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(54) Title: METHODS AND APPARATUS FOR MULTI-VESSEL RENAL NEUROMODULATION

(57) Abstract: Methods and apparatus are provided for multi-vessel neuromodulation, e.g., via a pulsed electric field. Such multi-vessel 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, the multi-vessel neuromodulation is applied to neural fibers that contribute to renal function. Such multi-vessel neuromodulation optionally may be performed bilaterally.



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METHODS AND APPARATUS FOR MULTI-VESSEL RENAL NEUROMODULATION

REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a Continuation-In-Part application of co-pending United States Patent Application No. 11/129,765, filed on May 13, 2005, which claims the benefit of U.S. Provisional Application Nos. (a) 60/616,254, filed on October 5, 2004, and (b) 60/624,793, filed on November 2, 2004.

[0002] All of these applications are incorporated herein by reference in their entireties.

INCORPORATION BY REFERENCE

[0003] 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

[0004] The present invention relates to methods and apparatus for neuromodulation. In some embodiments, the present invention relates to methods and apparatus for achieving renal neuromodulation.

BACKGROUND

[0005] 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.

[0006] 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.

[0007] 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.

[0008] It has been established in animal models that the heart failure condition results in abnormally high sympathetic activation of the kidneys. Such high levels of renal sympathetic nerve activity lead to decreased removal of water and sodium from the body, as well as increased secretion of renin. 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.

[0009] 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 denervation or other renal neuromodulation via irreversible electroporation, electrofusion or other processes. 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 via localized drug delivery (such as by a drug pump or

infusion catheter), a stimulation electric field, or other modalities 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.

[0010] 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.

[0011] Electroporation and electroporabilization 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 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 the field strength, pulse width, duty cycle, electric field orientation, cell type or size and/or other parameters.

[0012] 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.

[0013] 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.

[0014] 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.

[0015] In view of the foregoing, it would be desirable to provide additional methods and apparatus for achieving renal neuromodulation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] 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:

[0017] Figure 1 is a schematic view illustrating human renal anatomy.

[0018] Figure 2 is a schematic isometric detail view showing the location of the renal nerves relative to the renal artery.

[0019] Figures 3A and 3B are schematic isometric and end views, respectively, illustrating orienting of an electric field for selectively affecting renal nerves.

[0020] Figure 4 is a schematic side view, partially in section, illustrating an example of a multi-vessel method and apparatus for renal neuromodulation.

[0021] Figures 5A and 5B are schematic side views, partially in section, illustrating other examples of multi-vessel methods and apparatus for renal neuromodulation.

[0022] Figure 6 is a schematic side view, partially in section, illustrating another method of utilizing the apparatus of Figure 5A for multi-vessel renal neuromodulation.

[0023] Figures 7A and 7B are schematic top views, partially in cross-section, illustrating additional examples of multi-vessel methods and apparatus for renal neuromodulation.

[0024] Figure 8 is a schematic top view, partially in cross-section, illustrating an embodiment of the apparatus of Figures 7 for assessing renal catecholamine spillover.

[0025] Figures 9 is a schematic top view, partially in cross-section, illustrating an example of multi-vessel methods and apparatus for renal neuromodulation comprising overlapping bipolar electric fields.

DETAILED DESCRIPTION

A. Overview

[0026] 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. 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. 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. In several embodiments, neuromodulation is achieved via multi-vessel methods and apparatus with neuromodulatory elements positioned within multiple vessels and/or multiple branches of a single vessel.

[0027] In some patients, when the multi-vessel neuromodulatory methods and apparatus of the present invention are applied to renal nerves and/or other neural fibers that contribute to renal neural functions, the applicants believe that the neuromodulation may directly or indirectly increase urine output, decrease plasma renin levels, decrease tissue (e.g., kidney) and/or urine catecholamines, cause renal

catecholamine (e.g., norepinephrine) spillover, increase urinary sodium excretion, and/or control blood pressure. Furthermore, applicants believe that these or other changes may 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 and/or afferent nerve signals.

[0028] 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 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; while in other embodiments, modulation of the right and left neural fibers may be sequential. Bilateral renal neuromodulation may be continuous or intermittent, as desired.

[0029] When utilizing an electric field to achieve desired renal neuromodulation, 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.

[0030] 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

[0031] 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** generally 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 generally 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 relatively 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."

[0032] Referring to Figures 3A and 3B, the cellular misalignment of the renal nerves and the smooth muscle cells optionally 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 optionally 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 bipolar electrode pair positioned in different vessels and configured to create an electrical field aligned with or near the lengthwise dimension **L** of the renal artery **RA** to preferentially affect the 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.

[0033] 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° .

[0034] 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.

[0035] C. Embodiments of Systems and Methods for Multi-Vessel Neuromodulation

[0036] With reference to Figures 4-7, examples of multi-vessel PEF systems and methods are described. Figure 4 shows one embodiment of a multi-vessel pulsed electric field apparatus 100 that includes multiple electrodes 110 configured to deliver a pulsed electric field to renal neural fibers to achieve renal neuromodulation. The electrodes 110 are positioned intravascularly within multiple vessels that branch off from main renal artery **RA**. The apparatus 100 may further comprise a catheter 102 through which the electrodes 110 may be delivered to vessel branchings. The catheter also may comprise a positioning element 104, as described hereinafter. 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.

[0037] The proximal section of the apparatus 100 generally has one or more electrical connectors to couple the electrodes 110 to a pulse generator 101. The pulse generator is located external to the patient. The generator, 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 though the generator is not explicitly shown or described with each embodiment.

[0038] As seen in Figure 4, the electrodes 110 are positioned in multiple vessels that branch off from a renal artery **RA** in the vicinity of a kidney **K**. The electrical signals may be applied independently and/or dynamically to each of the electrodes 110 to facilitate a monopolar and/or a bipolar energy delivery between/among any of the electrodes and/or an external ground pad (not shown). A ground pad, for example, may be attached externally to the patient's skin (e.g., to the patient's leg, flank, back or side) when one or more of the electrodes deliver monopolar energy. Additionally or alternatively, the optional ground pad may be attached externally to the patient adjacent to the targeted kidney to induce desired directionality in a monopolar electrical field. A combination bipolar and monopolar PEF treatment may be more effective than a stand-alone bipolar and/or a stand-alone monopolar treatment for some patients or for some indications.

[0039] It is expected that applying a bipolar field between a desired pair of the electrodes 110 positioned in different vessels, e.g., between the electrode 110a and the electrode 110b, may modulate the function of the target neural fibers in a manner that at least partially denervates the patient's kidney. The electrodes 110a and 110b (as well as the electrodes 110b and 110c) optionally may be laterally spaced from one another along the lengthwise dimension of the renal artery **RA**, which is expected to preferentially align an electric field delivered between the electrodes with the target neural fibers. The neuromodulation 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.

[0040] 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, renal catecholamine (e.g., norepinephrine) spillover, 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.

[0041] Embodiments of the PEF system 100 optionally may comprise one or more positioning elements for centering or otherwise positioning the system or parts of the system within the patient's vasculature. The positioning element may, for example, comprise inflatable balloons and/or expandable wire baskets or cages. The positioning 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 positioning element is a balloon, it may temporarily block blood flow and thereby alter the impedance within the patient's vessel. Additionally or alternatively, the positioning element may further comprise one or more electrodes. In one embodiment, a balloon positioning element has a conductive exterior and/or is fabricated from a conductive polymer that may be used as an electrode in a multi-vessel PEF system.

[0042] In Figure 4, the PEF system 100 comprises an expandable positioning element 104 coupled to the catheter 102. The positioning element 104 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 4. With the positioning element in the fully expanded, deployed configuration of Figure 4, impedance characteristics within the renal artery **RA** may be altered, and/or delivery and retrieval of the electrode(s) 110 to the multiple vessel branchings may be facilitated.

[0043] As discussed previously, it is expected that a multi-vessel PEF therapy may effectuate one or more of 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 neuromodulation may at least partially denervate 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, renal catecholamine (e.g., norepinephrine) spillover, increased urinary sodium excretion, and/or controlled blood pressure. Furthermore, applicants believe that these or other changes may 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).

[0044] 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 several embodiments of the present invention can be achieved without completely physically severing, i.e., without fully cutting, the target neural fibers. However, it should be understood that such neuromodulation may functionally achieve results analogous to physically severing the neural fibers even though the fibers may not be completely physically severed.

[0045] 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 electrical parameters of the tissue will return to baseline values or approximate baseline values after terminating the PEF. However, if the electroporation is irreversible, the changes in the electrical parameters of the tissue will persist after terminating 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 conductivity measurements or impedance measurements, such as Electrical Impedance Tomography ("EIT"), electrical impedance or conductivity indices and/or other electrical impedance/conductivity measurements. Such electroporation monitoring data optionally may be used in one or more feedback loops to control delivery of PEF therapy.

[0046] 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 peak voltage divided by peak current, while conductance may be defined as the inverse of impedance (i.e., peak current divided by peak 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.

[0047] Referring now to Figures 5A and 5B, additional embodiments of multi-vessel methods and apparatus for renal neuromodulation are described. The PEF system 200 of Figure 5A comprises a guide catheter 210 through which a first element 220 having a first electrode 222 and an optional positioning element 224, as well as a second element 230 having a second electrode 232, may be advanced. The first electrode 222 is positioned in a first vessel that branches off of the renal artery RA and the second electrode 232 is positioned within a second vessel or branch of a vessel. The positioning element 224 is expanded within the first vessel branch to center or otherwise position the first electrode 222 within the vessel and/or to alter impedance within the vessel. The first electrode 222 may, for example, be an active electrode and

the second electrode 232 may be a return electrode for creating a bipolar electric field between the electrodes to modulate target neural fibers that contribute to renal function. Figure 5B illustrates an alternative embodiment in which the first element 220 comprises a catheter having a lumen with a side port 226. As shown, the second element 230 may be positioned in the lumen and may pass through the side port 226 of the first element 220 to position the second electrode 232 within a vessel branching of the renal artery **RA**. Although a separate guide catheter is not necessarily required for the embodiment shown in Figure 5B, the first element 220 in Figure 5B optionally may be advanced into position via a separate guide catheter, such as the guide catheter 210 of Figure 5A.

[0048] Referring now to Figure 6, another multi-vessel method of using the apparatus of Figure 5A for renal neuromodulation is described. In addition to positioning electrodes within multiple branchings of the renal artery **RA**, a multi-vessel renal neuromodulation may be achieved with the electrodes positioned within additional or alternative vessels. In Figure 6, the first element 220 has been advanced through the guide catheter 210 to a position within the renal artery **RA**. The second element 230 has been advanced to a position within the abdominal aorta **AA**. A bipolar electrical field may be delivered between the first electrode 222 and the second electrode 232 to achieve renal neuromodulation.

[0049] With reference now to Figures 7A and 7B, in addition to placement of the electrode(s) within (a) the renal artery **RA**, (b) branchings of the renal artery and/or (c) additional or alternative parts of the patient's arterial vasculature, multi-vessel renal neuromodulation may be achieved by locating one or more of the electrodes at least partially within the patient's venous vasculature. In Figures 7, electrodes are positioned within both the renal artery **RA** and the renal vein **RV** of the patient. The PEF system 300 can comprise a catheter 310 positioned within the renal artery **RA** and an element 320 positioned within the renal vein **RV**. The catheter 310 comprises a first electrode 312 and an optional positioning element 314. The catheter 310 may be advanced into position within the renal artery, for example, over a guide wire **G**, then the positioning element may be expanded to center or otherwise position the electrode 312 within the vessel and/or to alter impedance within the vessel. The element 320 comprises a

second electrode 330 that can be positioned within the renal vein, and the element 320 can optionally include a positioning element.

[0050] A bipolar electric field may be delivered between the first electrode 312 positioned within the renal artery and the second electrode 330 positioned within the renal vein to modulate target neural fibers that contribute to renal function via a multi-vessel approach. In Figure 7A, electrodes 312 and 330 are relatively laterally aligned with one another. In Figure 7B, the electrodes are laterally spaced apart from one another, which may facilitate preferential alignment of a bipolar electrical field delivered across the electrodes with the target neural fibers.

[0051] As discussed previously, a renal catecholamine (e.g., norepinephrine) spillover may indicate the extent of denervation or other renal neuromodulation achieved by methods in accordance with the present invention. A renal catecholamine spillover is defined as an imbalance between an amount of a renal catecholamine entering a kidney via a renal artery and an amount of the renal catecholamine exiting the kidney via a renal vein. For, example, neuromodulation may induce the kidney to excrete more norepinephrine into the renal vein than that which had entered the kidney via the renal artery. A baseline measurement of renal catecholamine spillover may be made prior to the renal neuromodulation. This baseline then may be compared to a measurement of the renal catecholamine spillover taken after the renal neuromodulation, and the difference may be attributed to the renal neuromodulation.

[0052] In order to measure the renal catecholamine spillover, blood may be drawn from the patient. For example, blood may be drawn from the renal artery and from the renal vein, and a differential in unit volume of the monitored renal catecholamine(s) between the arterial and venous blood may be used to quantify the renal catecholamine spillover and thus assess the degree of the renal neuromodulation. Such blood draws may, for example, be achieved by drawing blood through one or more guide catheters used to deliver a PEF system, such as the PEF system 300 of Figures 7, to the renal artery and the renal vein.

[0053] The blood draws additionally or alternatively may be made via one or blood ports integrated into the PEF system. In the embodiment of Figure 8, the catheter 310 of the PEF system 300 of Figures 7 comprises an arterial blood port 316 for drawing arterial blood, and the element 320 comprises a catheter having a venous blood port

322 for drawing venous blood. Additional and alternative methods and apparatus for monitoring of the renal catecholamine spillover will be apparent to those of skill in the art.

[0054] In addition to delivery of a bipolar electric field between a first electrode positioned within a first vessel or vessel branch, and a second electrode positioned within a second vessel or vessel branch, a bipolar electric field may be delivered between first and second electrodes positioned solely within a single vessel or vessel branch. As seen in Figure 9, a first bipolar electric field may be delivered between electrodes 312a and 312b positioned within a first vessel, such as the renal artery **RA**, while a second bipolar electric field may be delivered between electrodes 330a and 330b positioned within a second vessel, such as the renal vein **RV**. The first and second bipolar electric fields may be delivered in a manner that creates a zone of overlap **Z** between the bipolar fields.

[0055] Tissue positioned within the overlap zone **Z** may exhibit locally enhanced intensity of an induced electric field within the tissue, as compared to the intensity within tissue positioned outside of the overlap zone. When a target neural fiber, such as a target renal neural fiber **RN**, passes through the overlap zone **Z**, the locally enhanced intensity of the induced electric field within the target neural fiber may be of a magnitude sufficient to desirably modulate the neural fiber. Furthermore, the intensity of induced electric fields outside of the overlap zone desirably may be of magnitudes insufficient to cause damage to non-target tissues. Overlapping electric fields thus may reduce a risk of undesirable damage to non-target tissues, while locally providing an induced electric field of sufficient magnitude to achieve desired renal neuromodulation.

[0056] 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.

[0057] 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).

[0058] 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.

[0059] 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.

[0060] 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.

[0061] 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, one or more electrodes may be positioned in other parts of the patient's venous vasculature, such as within the patient's inferior vena cava or within vessel branchings of 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 multi-vessel renal neuromodulation of a patient, the method comprising:

placing a first electrode in a first vessel of a patient in proximity to a neural fiber that contributes to a function of a kidney of the patient;
placing a second electrode in a second vessel of the patient, wherein the second vessel is a different vessel than the first vessel; and
passing electrical current through the first electrode and the second electrode to modulate the function of the neural fiber.

2. The method of claim 1 wherein passing electrical current through the first and second electrodes comprises creating an electric field between the first and second electrodes.

3. The method of claim 1 wherein passing electrical current through the first and second electrodes comprises creating a first electric field between the first electrode and a remote electrode and a second electric field between the second electrode and the remote electrode.

4. The method of claim 3 wherein the first and second electric fields are created simultaneously.

5. The method of claim 3 wherein the first and second electric field are created sequentially.

6. The method of claim 1 wherein passing electrical current through the first and second electrodes comprises creating a first electric field between the first electrode and a first remote electrode in the first vessel and a second electric field between the second electrode and a second remote electrode in the second vessel.

7. The method of claim 6 wherein the first and second electric fields are created simultaneously.

8. The method of claim 6 wherein the first and second electric fields are created sequentially.

9. The method of claim 1, wherein passing electrical current further comprises passing pulsed electrical current.

10. The method of claim 1, wherein modulating the function of the neural fiber further comprises at least partially denervating the kidney.

11. 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, and combinations thereof.

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

13. The method of claim 1, wherein modulating the function of the neural fiber further comprises, on average during passage of the electrical current, modulating the function of the neural fiber substantially athermally.

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

15. The method of claim 14, 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.

16. The method of claim 1, wherein placing the first electrode in the first vessel further comprises placing the first electrode in a first vessel of a renal vasculature of the patient.

17. The method of claim 16, wherein placing the second electrode in the second vessel further comprises placing the second electrode in a second vessel of the renal vasculature of the patient, the second vessel being a different vessel of the renal vasculature than the first vessel.

18. The method of claim 17, wherein placing the second electrode in the second vessel of the renal vasculature of the patient further comprises placing the second electrode in a second vessel branching of the renal vasculature.

19. The method of claim 1, wherein placing the first electrode in the first vessel and the second electrode in the second vessel further comprises placing the first electrode and the second electrode in different vessels of the patient chosen from the group consisting of a renal artery, renal artery branchings, a renal vein, renal vein branchings, an inferior vena cava, an abdominal aorta, renal vasculature, venous vasculature, arterial vasculature, and combinations thereof.

20. The method of claim 1 further comprising altering impedance in the first vessel or the second vessel before passage of the electrical current.

21. The method of claim 20, wherein altering impedance further comprises temporarily altering blood flow within the first vessel or the second vessel.

22. The method of claim 1, wherein passing the electrical current further comprises preferentially aligning the electrical current with a longitudinal dimension of the neural fiber.

23. The method of claim 22, wherein aligning the electrical current further comprises placing the first electrode and placing the second electrode such that the

first electrode and the second electrode are spaced apart from one another about a lengthwise dimension of the neural fiber.

24. The method of claim 1 further comprising monitoring a change in a renal catecholamine spillover in response to the passage of the electrical current.

25. A method for a renal neuromodulation of a patient, the method comprising:
placing a first electrode within a first vessel of a patient at least substantially proximate to a neural fiber that contributes to a function of a kidney of the patient;
placing a second electrode within a second vessel of the patient, wherein the second vessel is a different vessel than the first vessel; and
delivering an electric field between the first electrode and the second electrode such that the resulting electric field is generally aligned with a longitudinal axis of a renal artery associated with the kidney, thereby modulating the function of the neural fiber.

26. The method of claim 25, wherein placing the first electrode within the first vessel and the second electrode within the second vessel further comprises placing the first electrode and the second electrode in different vessels of the patient chosen from the group consisting of the renal artery, renal artery branchings, a renal vein, renal vein branchings, an inferior vena cava, an abdominal aorta, renal vasculature, venous vasculature, arterial vasculature, and combinations thereof.

27. The method of claim 25 further comprising monitoring a change in a renal catecholamine spillover in response to the delivery of the electric field.

28. Apparatus for performing renal neuromodulation of a patient, the apparatus comprising:

an electric field generator;
a first element configured for placement within a first vessel of the patient, the first element comprising a first electrode electrically coupled to the electric field generator; and

a second element configured for placement within a second vessel of the patient that is different than the first vessel, the second element comprising a second electrode electrically coupled to the electric field generator,

wherein the apparatus is configured for delivery of an electric field between the first electrode and the second electrode to modulate a neural fiber that contributes to renal function while the first device is located within the first vessel and the second device is located within the second vessel.

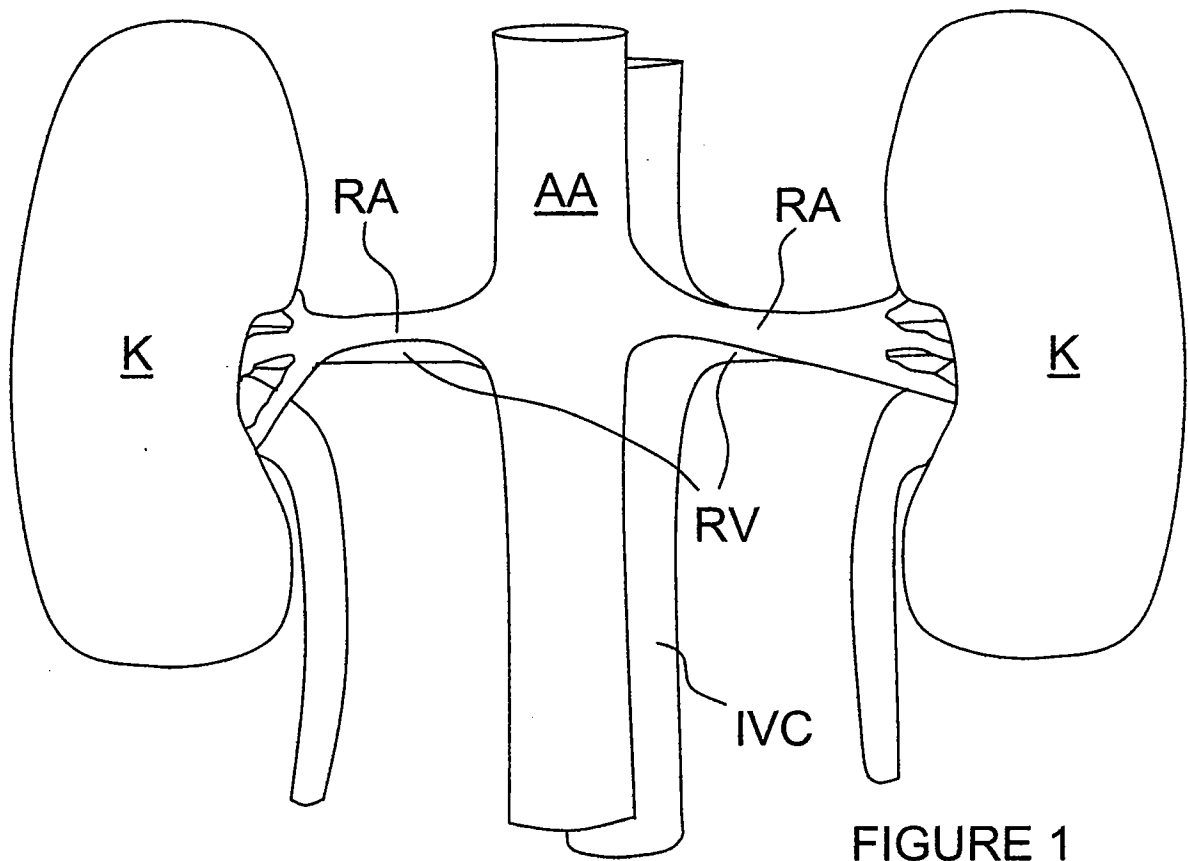
29. The apparatus of claim 28, wherein the first element or the second element comprises a positioning element.

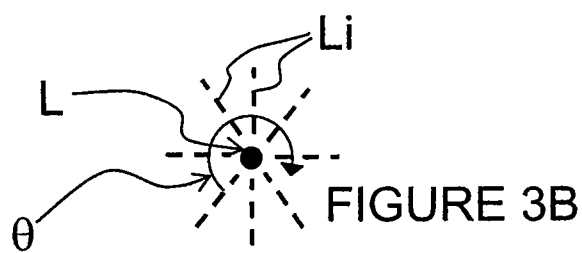
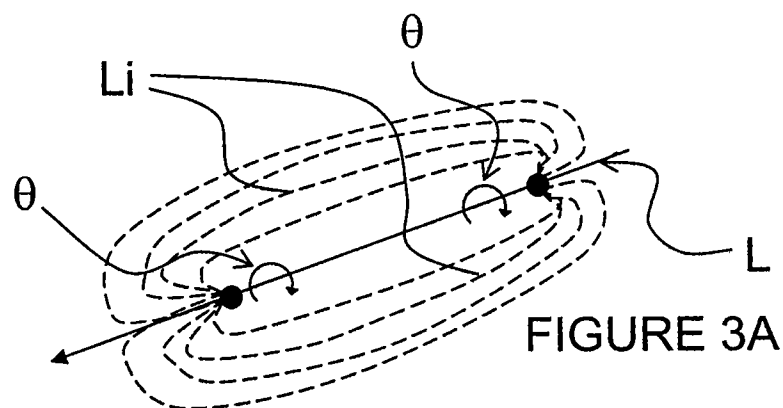
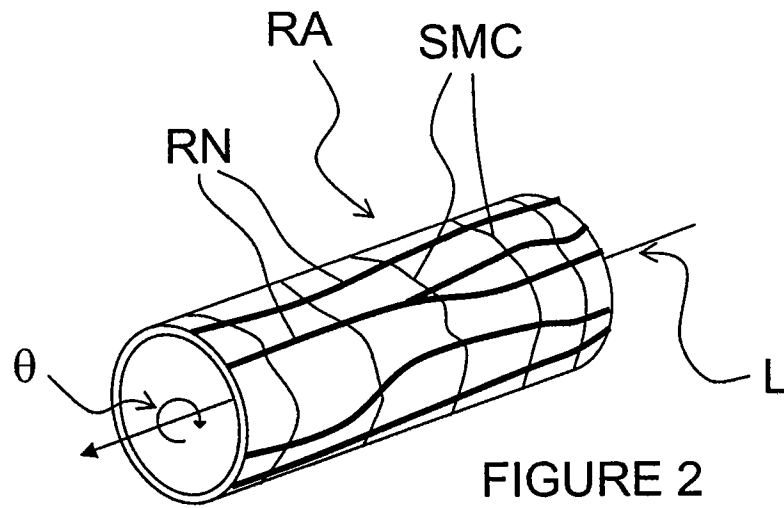
30. The apparatus of claim 29, wherein the positioning element is configured to alter impedance within a vessel of the patient.

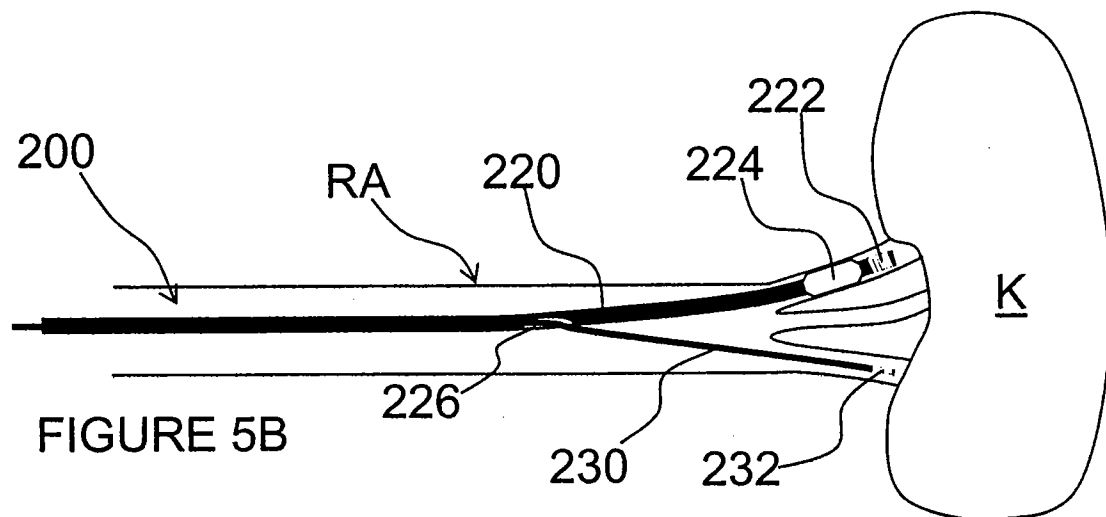
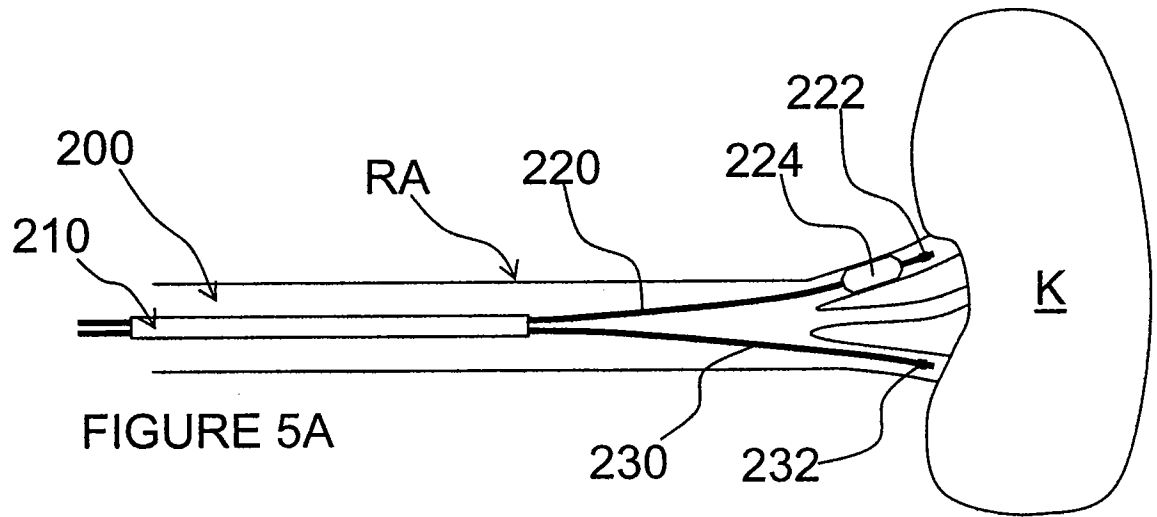
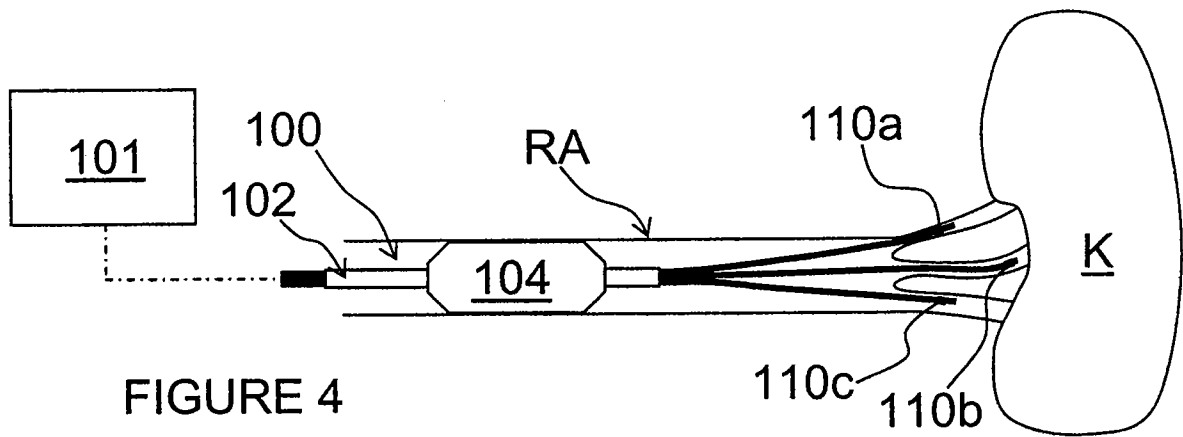
31. The apparatus of claim 28, wherein the apparatus is configured for monopolar delivery of the electric field between the first electrode or the second electrode and a ground pad positioned external to the patient.

32. The apparatus of claim 28 further comprising an element for monitoring alteration of a renal catecholamine spillover in response to delivery of the electric field.

33. The apparatus of claim 28 wherein the electric field is a pulsed electric field.







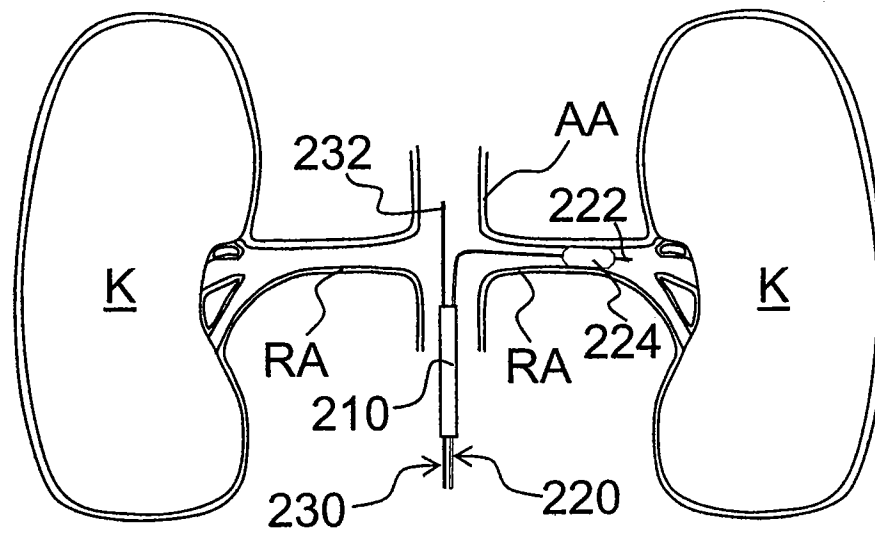


FIGURE 6

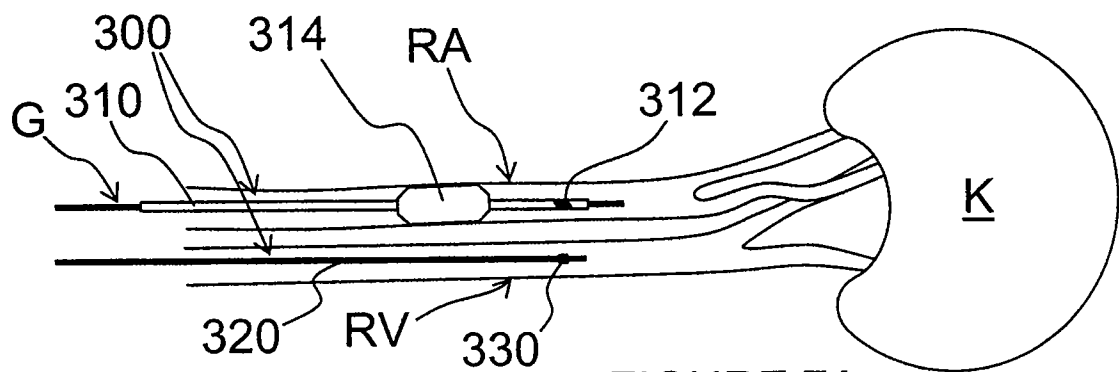


FIGURE 7A

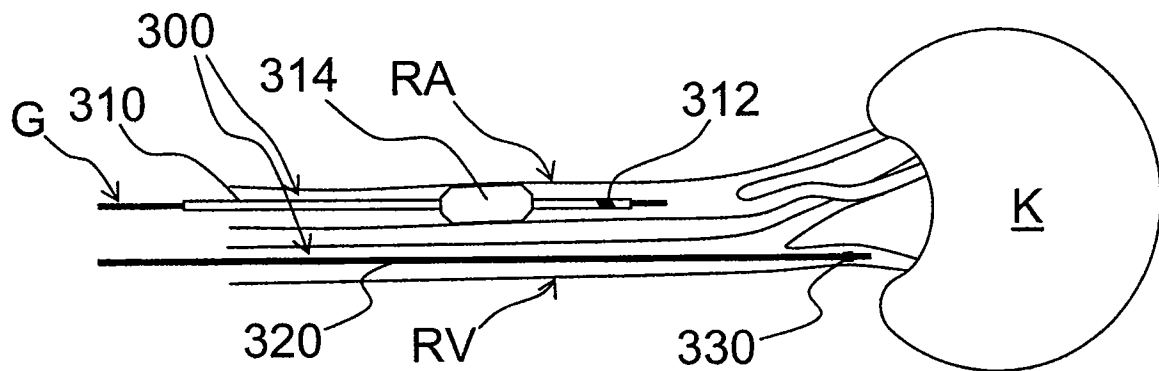


FIGURE 7B

