

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
25 October 2007 (25.10.2007)

PCT

(10) International Publication Number
WO 2007/121309 A2

(51) International Patent Classification:
A61N 1/00 (2006.01)

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(21) International Application Number:
PCT/US2007/066539

(22) International Filing Date: 12 April 2007 (12.04.2007)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11/403,329 13 April 2006 (13.04.2006) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: METHODS AND APPARATUS FOR MONOPOLAR RENAL NEUROMODULATION

(57) Abstract: Methods and apparatus are provided for monopolar neuromodulation, e.g., via a pulsed electric field. Such monopolar neuromodulation may effectuate irreversible electroporation or electrofusion, necrosis and/or inducement of apoptosis, alteration of gene expression, action potential attenuation or blockade, changes in cytokine up-regulation and other conditions in target neural fibers. In some embodiments, monopolar neuromodulation is applied to neural fibers that contribute to renal function. In some embodiments, such monopolar neuromodulation is performed bilaterally.



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METHODS AND APPARATUS FOR MONOPOLAR RENAL NEUROMODULATION

REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a Continuation-In-Part application of co-pending United States Patent Application Nos.:

[0002] (a) U.S. Patent Application No. 11/129,765, filed on May 13, 2005, which claims the benefit of U.S. Provisional Application Nos. 60/616,254, filed on October 5, 2004; and 60/624,793, filed on November 2, 2004. Further, this application is a continuation-in-part of U.S. Patent Application No. 10/408,665, filed on April 8, 2003 (published as United States Patent Publication 2003/0216792 on November 20, 2003), which claims the benefit of U.S. Provisional Patent Application Nos. 60/442,970, filed on January 29, 2003; 60/415,575, filed on October 3, 2002; and 60/370,190, filed on April 8, 2002.

[0003] (b) U.S. Patent Application No. 11/189,563, filed on July 25, 2005.

[0004] (c) U.S. Patent Application No. 11/266,933, filed on November 4, 2005.

[0005] (d) U.S. Patent Application No. 11/363,867, filed on February 27, 2006.

[0006] All of these applications, publications and patents are incorporated herein by reference in their entireties.

INCORPORATION BY REFERENCE

[0007] All publications and patent applications mentioned in this specification are herein incorporated by reference to the same extent as if each individual publication or patent application was specifically and individually indicated to be incorporated by reference.

TECHNICAL FIELD

[0008] The present invention relates to methods and apparatus for neuromodulation. In some embodiments, the present invention relates to methods and apparatus for achieving monopolar renal neuromodulation.

BACKGROUND

[0009] Congestive Heart Failure ("CHF") is a condition that occurs when the heart becomes damaged and reduces blood flow to the organs of the body. If blood flow decreases sufficiently, kidney function becomes altered, which results in fluid retention, abnormal hormone secretions and increased constriction of blood vessels. These results increase the workload of the heart and further decrease the capacity of the heart to pump blood through the kidneys and circulatory system.

[0010] It is believed that progressively decreasing perfusion of the kidneys is a principal non-cardiac cause perpetuating the downward spiral of CHF. Moreover, the fluid overload and associated clinical symptoms resulting from these physiologic changes result in additional hospital admissions, poor quality of life and additional costs to the health care system.

[0011] In addition to their role in the progression of CHF, the kidneys play a significant role in the progression of Chronic Renal Failure ("CRF"), End-Stage Renal Disease ("ESRD"), hypertension (pathologically high blood pressure) and other cardio-renal diseases. The functions of the kidneys can be summarized under three broad categories: filtering blood and excreting waste products generated by the body's metabolism; regulating salt, water, electrolyte and acid-base balance; and secreting hormones to maintain vital organ blood flow. Without properly functioning kidneys, a patient will suffer water retention, reduced urine flow and an accumulation of waste toxins in the blood and body. These conditions result from reduced renal function or renal failure (kidney failure) and are believed to increase the workload of the heart. In a CHF patient, renal failure will cause the heart to further deteriorate as fluids are retained and blood toxins accumulate due to the poorly functioning kidneys.

[0012] It has been established in animal models that the heart failure condition results in abnormally high sympathetic activation of the kidneys. An increase in renal sympathetic nerve activity leads to decreased removal of water and sodium from the body, as well as increased renin secretion. Increased renin secretion leads to vasoconstriction of blood vessels supplying the kidneys which causes decreased renal blood flow. Reduction of sympathetic renal nerve activity, e.g., via denervation, may reverse these processes.

[0013] Applicants have previously described methods and apparatus for treating renal disorders by applying a pulsed electric field to neural fibers that contribute to renal function. See, for example, Applicants' co-pending United States patent applications Serial No. 11/129,765, filed on May 13, 2005, and Serial No. 11/189,563, filed on July 25, 2005, both of which are incorporated herein by reference in their entireties. A pulsed electric field ("PEF") may initiate renal neuromodulation, e.g., denervation, for example, via irreversible electroporation or via electrofusion. The PEF may be delivered from apparatus positioned intravascularly, extravascularly, intra-to-extravascularly or a combination thereof. Additional methods and apparatus for achieving renal neuromodulation, e.g., via localized drug delivery (such as by a drug pump or infusion catheter) or via use of a stimulation electric field, etc, are described, for example, in co-owned and co-pending United States patent application Serial No. 10/408,665, filed April 8, 2003, and United States Patent No. 6,978,174, both of which are incorporated herein by reference in their entireties.

[0014] Electrofusion generally refers to the fusion of neighboring cells induced by exposure to an electric field. Contact between target neighboring cells for the purposes of electrofusion may be achieved in a variety of ways, including, for example, via dielectrophoresis. In tissue, the target cells may already be in contact, thus facilitating electrofusion.

[0015] Electroporation and electropermeabilization generally refer to methods of manipulating the cell membrane or intracellular apparatus. For example, the porosity of a cell membrane may be increased by inducing a sufficient voltage across the cell membrane through, e.g., short, high-voltage pulses. The extent of porosity in the cell membrane (e.g., size and number of pores) and the duration of effect (e.g., temporary or permanent) are a function of multiple variables, such as field strength, pulse width, duty cycle, electric field orientation, cell type or size and/or other parameters.

[0016] Cell membrane pores will generally close spontaneously upon termination of relatively lower strength electric fields or relatively shorter pulse widths (herein defined as "reversible electroporation"). However, each cell or cell type has a critical threshold above which pores do not close such that pore formation is no longer reversible; this result is defined as "irreversible electroporation," "irreversible

breakdown" or "irreversible damage." At this point, the cell membrane ruptures and/or irreversible chemical imbalances caused by the high porosity occur. Such high porosity can be the result of a single large hole and/or a plurality of smaller holes.

[0017] A potential challenge of using intravascular PEF systems for treating renal disorders is to selectively electroporate target cells without affecting other cells. For example, it may be desirable to irreversibly electroporate renal nerve cells that travel along or in proximity to renal vasculature, but it may not be desirable to damage the smooth muscle cells of which the vasculature is composed. As a result, an overly aggressive course of PEF therapy may persistently injure the renal vasculature, but an overly conservative course of PEF therapy may not achieve the desired renal neuromodulation.

[0018] Applicants have previously described methods and apparatus for monitoring tissue impedance or conductivity to determine the effects of pulsed electric field therapy, e.g., to determine an extent of electroporation and/or its degree of irreversibility. See, for example, Applicant's co-pending United States patent application Serial No. 11/233,814, filed September 23, 2005, which is incorporated herein by reference in its entirety. Pulsed electric field electroporation of tissue causes a decrease in tissue impedance and an increase in tissue conductivity. If induced electroporation is reversible, tissue impedance and conductivity should approximate baseline levels upon cessation of the pulsed electric field. However, if electroporation is irreversible, impedance and conductivity changes should persist after terminating the pulsed electric field. Thus, monitoring the impedance or conductivity of target and/or non-target tissue may be utilized to determine the onset of electroporation and to determine the type or extent of electroporation. Furthermore, monitoring data may be used in one or more manual or automatic feedback loops to control the electroporation.

[0019] In view of the foregoing, it would be desirable to provide additional methods and apparatus for achieving renal neuromodulation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Several embodiments of the present invention will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

[0021] Figure 1 is a schematic view illustrating human renal anatomy.

[0022] Figure 2 is a schematic isometric detail view showing the location of the renal nerves relative to the renal artery.

[0023] Figures 3A and 3B are schematic isometric and end views, respectively, illustrating orienting of an electric field for selectively affecting renal nerves.

[0024] Figure 4 is a schematic side view, partially in section, illustrating an example of a monopolar extravascular method and apparatus for renal neuromodulation.

[0025] Figure 5 is a schematic side view, partially in section, illustrating an example of a monopolar intra-to-extravascular method and apparatus for renal neuromodulation.

[0026] Figures 6A and 6B are schematic side views, partially in section, illustrating examples of monopolar intravascular methods and apparatus for renal neuromodulation.

[0027] Figures 7A-7D are schematic side views, partially in section, illustrating examples of monopolar intravascular methods and apparatus for renal neuromodulation comprising centering elements.

[0028] Figure 8 is a schematic side view, partially in section, illustrating a method for multi-location monopolar renal neuromodulation.

[0029] Figure 9 is a schematic side view, partially in section, illustrating an example of a monopolar intravascular method and apparatus for renal neuromodulation having one or more electrodes that contact the vessel wall.

[0030] Figure 10 is a schematic side view, partially in section, illustrating another example of a monopolar intravascular method and apparatus for renal neuromodulation having one or more electrodes that contact the vessel wall

[0031] Figure 11 is a schematic side view, partially in section, of a method for achieving monopolar bilateral renal neuromodulation, illustratively utilizing the apparatus of Figure 6A.

[0032] Figure 12 is a schematic side view, partially in section, illustrating an alternative method and apparatus for achieving monopolar bilateral renal neuromodulation.

DETAILED DESCRIPTION

A. Overview

[0033] Several embodiments of the present invention are methods and apparatus for neuromodulation via a pulsed electric field ("PEF"), a stimulation electric field, localized drug delivery, high frequency ultrasound, thermal techniques, athermal techniques, combinations thereof, and/or other techniques. In some embodiments, neuromodulation is achieved via monopolar (e.g., unipolar) methods and apparatus. Such neuromodulation may, for example, effectuate irreversible electroporation or electrofusion, necrosis and/or inducement of apoptosis, alteration of gene expression, action potential blockade or attenuation, changes in cytokine up-regulation and other conditions in target neural fibers.

[0034] In some patients, when the monopolar neuromodulatory methods and apparatus of the present invention are applied to renal nerves and/or other neural fibers that contribute to renal neural functions, applicants believe that the neuromodulatory effects induced by the neuromodulation might result in increased urine output, decreased plasma renin levels, decreased tissue (e.g., kidney) and/or urine catecholamines (e.g., norepinephrine), increased urinary sodium excretion, and/or controlled blood pressure. Furthermore, applicants believe that these or other changes might prevent or treat congestive heart failure, hypertension, acute myocardial infarction, end-stage renal disease, contrast nephropathy, other renal system diseases, and/or other renal or cardio-renal anomalies. The methods and apparatus described herein may be used to modulate efferent or afferent nerve signals, as well as combinations of efferent and afferent nerve signals.

[0035] Renal neuromodulation preferably is performed in a bilateral fashion such that neural fibers contributing to renal function of both the right and left kidneys

are modulated. Bilateral monopolar renal neuromodulation may provide enhanced therapeutic effect in some patients as compared to renal neuromodulation performed unilaterally, i.e. as compared to renal neuromodulation performed on neural tissue innervating a single kidney. In some embodiments, concurrent modulation of neural fibers that contribute to both right and left renal function may be achieved, or in other embodiments modulation of the right and left neural fibers may be sequential. Bilateral renal neuromodulation may be continuous or intermittent, as desired.

[0036] When utilizing an electric field, the electric field parameters may be altered and combined in any suitable combination. Such parameters can include, but are not limited to, voltage, field strength, frequency, pulse width, pulse duration, the shape of the pulse, the number of pulses and/or the interval between pulses (e.g., duty cycle), etc. For example, when utilizing a pulsed electric field, suitable field strengths can be up to about 10,000 V/cm and suitable pulse widths can be up to about 1 second. Suitable shapes of the pulse waveform include, for example, AC waveforms, sinusoidal waves, cosine waves, combinations of sine and cosine waves, DC waveforms, DC-shifted AC waveforms, RF waveforms, square waves, trapezoidal waves, exponentially-decaying waves, or combinations. The field includes at least one pulse, and in many applications the field includes a plurality of pulses. Suitable pulse intervals include, for example, intervals less than about 10 seconds. These parameters are provided as suitable examples and in no way should be considered limiting.

[0037] As discussed, the methods and apparatus of the present invention may be used to modulate neural fibers that contribute to renal function and may exploit any suitable neuromodulatory techniques that will achieve the desired neuromodulation. For example, any suitable electrical signal or field parameters, such as any electric field that will achieve the desired neuromodulation (e.g., electroporative effect), may be utilized. In some embodiments, the present invention provides methods and apparatus for achieving bilateral renal neuromodulation. To better understand the structures of devices of the present invention and the methods of using such devices for renal neuromodulation, it is instructive to examine the renal anatomy in humans.

B. Selected Embodiments of Methods for Neuromodulation

[0038] With reference now to Figure 1, the human renal anatomy includes kidneys **K** that are supplied with oxygenated blood by renal arteries **RA**, which are connected to the heart by the abdominal aorta **AA**. Deoxygenated blood flows from the kidneys to the heart via renal veins **RV** and the inferior vena cava **IVC**. Figure 2 illustrates a portion of the renal anatomy in greater detail. More specifically, the renal anatomy also includes renal nerves **RN** extending longitudinally along the lengthwise dimension **L** of renal artery **RA** generally within the adventitia of the artery. The renal artery **RA** has smooth muscle cells **SMC** that surround the arterial circumference and spiral around the angular axis θ of the artery. The smooth muscle cells of the renal artery accordingly have a lengthwise or longer dimension extending transverse (i.e., non-parallel) to the lengthwise dimension of the renal artery. The misalignment of the lengthwise dimensions of the renal nerves and the smooth muscle cells is defined as "cellular misalignment."

[0039] Referring to Figures 3A and 3B, the cellular misalignment of the renal nerves and the smooth muscle cells may be exploited to selectively affect renal nerve cells with reduced effect on smooth muscle cells. More specifically, because larger cells require a lower electric field strength to exceed the cell membrane irreversibility threshold voltage or energy for irreversible electroporation, embodiments of the present invention may be configured to align at least a portion of an electric field with or near the longer dimensions of the cells to be affected. In specific embodiments, the device has a monopolar electrode configured to create an electrical field aligned with or near the lengthwise dimension **L** of the renal artery **RA** to affect renal nerves **RN**. By aligning an electric field so that the field preferentially aligns with the lengthwise aspect of the cell rather than the diametric or radial aspect of the cell, lower field strengths may be used to affect target neural cells, e.g., to necrose or fuse the target cells, to induce apoptosis, to alter gene expression, to attenuate or block action potentials, to change cytokine up-regulation and/or to induce other suitable processes. This is expected to reduce total energy delivered to the system and to mitigate effects on non-target cells in the electric field.

[0040] Similarly, the lengthwise or longer dimensions of tissues overlying or underlying the target nerve are orthogonal or otherwise off-axis (e.g., transverse)

with respect to the longer dimensions of the nerve cells. Thus, in addition to aligning a pulsed electric field ("PEF") with the lengthwise or longer dimensions of the target cells, the PEF may propagate along the lateral or shorter dimensions of the non-target cells (i.e., such that the PEF propagates at least partially out of alignment with non-target smooth muscle cells **SMC**). Therefore, as seen in Figures 3A and 3B, applying a PEF with propagation lines **Li** generally aligned with the longitudinal dimension **L** of the renal artery **RA** is expected to preferentially cause electroporation (e.g., irreversible electroporation), electrofusion or other neuromodulation in cells of the target renal nerves **RN** without unduly affecting the non-target arterial smooth muscle cells **SMC**. The pulsed electric field may propagate in a single plane along the longitudinal axis of the renal artery, or may propagate in the longitudinal direction along any angular segment θ through a range of 0° - 360° .

[0041] A PEF system placed within and/or in proximity to the wall of the renal artery may propagate an electric field having a longitudinal portion that is aligned to run with the longitudinal dimension of the artery in the region of the renal nerves **RN** and the smooth muscle cells **SMC** of the vessel wall so that the wall of the artery remains at least substantially intact while the outer nerve cells are destroyed, fused or otherwise affected. Monitoring elements optionally may be utilized to assess an extent of, e.g., electroporation, induced in renal nerves and/or in smooth muscle cells, as well as to adjust PEF parameters to achieve a desired effect.

C. Embodiments of Systems and Methods for Neuromodulation

[0042] With reference to Figures 4-10, examples of monopolar PEF systems and methods are described. Figure 4 shows one embodiment of an extravascular, monopolar pulsed electric field apparatus 200 that includes one or more electrodes configured to deliver a monopolar pulsed electric field to renal neural fibers to achieve renal neuromodulation. The apparatus of Figure 4 is configured for temporary extravascular placement; however, it should be understood that partially or completely implantable extravascular apparatus additionally or alternatively may be utilized. Applicants have previously described extravascular PEF systems, for example, in co-pending U.S. patent application Serial No. 11/189,563, filed July 25, 2005, which has been incorporated herein by reference in its entirety.

[0043] Apparatus 200 of Figure 4 comprises a laparoscopic or percutaneous PEF system having a probe 210 configured for insertion in proximity to the track of the renal neural supply. For example, the probe 210 can be configured to be placed along the renal artery or vein, the hilum, and/or within Gerota's fascia under CT, radiographic, ultrasonic, or other suitable guidance. The proximal section of the probe 210 generally has an electrical connector to couple the probe to a pulse generator 100, and the distal section has at least one electrode 212.

[0044] The pulsed electric field generator 100 is located external to the patient, and the electrode(s) 212 are electrically coupled to the generator via the probe 210 and wires 211. The generator 100, as well as any of the electrode embodiments described herein, may be utilized with any embodiment of the present invention described hereinafter for delivery of a PEF with desired field parameters. It should be understood that electrodes of embodiments described hereinafter may be electronically connected to the generator even if the generator is not explicitly shown or described with each embodiment.

[0045] The electrode(s) 212 can be individual electrodes, a common but segmented electrode, or a common and continuous electrode. A common but segmented electrode may be formed by providing a slotted tube fitted onto the probe, or by electrically connecting a series of individual electrodes. Individual electrodes or groups of electrodes 212 may be configured to provide a monopolar or bipolar signal. The electrodes 212 may be dynamically assignable to facilitate monopolar and/or bipolar energy delivery between/among any of the electrodes on the probe 210 and/or an external ground pad 150. The ground pad 150, for example, may be attached externally to the patient's skin (e.g., to the patient's leg, flank, back or side). Additionally or alternatively, the ground pad 150 may be attached externally to the patient adjacent to the targeted kidney to induce desired directionality in the monopolar electrical field.

[0046] As seen in Figure 4, the electrode 212 may comprise a single electrode that is used in conjunction with a separate ground pad 150 located on the exterior of the patient and coupled to the generator 100 for monopolar use. The probe 210 optionally may comprise a conductive material that is insulated in regions other than its distal tip to form a distal tip electrode 212. Alternatively, the electrode 212 may be delivered through a lumen of the probe 210. The probe 210 and the electrode

212 may be of the standard needle or trocar-type used clinically for pulsed RF nerve block. Alternatively, the apparatus 200 may comprise a flexible and/or custom-designed probe for the renal application described herein.

[0047] In Figure 4, the percutaneous probe 210 has been advanced through a percutaneous access site **P** into proximity within renal artery **RA**. Once properly positioned, a pulsed electric field F_0 may be applied to target neural fibers across the monopolar electrode 212 and the ground pad 150. The pulsed electric field F_0 shown in Figure 4 is generally aligned with the longitudinal dimension of the neural fibers along the renal artery **RA** that control the kidney **K** to preferentially modulate the neural fibers without unduly affecting the smooth muscle cells of the renal artery **RA**. The monopolar electric field F_0 , however, can be orientated differently relative to the renal artery **RA** in other embodiments. After treatment, the apparatus 200 may be removed from the patient to conclude the procedure.

[0048] It is expected that applying a monopolar field between the electrode 212 and the ground pad 150 may modulate the function of the target neural fibers in a manner that at least partially denervates the patient's kidney. The neural modulation may be achieved thermally or substantially athermally. Such PEF therapy may alleviate clinical symptoms of CHF, hypertension, renal disease, myocardial infarction, contrast nephropathy and/or other renal or cardio-renal diseases for a period of months (e.g., potentially up to six months or more). This time period may be sufficient to allow the body to heal to potentially reduce the risk of CHF onset after an acute myocardial infarction and mitigate the need for subsequent re-treatment. Alternatively, as symptoms reoccur, or at regularly scheduled intervals, the patient can return to the physician for a repeat therapy.

[0049] The effectiveness of the initial therapy, and thus the potential need for repeating the therapy, can be evaluated by monitoring several different physiologic parameters. For example, plasma renin levels, urine catecholamines, or other neurohormones that are indicative of increased sympathetic nervous activity can provide an indication of the extent of denervation. Additionally or alternatively, a nuclear imaging test, such as a test utilizing 131 -Iodine metaiodobenzylguanidine ("MIBG"), may be performed to measure a degree of adrenergic innervation. As another option, imaging may be performed with Technetium-99m

mercaptoacetylglycine ("Tc-99m MAG3") to evaluate renal function. Alternatively, provocative maneuvers known to increase sympathetic nervous activity, such as head-out water immersion testing, may be conducted to determine the need for repeat therapy.

[0050] In some embodiments, the apparatus 200 may comprise a probe having an introducer with an expandable distal segment having one or more electrodes. After insertion in proximity to target neural fibers, the distal segment may be opened or expanded into an expanded configuration. In one embodiment, this expanded configuration would follow a contour of the renal artery and/or vein to treat a number of neural fibers with a single application of PEF therapy. For example, in the expanded configuration, the distal segment may partially or completely encircle the renal artery and/or vein. In another embodiment, the expanded configuration may facilitate mechanical dissection, for example, to expand Gerota's fascia and create a working space for placement of the electrodes and/or for delivery of PEF therapy. The distal segment optionally may be translated independently of the probe or introducer.

[0051] When utilized as an electrode, the distal segment may, for example, be extended out of an introducer placed near the treatment area. The conducting distal segment may be advanced out of the sheath until a desired amount of renal neural tissue is in proximity to the distal segment, and then PEF therapy may be delivered via the distal segment electrode. Alternatively, the conducting distal segment may be allowed to reform or expand into a spiral of one or more loops, a random space-occupying shape, or another suitable configuration. Mesh, braid, or conductive gels or liquids could be employed in a similar manner.

[0052] Figure 5 schematically illustrates a monopolar intra-to-extravascular (ITEV) PEF system 300 having electrode(s) that are initially delivered endoluminally in a retracted configuration (not shown) to an intravascular position near target neural fibers for modulating renal function. The distal portions of the electrodes then pierce through/across the vessel wall to an extravascular position prior to delivery of the PEF therapy. Intra-to-extravascular positioning of the electrode(s) may place the electrode(s) in closer proximity to target neural fibers during the PEF therapy compared to fully intravascular positioning of the electrode(s). Applicants have previously described intra-to-extravascular PEF systems, for example, in co-pending

U.S. patent application Serial No. 11/324,188, filed December 29, 2005, which is incorporated herein by reference in its entirety.

[0053] The example of the monopolar ITEV PEF system 300 shown in Figure 5 comprises a catheter 310 having an expandable element 312 with one or more needle-like ITEV electrodes 314 coupled to the expandable element. When multiple needle electrodes 314 are provided, they may be spaced circumferentially and/or longitudinally about/along the expandable element 312. The system 300 further comprises the previously described ground pad 150, which may be attached to or otherwise placed against the skin **S** of the patient along the exterior of the patient (e.g., to the patient's flank, back, thigh or side). The ground pad 150 is also coupled to the PEF generator 100 as a return electrode (see Figure 4). The ground pad 150 optionally may be positioned substantially directly lateral to the ITEV electrode(s) 314 to direct the PEF therapy along the patient's vasculature (e.g., along renal artery **RA**).

[0054] The expandable element 312 comprises a member or structure configured for intravascular delivery to (and retrieval from) a target location in a low profile configuration and for expansion to an expanded deployed configuration at the target location. The expandable element 312 may comprise, for example, an inflatable balloon, an expandable basket or cage, or some other expandable structure. As seen in Figure 5, expansion of the expandable element 312 causes the ITEV electrode(s) 314 to pierce the wall of renal artery **RA** and move from an intravascular location to an extravascular location. With the ITEV electrode(s) 314 positioned extravascularly and coupled to the PEF generator 100, the ITEV electrode(s) may be energized (e.g., one at a time or all together) as active electrodes in a monopolar PEF therapy with the external ground pad 150 serving as the return electrode. Additionally or alternatively, bipolar PEF therapy may be delivered between any pair of the ITEV electrodes 314 in conjunction with or in lieu of monopolar therapy.

[0055] With reference now to Figures 6A and 6B, in addition to monopolar extravascular and monopolar ITEV PEF systems, another example of the invention is a monopolar intravascular PEF system 400. Applicants have previously described intravascular PEF systems, for example, in co-pending U.S. patent application Serial

No. 11/129,765, filed May 13, 2005, which has been incorporated herein by reference in its entirety.

[0056] The monopolar intravascular PEF system 400 of Figure 6A comprises a catheter 410 having a monopolar electrode 412 coupled to the shaft of the catheter. The catheter 410 comprises a guide wire lumen for endoluminally advancing the system 400 to a desired intravascular position over a guide wire **G** (e.g., to a position within a patient's renal artery **RA**). The electrode 412 may or may not contact the wall of the artery during PEF therapy. The electrode 412 preferably is fabricated from platinum or another material that exhibits relatively high conductivity and radiopacity.

[0057] The system 400 further comprises the previously described external ground pad 150, which may be coupled to the PEF generator 100 (Figure 4) and electrically coupled to the skin **S** of the patient along the exterior of the patient (e.g., to the patient's flank, back or thigh). As with previous embodiments, the ground pad 150 optionally may be positioned substantially directly lateral to the monopolar electrode 412 to direct the PEF therapy along the patient's vasculature (e.g., the renal artery **RA**) and/or through the patient's kidney. Such lateral positioning of the ground pad also may provide a relatively uniform distribution of energy about the circumference of the patient's renal artery **RA**.

[0058] Figure 6B illustrates an alternative embodiment of system 400 comprising a plurality of the electrodes 412 coupled to the shaft of the catheter 410. Providing a plurality of the electrodes may facilitate the monopolar PEF treatment at multiple intravascular locations without necessitating repositioning of the catheter 410. The electrodes may be selectively energized as monopolar (i.e., active) electrodes in any order or combination as desired. In one example, the electrodes may be individually activated in sequence from proximal to distal. In another example, the electrodes may be individually activated in sequence from distal to proximal. In another example, some electrodes are not activated at all. In yet another example, one or more electrodes are activated in combination with one or more other electrodes. In still another example, the electrodes are activated in a pre-determined sequence or in a random sequence. Additional activation protocols will be apparent to those of skill in the art.

[0059] In addition or as an alternative to their use in monopolar treatment, the plurality of the electrodes 412 of Figure 6B optionally may be used for a bipolar PEF treatment. Such a bipolar PEF treatment may be delivered across any pair or pairs of the electrodes 412, as desired. A combination bipolar and monopolar PEF treatment may be more effective than stand-alone bipolar and/or stand-alone monopolar treatment for some patients or for some indications.

[0060] Referring to Figures 7A-7D, embodiments of the intravascular monopolar PEF system 400 optionally may comprise one or more centering elements for centering the monopolar electrode(s) within the patient's vasculature. The centering element(s) may be partially expanded such that they partially center the monopolar electrode(s) within the vessel, or may be fully expanded as in Figures 7A-7D, such that they substantially fully center the electrode(s) within the vessel. The centering elements 420 may, for example, comprise inflatable balloons and/or expandable wire baskets or cages.

[0061] The centering element optionally may comprise an impedance-altering element configured to alter impedance within the patient's vasculature to better direct an applied electric field across the vessel wall to target neural fibers. When the centering element is a balloon, it may temporarily block blood flow and thereby alter the impedance within the patient's vessel. Additionally or alternatively, the centering element may comprise the monopolar electrode. In one embodiment, a balloon centering element comprises a conductive exterior and/or is fabricated from a conductive polymer and is used as the monopolar electrode.

[0062] In Figure 7A, the PEF system 400 comprises an expandable centering element 420 coupled to the catheter 410. The element 420 is configured for delivery and retrieval from a treatment site in a reduced profile delivery configuration, and for expansion at the treatment site to the deployed configuration of Figure 7A. With the centering element in the fully expanded, deployed configuration of Figure 7A, the monopolar electrode(s) 412 are substantially centered within the vessel during the PEF therapy.

[0063] In the embodiment of Figure 7A, the system 400 comprises a unitary monopolar electrode 412 positioned along the shaft of the catheter 410 proximal of the centering element 420. The centering element is accordingly positioned

between the monopolar electrode 412 and the ground pad 150 in this embodiment. In the embodiment of Figure 7B, the monopolar electrode 412 is positioned distal of the centering element such that the centering element is not positioned between the monopolar electrode and the ground pad. In the embodiment of Figure 7C, the monopolar electrode 412 is positioned in line with the centering element 420 along the shaft of the catheter 410. In the embodiment of Figure 7D, the monopolar electrode 412 is positioned between first and second centering elements 420a and 420b, respectively. As will be apparent, additional monopolar and/or bipolar electrodes may be provided with any of the embodiments of the system 400 of Figures 7A-7D at any desired position(s) along the catheter 410. Furthermore, one or more electrodes may be coupled to the centering element(s) 420 such that the electrodes contact the wall of the patient's vasculature during delivery of the PEF therapy.

[0064] As discussed previously, it is expected that the monopolar PEF therapy, whether delivered extravascularly, intravascularly, intra-to-extravascularly or a combination thereof, may effectuate the following: irreversible electroporation or electrofusion; necrosis and/or inducement of apoptosis; alteration of gene expression; action potential blockade or attenuation; changes in cytokine up-regulation; and other conditions in target neural fibers. In some patients, when such neuromodulatory methods and apparatus are applied to renal nerves and/or other neural fibers that contribute to renal neural functions, applicants believe that the neuromodulatory effects induced by the neuromodulation might result in at least partial denervation of the patient's kidney(s). This may result in increased urine output, decreased plasma renin levels, decreased tissue (e.g., kidney) and/or urine catecholamines (e.g., norepinephrine), increased urinary sodium excretion, and/or controlled blood pressure. Furthermore, applicants believe that these or other changes might prevent or treat congestive heart failure, hypertension, myocardial infarction, renal disease, contrast nephropathy, other renal system diseases, and/or other renal or cardio-renal anomalies for a period of months (e.g., potentially up to six months or more).

[0065] The methods and apparatus described herein could be used to modulate efferent or afferent nerve signals, as well as combinations of efferent and afferent nerve signals. Neuromodulation in accordance with the present invention preferably

is achieved without completely physically severing, i.e., without fully cutting, the target neural fibers. However, it should be understood that such neuromodulation may functionally sever the neural fibers even though the fibers may not be completely physically severed. Apparatus and methods described herein illustratively are configured for percutaneous use. Such percutaneous use may be endoluminal, laparoscopic, a combination thereof, etc.

[0066] The apparatus described herein additionally may be used to quantify the efficacy, extent or cell selectivity of PEF therapy to monitor and/or control the therapy. When a pulsed electric field initiates electroporation, the impedance of the electroporated tissue begins to decrease and the conductivity of the tissue begins to increase. If the electroporation is reversible, the tissue electrical parameters will return or approximate baseline values upon cessation of the PEF. However, if the electroporation is irreversible, the changes in tissue parameters will persist after termination of the PEF. These phenomena may be utilized to monitor both the onset and the effects of PEF therapy. For example, electroporation may be monitored directly using, for example, conductivity measurements or impedance measurements, such as Electrical Impedance Tomography ("EIT") and/or other electrical impedance/conductivity measurements like an electrical impedance or conductivity index. Such electroporation monitoring data optionally may be used in one or more feedback loops to control delivery of PEF therapy.

[0067] In order to collect the desired monitoring data, additional monitoring electrodes optionally may be provided in proximity to the monitored tissue. The distance between such monitoring electrodes preferably would be specified prior to therapy delivery and used to determine conductivity from impedance or conductance measurements. For the purposes of the present invention, the imaginary part of impedance may be ignored such that impedance is defined as voltage divided by current, while conductance may be defined as the inverse of impedance (i.e., current divided by voltage), and conductivity may be defined as conductance per unit distance. Applicants have previously described methods and apparatus for monitoring PEF therapy and have provided illustrative PEF waveforms, for example, in co-pending U.S. patent application Serial No. 11/233,814, filed September 23, 2005, which has been incorporated herein by reference in its entirety.

[0068] With reference now to Figure 8, a method for multi-location, monopolar renal neuromodulation is described. In this embodiment, monopolar renal neuromodulation may be performed at a plurality of treatment sites **T** positioned along the length of renal artery **RA**. Such multi-location treatment may be achieved utilizing one or more monopolar electrodes positioned intravascularly, intra-to-extravascularly, extravascularly, etc. In Figure 8, the multi-location treatment is performed with substantially uniform circumferential energy delivery about the renal artery **RA**. However, it should be understood that non-uniform circumferential energy delivery alternatively may be utilized. For example, in some embodiments the monopolar electrode(s) may contact the vessel wall and may preferentially deliver energy to target neural fibers located in proximity to the contacted side of the wall.

[0069] In one embodiment, the catheter 410 of the PEF system 400 of Figure 6A is repositioned along the renal artery **RA** for repeat therapy with electrode 412 at multiple locations within the renal artery. In another embodiment, the multiple electrodes 412 of the PEF system 400 of Figure 6B are utilized to achieve renal neuromodulation at multiple treatment sites **T** without repositioning the catheter 410. Such multi-location treatment may be achieved, for example, by simultaneously activating multiple electrodes 412 along the length of catheter 410, or by sequentially activating a series of electrodes. All or a subset of the monopolar electrodes of the embodiment of Figure 6B may be activated to achieve desired renal neuromodulation.

[0070] Figure 9 schematically illustrates an embodiment of a monopolar PEF system 500 having a plurality of monopolar electrodes that may be expanded into contact with the vessel wall. The PEF system 500 comprises a catheter 510 having an expandable distal cage or basket 520 formed from a plurality of circumferential struts or members. A plurality of electrodes 524 are formed along the members 522 of the basket 520. Each member of the basket illustratively comprises a monopolar electrode configured to contact a wall of the renal artery **RA** or another desired blood vessel.

[0071] The basket 520 may be fabricated, for example, from a plurality of shape-memory wires or ribbons, such as Nitinol, spring steel or elgiloy wires or

ribbons, which form the basket members 522. When the basket members comprise ribbons, the ribbons may be moved such that a surface area contacting the vessel wall is increased. The basket members 522 are coupled to the catheter 510 at the proximal and the distal connections 526a and 526b, respectively. In such a configuration, the basket may be collapsed for delivery within a delivery sheath and may self-expand into contact with the wall of the artery upon removal from the sheath. The proximal and/or the distal connection 526 optionally may be configured to translate along the shaft of the catheter 510 for a specified or unspecified distance in order to facilitate the expansion and collapse of the basket.

[0072] The basket 520 alternatively may be formed from a slotted and/or a laser-cut hypotube. In such a configuration, the catheter 510 may, for example, comprise an inner and an outer shaft that are moveable relative to one another. The distal connection 526b of the basket 520 may be coupled to the inner shaft, and the proximal connection 526a of the basket may be coupled to the outer shaft. The basket 520 may be expanded from a collapsed delivery configuration to the deployed configuration of Figure 9 by approximating the inner and the outer shafts of the catheter 510, thereby approximating the proximal and distal connections 526 of the basket and expanding the basket. Likewise, the basket may be collapsed by separating the inner and outer shafts of the catheter.

[0073] As seen in Figure 9, individual electrodes may be arranged along the basket struts or members 522. In one embodiment, the struts are formed from a conductive material coated with a dielectric material, and the electrodes 524 are formed by removing regions of the dielectric coating. The insulation optionally may be removed only along radially outer surfaces of the members such that the electrodes 524 remain insulated on their radially interior surfaces; it is expected that this will direct the current flow outward into the vessel wall.

[0074] Other optional fabrication techniques include affixing the electrodes to the inside surfaces and/or outside surfaces of the basket struts, or embedding the electrodes within the struts. The electrode(s) placed along each strut or member may comprise individual electrodes, a common but segmented electrode, or a common and continuous electrode. Individual electrodes or groups of electrodes may be configured to provide a bipolar signal, or all or a subset of the electrodes

may be actuated together in conjunction with an external patient ground for monopolar use.

[0075] One advantage of having electrodes 524 contact the vessel wall as shown in the embodiment of Figure 9 is that it may reduce the need for an insulating element, such as an expandable balloon, to achieve renal denervation or other neuromodulation. However, it should be understood that such an insulating element may be provided and, for example, expanded within the basket. Furthermore, having the electrodes contact the wall may provide improved field geometry, i.e., may provide an electric field more aligned with the longitudinal axis of the vessel. Such contacting electrodes also may facilitate stimulation of the renal nerves before, during or after neuromodulation to better position the catheter 510 before treatment or for monitoring the effectiveness of treatment. Furtherstill, wall contact may facilitate multi-location therapy, as in Figure 8.

[0076] Figure 10 shows another PEF system 600 having one or more monopolar electrodes that contact the vessel wall. In this embodiment, the PEF system 600 comprises a catheter 610 with an optional expandable centering element 620 (e.g., an optional expandable balloon). The PEF system 600 further comprises an expandable helical electrode 630 configured for delivery in a reduced profile configuration through a guidewire lumen 612 of the catheter 610. The helical electrode 630 may, for example, be fabricated from a self-expanding material, such as Nitinol, elgiloy or spring steel.

[0077] As seen in Figure 10, after positioning the catheter 620 in a target vessel (e.g. renal artery **RA**), the optional centering element 620 may be expanded, e.g., inflated until it contacts the wall of the vessel to hold the catheter at a desired location within the vessel and/or to insulate or increase the impedance of the interior of the vessel. The helical electrode 630 is pushed through the lumen 612 until the helical electrode extends beyond the catheter shaft; the electrode then expands or otherwise moves into the helical configuration to physically contact the vessel wall. A monopolar pulsed electric field then may be delivered between the helical electrode 630 and external ground pad 150.

[0078] Figure 11 illustrates a method for bilateral monopolar renal neuromodulation utilizing the apparatus of Figure 6A. It should be understood that

such bilateral monopolar renal neuromodulation alternatively may be achieved utilizing the extravascular apparatus of Figure 4 or any other of the foregoing intravascular apparatus, extravascular apparatus, intra-to-extravascular apparatus, or combinations thereof. Bilateral renal neuromodulation may enhance the therapeutic effect in some patients as compared to unilateral renal neuromodulation (i.e., renal neuromodulation performed on neural tissue innervating a single kidney). For example, bilateral renal neuromodulation may further reduce clinical symptoms of CHF, hypertension, myocardial infarction, contrast nephropathy, renal disease and/or other cardio-renal diseases.

[0079] As seen in Figure 11, the catheter 410 of the monopolar PEF system 400 of Figure 6A may be advanced over a guide wire **G** into position within the patient's abdominal aorta **AA** such that the monopolar electrode 412 is substantially in line with the patient's renal arteries **RA**. First and second ground pads 150a and 150b, respectively, are electrically coupled to the patient's skin **S** substantially directly lateral to the renal arteries **RA**. Once the catheter is properly positioned for PEF therapy, the guide wire **G** may be retracted from the treatment zone (e.g., may be removed from the patient or may be positioned more proximally within the patient's aorta). A pulsed electric field then may be delivered to the active monopolar electrode 412 from the PEF generator 100. The pulsed electric field propagates from the monopolar electrode 412 to the ground pads 150a and 150b to achieve desired bipolar renal neuromodulation.

[0080] Monopolar bilateral renal neuromodulation optionally may be performed sequentially by sequentially advancing a monopolar electrode within, or in proximity to, each renal artery **RA** for PEF therapy. Alternatively, as in the illustrative embodiment Figure 12, the monopolar electrodes may be positioned simultaneously within both renal arteries **RA**, but in other embodiments the electrodes can be positioned extravascularly or intra-to-extravascularly with respect to both renal arteries. Monopolar bilateral PEF therapy then may proceed concurrently or sequentially to modulate target neural fibers that contribute to both right and left renal function.

[0081] Figure 12 illustrates one embodiment of a bilateral monopolar PEF system 700 that comprises a catheter 710 having a first distal segment 720a with a

first monopolar electrode 730a and a second distal segment 720b with a second monopolar electrode 730b. As seen in Figure 12, the first distal segment 720a may be advanced within a first renal artery **RA** to position the first monopolar electrode 730a for monopolar therapy in combination with the first ground pad 150a. Likewise, the second distal segment 720b may be advanced within a second renal artery **RA** to position the second monopolar electrode 730b for monopolar therapy in combination with the second ground pad 150b. As discussed, the bilateral renal neuromodulation may be performed concurrently or sequentially.

[0082] Ablation of conductive tissue pathways is another commonly used technique to control arterial or ventricular tachycardia of the heart. Ablation can be performed by introduction of a catheter into the venous system in close proximity of the sympathetic renal nerve subsequent ablation of the tissue. Catheter based ablation devices were previously used to stop electric stimulation of nerves by heating nerve tissue with RF energy that can be delivered by a system of electrodes. RF energy thus delivered stops the nerve conduction. U.S. Pat. No. 6,292,695 describes in detail a method and apparatus for transvascular treatment of tachycardia and fibrillation with nerve stimulation and ablation. Similar catheter based apparatus can be used to ablate the renal nerve with an intent to treat CRF. The method described in this invention is applicable to irreversible ablation of the renal nerve by electric energy, cold, or chemical agents such as phenol or alcohol.

[0083] Thermal means may be used to cool the renal nerve and adjacent tissue to reduce the sympathetic nerve stimulation of the kidney. Specifically, the renal nerve signals may be dampened by either directly cooling the renal nerve or the kidney, to reduce their sensitivity, metabolic activity and function, or by cooling the surrounding tissue. An example of this approach is to use the cooling effect of the Peltier device. Specifically, the thermal transfer junction may be positioned adjacent the vascular wall or a renal artery to provide a cooling effect. The cooling effect may be used to dampen signals generated by the kidney. Another example of this approach is to use the fluid delivery device to deliver a cool or cold fluid (e.g. saline).

[0084] After the catheter is positioned within the vessel at a desired location with respect to the target neurons, it may be stabilized within the vessel (e.g., braced against the vessel wall) and energy is delivered to the target nerve or neurons. In

one variation, RF energy is delivered to the target to create a non-thermal nerve block, reduce neural signaling, or otherwise modulate neural activity. Alternatively or additionally, cooling, cryogenic, thermal RF, thermal or non-thermal microwave, focused or unfocused ultrasound, thermal or non-thermal DC, as well as any combination thereof, may be employed to reduce or otherwise control neural signaling.

[0085] Other embodiments of pulsed electric field systems include electrodes that do not physically contact the vessel wall. RF energy, both traditional thermal energy and relatively non-thermal pulsed RF, are examples of electric fields that can be conducted into tissue to be treated from a short distance away from the tissue itself. Other types of electric fields can also be used in situations in which the electrodes do not physically contact the vessel wall. As such, the electric fields can be applied directly to the nerve via physical contact between the electrode contacts and the vessel wall or other tissue, or the electric fields can be applied indirectly to the nerve without physically contacting the electrode contacts with the vessel wall. The term "nerve contact" accordingly includes physical contact of a system element with the nerve and/or tissue proximate to the nerve, and also electrical contact alone without physically contacting the nerve or tissue. To indirectly apply the electrical field, the device has a centering element configured to position the electrodes in a central region of the vessel or otherwise space the electrodes apart from the vessel wall. The centering element may comprise, for example, a balloon or an expandable basket. One or more electrodes may be positioned on a central shaft of the centering element--either longitudinally aligned with the element or positioned on either side of the element. When utilizing a balloon catheter, the inflated balloon may act as an insulator of increased impedance for orienting or directing a pulsed electric field along a desired electric flow path. As will be apparent, alternative insulators may be utilized.

[0086] A thermocouple may be incorporated into, or provided in proximity to, each electrode, and chilled (i.e., lower than body temperature) fluid or saline may be infused proximally of the thermocouple(s). A time lag for the temperature decrease to register between the thermocouple(s) may be used to quantify flow characteristic(s). A baseline estimate of the flow characteristic(s) of interest may be

determined prior to stimulation of the renal nerves and may be compared with a second estimate of the characteristic(s) determined after stimulation.

[0087] Although preferred illustrative variations of the present invention are described above, it will be apparent to those skilled in the art that various changes and modifications may be made thereto without departing from the invention. For example, although the monopolar bilateral methods and apparatus for renal neuromodulation of Figures 11 and 12 illustratively utilize dual ground pads, it should be understood that such monopolar bilateral renal neuromodulation alternatively may be performed with a single ground pad. Furthermore, although the illustrative variations described herein generally deliver monopolar renal neuromodulation from within or in proximity to a patient's renal artery, it should be understood that such neuromodulation additionally or alternatively may be delivered from other locations within or in proximity to the patient's renal vasculature, such as within or in proximity to the patient's renal vein. It is intended in the appended claims to cover all such changes and modifications that fall within the true spirit and scope of the invention.

CLAIMS

I/We claim:

1. A method for renal neuromodulation of a patient, the method comprising:
placing a monopolar electrode in proximity to a neural fiber that contributes to renal function of a kidney of a patient;
electrically coupling a ground electrode to an exterior of the patient; and
delivering an electric field between the monopolar electrode and the ground electrode to modulate a function of the neural fiber.
2. The method of claim 1, wherein delivering the electric field further comprises delivering a pulsed electric field.
3. The method of claim 1, wherein modulating the function of the neural fiber further comprises at least partially denervating the kidney.
4. The method of claim 1, wherein placing a monopolar electrode in proximity to a neural fiber that contributes to renal function of a kidney of a patient further comprises positioning the electrode within a renal vasculature of the patient.
5. The method of claim 4, wherein positioning the electrode within the renal vasculature of the patient further comprises contacting the electrode with a vessel wall of the renal vasculature of the patient.
6. The method of claim 1, wherein modulating the function of the neural fiber further comprises inducing an effect in the neural fiber chosen from the group consisting of irreversible electroporation, electrofusion, necrosis, apoptosis, gene expression alteration, cytokine up-regulation alteration, ablation, and combinations thereof.

7. The method of claim 1, wherein modulating the function of the neural fiber further comprises thermally modulating the function of the neural fiber.

8. The method of claim 1, wherein modulating the function of the neural fiber further comprises at least partially ablating the neural fiber.

9. The method of claim 1, wherein modulating the function of the neural fiber further comprises, on average during delivery of the electric field, modulating the function of the neural fiber substantially athermally.

10. The method of claim 1, wherein placing the monopolar electrode in proximity to the neural fiber that contributes to renal function further comprises placing the electrode at a position chosen from the group consisting of within renal vasculature, external to renal vasculature, external to renal vasculature via a laparoscopic approach, external to renal vasculature via an intra-to-extravascular approach and combinations thereof.

11. The method of claim 1, wherein electrically coupling the ground electrode to the exterior of the patient further comprises attaching a ground pad to skin of the patient.

12. The method of claim 1, wherein modulating the function of the neural fiber further comprises treating a medical condition afflicting the patient.

13. The method of claim 12, wherein treating the medical condition afflicting the patient further comprises treating a medical condition chosen from the group consisting of heart failure, hypertension, myocardial infarction, renal disease, contrast nephropathy and combinations thereof.

14. The method of claim 1 further comprising monitoring tissue impedance with the monopolar electrode.

15. A method for a renal neuromodulation of a patient, comprising:
placing a monopolar electrode at least substantially proximate to a neural fiber that contributes to renal function of a kidney of a patient;
electrically coupling a ground electrode to an exterior of the patient; and
delivering an electric field between the monopolar electrode and the ground electrode such that the resulting electric field is generally aligned with a longitudinal axis of a renal artery associated with the kidney, thereby modulating a function of the neural fiber.
16. The method of claim 15 wherein:
delivering the electric field further comprises delivering a pulsed electric field; and
modulating the function of the neural fiber further comprises at least partially denervating the kidney.
17. The method of claim 15 wherein placing the monopolar electrode further comprises positioning the electrode at a location chosen from the group consisting of within the renal vasculature, external to the renal vasculature, through a vessel wall of the renal vasculature, and combinations thereof.
18. Apparatus for performing renal neuromodulation of a patient, the apparatus comprising:
an electric field generator;
a device configured for percutaneous placement proximate a renal vasculature of the patient, the device comprising a monopolar electrode electrically coupled to the electric field generator; and
a ground electrode configured for electrical coupling to an exterior of the patient,
wherein the apparatus is configured for delivery of an electric field between the monopolar electrode and the ground electrode to modulate a neural fiber that contributes to renal function while the device is located proximate the renal vasculature.

19. The apparatus of claim 18, wherein the monopolar electrode is configured for placement at a position chosen from the group consisting of within the renal vasculature, adjacent to the renal vasculature, external to the renal vasculature, external to the renal vasculature via a laparoscopic approach, external to the renal vasculature via an intra-to-extravascular approach and combinations thereof.

20. The apparatus of claim 18, wherein the device is configured for intravascular placement, the device further comprising an expandable element configured for expansion from a collapsed delivery configuration to an expanded deployed configuration within the renal vasculature of the patient.

21. The apparatus of claim 20, wherein the expandable element is configured to center the monopolar electrode within the renal vasculature of the patient.

22. The apparatus of claim 20, wherein the expandable element is configured to position the monopolar electrode in contact with a wall of the renal vasculature of the patient.

23. The apparatus of claim 20, wherein the expandable element is configured to position the monopolar electrode external to the renal vasculature of the patient via an intra-to-extravascular approach.

24. The apparatus of claim 20, wherein the expandable element is configured to alter impedance between the monopolar electrode and the ground electrode when positioned within the renal vasculature of the patient.

25. The apparatus of claim 20, wherein the expandable element comprises an inflatable balloon.

26. The apparatus of claim 25, wherein the inflatable balloon comprises the monopolar electrode.

27. The apparatus of claim 26, wherein the inflatable balloon is fabricated from a conductive polymer.

28. The apparatus of claim 18, wherein the ground electrode further comprises a ground pad configured for attachment to skin of the patient.

29. The apparatus of claim 18, wherein the apparatus is configured to deliver a thermal electric field to the neural fiber.

30. The apparatus of claim 29, wherein the thermal electric field is configured to at least partially ablate the neural fiber.

31. The apparatus of claim 18, wherein the monopolar electrode further comprises a thermocouple.

32. The apparatus of claim 18, wherein the monopolar electrode is configured to monitor tissue impedance.

33. The apparatus of claim 18, wherein the apparatus is configured to deliver a pulsed electric field.

34. A method for at least partially denervating a kidney of a patient, the method comprising:

placing a monopolar electrode in proximity to a neural fiber that contributes to renal function of the kidney;
electrically coupling a ground electrode to an exterior of the patient; and
delivering an electric field between the monopolar electrode and the ground electrode to at least partially denervate the kidney.















