** may be made of a combination of one or more materials, including, but not limited to, materials mentioned above. Electrode base **16** may be circular, rectangular, or otherwise shaped, with a surface area in the range of about 1 square centimeter to about 40 square centimeters. For example, a size and shape of electrode base **16**, or of brush electrode **10**, may be selected to approximately match (e.g., such that strand electrodes **12** cover) a target region of the skin surface to which brush electrode **10** is to be applied.

[0071] In the example shown, all strand electrodes **12** extended distally outward in a direction that is substantially perpendicular to electrode base **16**. In other examples, some or all of strand electrodes **12** may extend distally outward from electrode base **16** at an oblique angle to electrode base **16**.

[0072] In some cases, each strand electrode **12** may extend distally outward from electrode base **16** by a distance that is no longer than 3 cm. In some cases, each strand electrode **12** may extend outward from electrode base **16** by less than 2 cm, e.g., between 1 cm and 2 cm.

[0073] Strand electrodes **12** may be flexible, elastic, or plastic, e.g., depending on a material from which each strand electrode **12** is constructed, and on a lateral thickness of each strand electrode **12**. For example, strand electrode **12** may be constructed of, or may include, conductive or nonconductive PA 6 nylon, PA 6,6 nylon, PA 6,10 nylon, PA 6,12 nylon, or viscose. A strand electrode **12** may be made of Thunderon™, silicone, polyethylene or other polymer, elastomer, metal, agave bristle, animal hair, or other materials. In some cases, strand electrodes **12** may be coated with a conductive material. In some cases, strand electrode **12** is not conductive but is coated with a conductive material.

[0074] A lateral thickness (e.g., diameter or other representative distance from one side of a strand electrode **12** to another) may range from 0.01 mm to 1 mm, e.g., in a range of lateral thickness from

about 0.05 mm to about 0.8 mm, or, more particularly, from about 0.15 mm to about 0.6 mm. A strand electrode **12** may have another lateral thickness.

[0075] A density of an arrangement of strand electrodes **12**, e.g., on a surface of electrode base **16**, may range from about 20 strand electrodes **12** per square centimeter of surface area to about 200 strand electrodes **12** per square centimeter of surface area. In some cases, the density may be selected in accordance with lateral thickness of each strand electrode **12**.

[0076] Strand electrodes **12** may be made of a material with a volume resistivity ranging from about  $10 \times 10^8 \Omega\text{-cm}$  to less than  $10 \times 10^3 \Omega\text{-cm}$ . Similarly, surface resistivity may range from about  $10 \times 10^8 \Omega/\text{square}$  to less than  $10 \times 10^3 \Omega/\text{square}$ .

[0077] According to some embodiments, strand electrode **12** made of different materials, or otherwise having different properties or characteristics, may be included in a single brush electrode **10**.

[0078] Each strand electrode **12** may be electrically connected to an external device. For example, the external device may be configured to generate an electrical signal, to receive an electrical signal, or both. The external device may be wearable or other portable device, or may be a non-portable, e.g., desktop or other fixed, device. The external device may be battery powered, may be connected to a computer or computing circuitry, or may be otherwise powered.

[0079] A proximal end of each strand electrode **12** of brush electrode **10** may be held, e.g., by electrode base **16**, in electrical contact with electrode conductor **14**. Typically, e.g., when single electrical signal is to be applied concurrently to all strand electrodes **12**, or when all strand electrodes **12** are to conduct a single electrical signal from a skin surface **11** to the external device, all strand electrodes **12** may be connected to a single common electrode conductor **14**. For example, electrode conductor **14** may be in the form of one or more plates or bars that are constructed of a conducting metal, polymer, or other conducting material. The plates or bars of electrode conductor **14** may be in electrical contact with one another, e.g., directly or via a common conductor to which all of the plates or bars are electrically connected. In some cases, e.g., where different strand electrodes **12** are configured to carry concurrently different electrical signals, electrode conductor **14** may include two or more conducting plates or bars that are not electrically connected to one another.

[0080] For example, electrode conductor **14** may be connected via internal conductor **17** (e.g., that includes one or more conducting wires, cables, or bars) to external connector **18**. For example, in some cases (e.g., where brush electrode **10** is configured to function in place of a traditional ECG or EEG electrode) external connector **18** may include a simple male snap connector. In other cases, external connector **18** may include another type of connector.

[0081] External connector **18** may be connected to an external device by a device connector **20**, e.g., that is connected to the external device by device connection **22**. For example, where external connector **18** is in the form of a male snap connector, device connector **20** may be in the form of a female snap connector. In other examples, device connector **20** may represent another type of connector. In some cases, device connector **20** may include electrical or electronic circuitry. Device connection **22** may include an electrical cable, or another type of wired or wireless connection to the external device.

[0082] In some cases, strand electrodes **12** may be arranged on electrode base **16** in clusters of densely packed strand electrodes **12**, with neighboring clusters being separated by gaps with no strand electrodes. The arrangement in clusters may facilitate holding of a conductive substance, e.g., by capillary forces between the surfaces of different strand electrodes **12** in a cluster. The facilitated holding of the conductive substance may increase or facilitate conductivity between strand electrodes **12** and a skin surface **11**.

[0083] FIG. 2 schematically illustrates a cross section of a brush electrode having strand electrodes arranged in clusters in the form of tufts held in place by staples.

[0084] In the example shown, strand electrodes **12** are arranged in clusters in the form of electrode



tufts **32**. A plurality of strand electrodes **12** in each electrode tuft **32** are connected to one another at their proximal ends. For example, in some cases, the proximal ends of each strand electrode **12** in an electrode tuft **32** may be formed by bending or folding a single strand (e.g., that is approximately twice as long as each strand electrode **12**) at proximal bend **35** to form two strand electrodes **12**. An electrode tuft **32** may be otherwise formed by a plurality of strand electrodes **12**. [0085] Each electrode tuft **32** may be held within electrode base **16** by tuft staple **34**. Tuft staple **34** may provide an electrical connection between each strand electrode **12** of electrode tuft **32** and electrode conductor **14**. For example, tuft staple **34** may include a wire loop that surrounds both proximal bend **35** and connects to electrode conductor **14** or another part of electrode base **16** or of electrode casing **15**. As another example, a tuft staple may be U-shaped. Such a U-shaped staple may be configured such as the base of the U-shape holds proximal bend **35** of each electrode tuft **32** to (e.g., in electrical contact with) electrode base **16** when the arms of the U-shape are inserted into electrode base **16**.

[0086] Each pair of neighboring electrode tufts **32** is separated by a cluster gap **28**.

[0087] FIG. **3** schematically illustrates a cross section of a brush electrode having clusters of strand electrodes that are held in place by ferrules.

[0088] Each electrode ferrule **36** is configured to hold in place within electrode base **16** the proximal ends of a plurality of strand electrodes **12** of an electrode cluster **30**. For example, at least an interior part of electrode ferrule **36** may be electrically conducting. Each electrode ferrule **36** may be connected via ferrule connector **38** to electrode conductor **14**, or otherwise to an external device. Thus, electrode ferrule **36** may connect strand electrodes **12** in each electrode cluster **30** (e.g., via internal conductor **17** and external connector **18**) to the external device. Each pair of neighboring electrode clusters **30** is separated by a cluster gap **28**.

[0089] For example, the number of strand electrodes **12** in each electrode cluster **30** may range from 5 strand electrodes **12** to more than 20. The lateral thickness of each electrode cluster **30** may be circular or oval, ranging from about 0.5 mm to about 4 mm, and may have a cross-section area of in the range of about 1 square millimeter to about 40 square millimeters. The length of an electrode cluster **30** may range from about 5 mm to about 20 mm.

[0090] A density of a distribution of electrode clusters **30**, e.g., on a distal surface of electrode base **16**, may range from less than 2 electrode clusters **30** per square centimeter to 100 electrode clusters **30** per square centimeter. A representative length of cluster gap **28** (e.g., a minimum distance between adjacent electrode clusters **30**) may range from about 0.5 mm to about 8 mm.

[0091] When all strand electrodes **12** in an electrode cluster **30** are of equal length and extend perpendicularly distally outward from electrode base **16**, then a distal face of electrode cluster **30** may be substantially flat. In some cases, different strand electrodes **12** of a single electrode cluster **30** may have different lengths. In such a case, a distal face **33** of electrode cluster **30** may be substantially flat, perpendicular to strand electrodes **12**, and parallel to electrode base **16**. In other cases, strand electrodes **12** of different lengths may be arranged to form a distal face that is planar but tilted, convex, or otherwise shaped. A single electrode cluster **30** may include strand electrodes **12** of different materials and dimensions.

[0092] A brush electrode **10** may be configured to hold a conductive substance. For example, the conductive substance may be applied by a user of brush electrode **10**, e.g., by dipping strand electrodes **12**, or an electrode cluster **30**, into a conductive substance in the form of a liquid or gel (e.g., an electrolyte solution or other conductive substance in the form of liquid or gel). As another example, a brush electrode **10** may be provided by a producer or vendor of brush electrode **10** with a conductive substance already applied to strand electrodes **12** or to electrode clusters **30** (e.g., within a sealed container, envelope, or packaging).

[0093] FIG. **4** schematically illustrates a cross section of a brush electrode as shown in FIG. **3**, with an electrolyte solution adhering to the clusters of conductive strand electrodes.

[0094] As used herein, a strand electrode, or a part of a strand electrode, is considered to be

conductive when constructed of an electronically conductive material that is configured to conduct electrical current in the form of electrons (e.g., such as a metal or other electronically conductive substance).

[0095] Each electrode cluster **30** is shown as holding conductive substance **40** among electronically conductive strand electrodes **31**. For example, conductive substance **40** may be held within electrode cluster **30** by capillary forces among electronically conductive strand electrodes **31**.

[0096] In the example shown, electronically conductive strand electrodes **31** may be assumed to be conductive so as to facilitate electrolysis, e.g., within conductive substance **40**.

[0097] Other types of electrodes, or combinations of different types of electrodes, may be included in a brush electrode **10** whose strand electrodes are configured to hold a conductive substance **40**.

[0098] In an example of a brush electrode **10**, an electrode cluster **30** includes approximately 40 strand electrodes (e.g., electrically conductive or otherwise), each about 1.2 mm long with a diameter of about 0.3 mm. In some examples, the strand electrodes may be made of or may include conductive nylon PA6.

[0099] The structure of electrode cluster **30** is such that a liquid electrolyte may be held between the strand electrodes by physical or chemical properties of the electrolyte, properties of the surfaces of the strand electrodes, structural properties of electrode cluster **30** (e.g., density or another property of the distribution of the strand electrodes), or a combination of these properties. For example, the strand electrodes may be elastic. Therefore, placing brush electrode **10** on a target region of skin surface **11** may cause the strand electrodes to bend to accommodate any curvature or other topography of skin surface **11** while continuing to hold the electrolyte. The elasticity may enable the strand electrodes to move together without separating from one another, so that at least some of the electrolyte remains held between neighboring strand electrodes to facilitate electrolysis and ionic conduction of an ionic electric signal.

[0100] In another example, the elasticity of the strand electrodes may be sufficiently weak (e.g., weaker than physical forces, e.g., capillary forces or surface tension, holding a liquid electrolyte between neighboring strand electrodes) such that a change in the position of one or more strand electrodes, for example by bending, may affect one or more neighboring or adjacent strand electrodes to change position in a similar manner (e.g., by a force transmitted via an electrolyte or other liquid held among the strand electrodes).

[0101] FIG. 5A schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. 4, with segmented strand electrodes that are partially electrically conductive and partially nonconductive. FIG. 5B schematically illustrates a segmented strand electrode of the brush electrode shown in FIG. 5A.

[0102] As used herein, a strand electrode, or part of a strand electrode, is referred to as nonconductive when that strand electrode, or that part of a strand electrode, does not conduct electrons. The nonconductive strand electrode or part may be electrically insulating (e.g., as defined by a low electric conductivity), or may be configured to primarily conduct electricity by motion of ions. For example, a strand electrode may be ionically conducting if constructed of an ionically conductive material, e.g., of an ion-conducting polymer such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) or another ion-conducting polymer, or may be coated with a conductive substance **40** that is conductive of ions.

[0103] In the example shown, proximal segment **44** of each segmented strand electrode **42** is electrically conductive. The electrically conductive proximal segment **44** may facilitate electrolysis within conductive substance **40**. Distal region **46** of each segmented strand electrode **42** is electrically nonconductive. Electrically nonconductive distal region **46** may provide a medium to enable conductive substance **40** and ionic charges to reach a skin surface **11** against which distal regions **46** are placed in contact.

[0104] FIG. 6 schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. 4, where each electrode cluster includes different types of strand electrodes.

[0105] In the example shown, each electrode cluster **30** includes both conductive electronically conductive strand electrodes **31**, and nonconductive strand electrodes **48**. For example, conductive electronically conductive strand electrodes **31** may facilitate electrolysis, e.g., in conductive substance **40**. Nonconductive strand electrodes **48** may function as a medium to enable conductive substance **40** to reach skin surface **11**. Nonconductive strand electrodes **48** may be electrically insulating or may be ion conducting.

[0106] In other examples, different types of strand electrodes may have different mechanical characteristics, electrical characteristics, chemical characteristics, or may differ with regard to other types of characteristics.

[0107] FIG. **7** schematically illustrates a variant of a cross section of a brush electrode as shown in FIG. **4**, where electrolysis is configured to occur at a proximal end of each strand electrode.

[0108] In the example shown, conductive substance **40** is present within electrode base **16**. For example, conductive substance **40** may be present within each electrode ferrule **36**, as shown, or elsewhere within electrode base **16**.

[0109] In this case may be configured to conduct the ions from electrode base **16** to a skin surface **11** with which the distal ends of the strand electrodes are in contact. In the example shown, strand electrodes in the form of nonconductive strand electrodes **48** are coated with conductive substance **40**. Alternatively or in addition, nonconductive strand electrodes **48** may be ionically conductive (e.g., without conductive substance **40**), or the strand electrodes may include electronically conductive strand electrodes **31** that are coated with conductive substance **40**.

[0110] FIG. **8** schematically illustrates an example of a cross section of a brush electrode that includes an electrolyte reservoir within the electrode casing.

[0111] In the example shown, electrode conductor **14** is connected to a plurality of electrolysis electrodes **52**. Each electrolysis electrode is configured to be at least partially immersed in an electrolyte within electrolyte reservoir **50**.

[0112] In the example shown, electrolyte reservoir **50** is enclosed in electrode casing **15** outside of electrode base **16**. Alternatively or in addition, electrolyte reservoir **50** may be located within electrode base **16**. Electrolysis may occur within electrolyte reservoir **50**, e.g., at electrolysis electrodes **52**. The strand electrodes may include nonconductive strand electrodes **48**, e.g., that are ionically conducting. Alternatively or in addition, the strand electrodes may include electronically conductive strand electrodes **31** or resistive nonconductive strand electrodes **48** that covered by a conductive substance **40**.

[0113] In some cases, strand electrodes or electrode clusters of a brush electrode **10** may be configured to facilitate contact of the distal ends of the strand electrodes with a skin surface **11**.

[0114] FIG. **9** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, with strand electrodes having different lengths.

[0115] In the example shown outer electrode clusters **54a** are located near a lateral edge of brush electrode **10**, while inner electrode clusters **54b** are located interior to (e.g., further away from an edge than) outer electrode clusters **54a**. In the example shown, strand electrodes **56a** of outer electrode clusters **54a** are longer than strand electrodes **56b** of inner electrode clusters **54b**. This configuration may facilitate contact of the distal ends of strand electrodes **56a** and **56b** with a convex skin surface **11** (e.g., a head, limb, or other convex surface).

[0116] In other examples, inner strand electrodes **56b** may be longer than outer strand electrodes **56a**, e.g., to facilitate contact with a concave skin surface **11**.

[0117] Typically, a brush electrode **10** may include more than four electrode clusters (e.g., more than in the example shown). In such a case, the lengths of the strand electrodes in the electrode clusters may gradually increase or decrease with increasing distance from a center of that brush electrode **10**.

[0118] FIG. **10** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, having a curved electrode base.

[0119] In the example shown, all strand electrodes **12** have the same length. However, curved electrode base **60** is concave (e.g., as viewed from the direction of a skin surface **11**). Such a concave curved electrode base **60** may facilitate contact of the distal ends of strand electrodes **12** (e.g., where all strand electrodes **12** extend distally by equal lengths from a connection of each strand electrode **12** with concave curved electrode base **60**) with a convex skin surface **11** (e.g., on a head, limb, or other convex surface).

[0120] In other examples, curved electrode base **60** may be convex, e.g., to facilitate contact of the distal ends of strand electrodes **12** with a concave skin surface **11** (e.g., at an inner joint in a limb or in the neck region).

[0121] In some cases, a brush electrode **10** may include both electrode clusters of different lengths and a curved electrode base **60**.

[0122] FIG. **11** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, having tilted strand electrodes.

[0123] Strand electrodes **12** of each tilted electrode cluster **62** extend distally outward at an oblique angle to (e.g., the distal face of) electrode base **16**. For example, the tilt of each tilted electrode cluster **62** may facilitate penetration of hair to an underlying skin surface **11**, or may increase comfort of a subject whose skin is contacted by strand electrodes **12**.

[0124] FIG. **12** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **11**, having strand electrodes that are tilted laterally outward.

[0125] In the example shown, strand electrodes **12** of each outwardly tilted electrode cluster **64** are tilted laterally outward (e.g., such that their distal end of each strand electrode **12** is further from a center of brush electrode **10** than its proximal end), each at an oblique angle to (e.g., the distal face of) electrode base **16**. The laterally outward tilt may, in addition to facilitating hair penetration and promoting comfort, may contribute to stability of placement of brush electrode **10** on a skin surface **11**. For example, the outward lateral tilt may impede lateral sliding of brush electrode **10** across skin surface **11**.

[0126] In other examples, outwardly tilted electrode cluster **64** may have other orientations. For example, in addition to a laterally outward tilt, each outwardly tilted electrode cluster **64** may also have an azimuthal tilt or slant. The azimuthal slant may, in some cases, enable placement of brush electrode **10a** skin surface **11** with a lateral twisting motion. Such an azimuthal slant may further facilitate hair penetration and contact of strand electrodes **12** with a skin surface **11**.

[0127] In some cases, different parts of a brush electrode **10** may be configured to apply or sense different electrical signals, or to facilitate placement of different brush electrodes **10** in close proximity to one another, e.g., to facilitate application or sensing of different electrical signals.

[0128] FIG. **13** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, configured to separately connect each electrode cluster to an external device.

[0129] In the example shown, each electrode cluster **30** is connected to a separate external connector **58** via a separate internal conductor **57**. Each external connector **58** may be separately connected to a different external device, or to a different port or connector of the external device. Thus, a different electrical signal may be separately applied to each electrode cluster **30**, or may be separately sensed via each electrode cluster **30**. For example, in some cases, an electrical signal may be applied to one or more electrode clusters **30**, while an electrical signal may be concurrently sensed by one or more other electrode clusters **30**.

[0130] In other examples, groups of two or more electrode clusters **30** (e.g., neighboring electrode clusters **30**) may be connected to different external connectors **58**.

[0131] FIG. **14** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, with isolating barriers.

[0132] Isolating barriers **68** may be electrically insulating. Isolating barriers **68** may enable placement of two brush electrodes **10** in close proximity to one another. In this case, isolating barriers **68** may prevent contact between strand electrodes **12** or conductive substances **40** of

adjacent brush electrodes **10**. Isolating barriers **10** may include a hydrophobic material to inhibit passage of water or of water-based substances, or may be water absorptive to absorbing any electrolyte that may otherwise seep between isolating barriers **68** and skin surface **11**.

[0133] FIG. **15** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **13**, having isolating barriers between electrode clusters.

[0134] Isolating barriers **68** may prevent contact between strand electrodes **12** of neighboring electrode clusters **30**. This may be advantageous especially when a different electrical signal is applied to, or is sensed by, each electrode cluster **30**.

[0135] In some cases, electrical ionic contact between strand electrodes **12** and a skin surface **11** may be facilitated by connecting the distal ends of groups of one or more strand electrodes **12** to an ionically conducting tip.

[0136] FIG. **16** schematically illustrates a variant of the cross section of a brush electrode shown in FIG. **3**, where the distal ends of groups of strand electrodes within a single electrode cluster terminate in an ion-conducting tip.

[0137] In the example shown, each group of neighboring strand electrodes **12** within an electrode cluster **30** terminates in a single ion-conducting tip **70**. For example, strand electrodes **12** may be electronically conductive and ion-conducting tip **70** may be made of an ionically conductive material.

[0138] FIG. **17** schematically a variant of the cross section of a brush electrode shown in FIG. **3**, where all strand electrodes in an electrode cluster terminate in a single ion-conducting tip.

[0139] Distal ends of all strand electrodes **12** in a single electrode cluster **30** terminate in a single ion-conducting cluster tip **71**.

[0140] FIG. **18** schematically illustrates variants of electrode clusters of the cross section of a brush electrode shown in FIG. **17**.

[0141] For example, interwoven electrode cluster **72** may include strand electrodes **12** that are braided, twisted together, or otherwise interwoven or interlocked.

[0142] In electrode cluster **30a**, distal segments of strand electrodes **12** are covered by partial sleeve **74**. Partial sleeve **74** may enable wetting of the distal segments with an electrolyte without wetting skin surface **11**. The electrolyte may be introduced at a proximal end of partial sleeve **74**. For example, partial sleeve **74** may be constructed of silicone, nylon, or another material that is flexible and impermeable to an electrolyte.

[0143] In electrode cluster **30b**, strand electrodes **12** are completely covered by full sleeve **76**. Full sleeve **76** may enable wetting of the entire lengths of strand electrodes **12** without wetting skin surface **11**. The electrolyte may be introduced into full sleeve **76**, e.g., from within electrode base **16** or elsewhere within electrode casing **15**. For example, full sleeve **76** may be constructed of silicone, nylon, or another material that is flexible and impermeable to an electrolyte.

[0144] Strand electrodes may have various forms, e.g., in addition to those of electronically conductive strand electrode **31**, segmented strand electrode **42**, and nonconductive strand electrode **48**, described above.

[0145] FIG. **19** schematically illustrates variants in the forms of longitudinal cross sections strand electrodes for a brush electrode as shown in FIG. **1**.

[0146] Porous strand electrode **80** may be constructed of a porous material, e.g., to facilitate adherence of a conductive substance **40**. Braided strand electrode **82** may be constructed of a plurality of braided or interwoven thin strands, e.g., to enable absorption of an electrolyte. A diameter or other lateral dimension of non-uniform profile strand electrode **84** may vary along its length, either monotonically, as in the example shown, or otherwise. Tipped strand electrode **86** may include an ion-conducting electrode tip **88**.

[0147] Strand electrodes may be constructed with different transverse cross-sectional shapes.

[0148] FIG. **20** schematically illustrates variants of a transverse cross-sectional shape of a strand electrode for a brush electrode as shown in FIG. **1**.

[0149] Cross sectional shapes may include, for example, solid circular **90**, porous circular **92** (e.g., to enable absorption of an electrolyte), serrated **94** (e.g., to facilitate adsorption of an electrolyte), hollow circular **96** (e.g., to enable holding an electrolyte within the strand electrode), trefoil **98**, triangular **100** (or other regular polygonal), cross-shaped **102** (or other irregular polygonal), or other shapes (e.g., oval, hollow, porous, or solid variants, or other shapes, such as ovals or other shapes).

[0150] Selection of a form of a strand electrode may be determined, at least in part, by various electrical, chemical, or mechanical properties for a particular application.

[0151] Although electrode base **16** has been shown in cross section in FIGS. **1-18**, electrode base **16** typically extends in two lateral dimensions (e.g., length and width, in addition to its thickness or height).

[0152] FIG. **21** schematically illustrates a face of an electrode base of a brush electrode as shown in cross section in FIG. **3**.

[0153] Electrode base face plate **104** is configured to cover a distal face of electrode base **16** (e.g., a face that faces skin surface **11** when in use). Each electrode cluster opening **106** is configured to enable an electrode cluster **30** to extend distally outward through electrode base face plate **104**. Spaces between electrode cluster openings **106** may determine the sizes of cluster gaps **28**.

[0154] Although in the example shown, electrode cluster openings **106** are arranged in a rectangular array, other arrangements are possible. The arrangement and distribution (e.g., diameter or other lateral size, spacing between, or other characteristics of the arrangement or distribution) of electrode cluster openings **106** may be selected as appropriate to a particular application of a brush electrode **10**.

[0155] FIG. **22** schematically illustrates a system that includes a plurality of brush electrodes, in accordance with an embodiment of the present invention.

[0156] Brush electrode system **110** includes an external device **112** that is connected to a plurality of brush electrodes **10**.

[0157] External device **112** may include one or more devices. For example, a device of external device **112** may be configured to generate one or more electrical signals that may be applied to skin surface **11** via brush electrodes **10**. A device of external device **112** may be configured to sense an electrical signal (e.g., an EEG signal or other signal) that is generated within a body and that may be detected by a brush electrode **10** in contact with skin surface **11**.

[0158] Each brush electrode **10** may be configured to enable identification by external device **112**. For example, an identification mechanism may include application of Inter-Integrated Circuit (I.sup.2C) technology or may include providing each brush electrode **10** with a unique impedance footprint that is identifiable by external device **112**. The identification mechanism or a database that is accessible by a processor of external device **112** may enable identification of one or more features or characteristics of each brush electrode **10**. Such features and characteristics may include, for example, contact area, configuration of strand electrodes **12**, or other features or characteristics.

[0159] For example, external device **112** may be connected by one or more device connections **22** to one or more device connectors **20**. Each device connector **20** may be connected to a separate brush electrode **10**.

[0160] FIG. **23** schematically illustrates a brush electrode with hollow strand electrodes, in accordance with an embodiment of the present invention.

[0161] In brush electrode **120**, hollow strand electrodes **122** are organized in clusters **128**. Control circuitry **132** may be electrically connected to each cluster **128** by cluster conductor **134**.

[0162] Each hollow strand electrode **122** has a hollow core and is coated with insulating coating **124**. Insulating coating **124** may prevent electrical contact between adjacent hollow strand electrodes **122**. A distal end of each hollow strand electrode **122** terminates in an ion-conducting tip **126**.

[0163] An electrolyte may be introduced into electrode casing **15** via electrolyte orifice **130**. For example, electrolyte orifice **130** may be configured to enable electrolyte to flow into electrode casing **15**, and to impede or prevent outflow of electrolyte from electrode casing **15**.

[0164] The electrolyte may flow from electrode casing **15** into the hollow core of each hollow strand electrode **122**. Thus, electrolysis may occur within each hollow strand electrode **122**. The ionic current may be conducted via ion-conducting tip **126** into a skin surface with which ion-conducting tip **126** is in contact.

[0165] Different embodiments are disclosed herein. Features of certain embodiments may be combined with features of other embodiments; thus certain embodiments may be combinations of features of multiple embodiments. The foregoing description of the embodiments of the invention has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. It should be appreciated by persons skilled in the art that many modifications, variations, substitutions, changes, and equivalents are possible in light of the above teaching. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

[0166] While certain features of the invention have been illustrated and described herein, many modifications, substitutions, changes, and equivalents will now occur to those of ordinary skill in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

## Claims

1. A brush electrode comprising: an electrode base that is connectable to an external device that is configured to generate an electrical signal or receive an electrical signal; and a plurality of strand electrodes that extend outward from the electrode base, a distal end of each strand electrode configured to contact a skin surface, said plurality of strand electrodes configured to facilitate conduction of the electrical signal to or from the skin surface, wherein the strand electrodes are clustered into a plurality of clusters of strand electrodes, neighboring clusters of said plurality of clusters being separated from one another by gaps without any strand electrodes, wherein different clusters comprise strand electrodes of different lengths, and wherein all the strand electrodes extend outward from the electrode base at an oblique angle to the electrode base.
2. The brush electrode of claim 1, wherein the strand electrodes are configured to hold an electrolyte to facilitate ionic conduction.
3. The brush electrode of claim 2, wherein a cluster of said plurality of clusters is held to the base by a staple or a ferrule.
4. The brush electrode of claim 2, wherein said plurality of clusters are electrically connected to a single external connector for connecting to the external device.
5. The brush electrode of any of claim 2, wherein at least two clusters of said plurality of clusters are connected to different external connectors for connecting separately to the external device.
6. The brush electrode of claim 1, further comprising an isolating barrier for electrically isolating two clusters of said plurality of clusters from one another.
7. The brush electrode of claim 2, wherein said plurality of strand electrodes are configured to hold the electrolyte by capillary forces.
8. The brush electrode of claim 2, wherein a strand electrode of said plurality of strand electrodes includes a hollow core that is configured to be filled with the electrolyte, or is configured to absorb or adsorb the electrolyte.
9. The brush electrode of claim 1, wherein a strand electrode of said plurality of strand electrodes is electrically resistive or ionically conducting.
10. The brush electrode of claim 1, wherein a proximal segment of a strand electrode of said

plurality of strand electrodes is electronically conducting, and a distal segment of that strand electrode is electrically resistive or ionically conducting.

**11.** The brush electrode of claim 1, further comprising an electrolyte reservoir.

**12.** The brush electrode of claim 1, wherein the electrode base is curved.

**13.** The brush electrode of claim 1, wherein the strand electrodes are tilted laterally outward.

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