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(54) **ACTIVE MRI INTRAMYOCARDIAL
INJECTION CATHETER WITH
DEFLECTABLE DISTAL SECTION**

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3, 2004, now Pat. No. 7,725,161.

(60) Provisional application No. 60/444,430, filed on Feb.
3, 2003.

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A61B 5/055 (2006.01)

(52) **U.S. Cl.** **600/424**; 600/410; 600/411; 600/420;
600/423

(58) **Field of Classification Search** 600/410,
600/411, 415, 420, 424, 423
See application file for complete search history.

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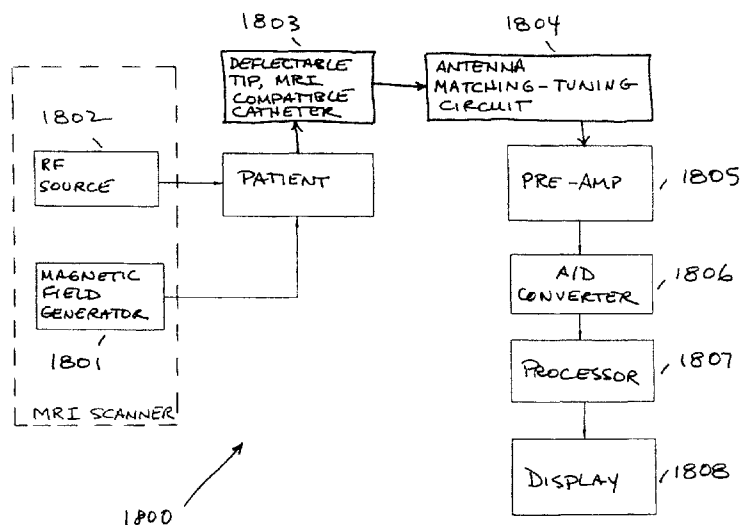
Primary Examiner — Peter Luong

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(57) **ABSTRACT**

A deflectable tip catheter that is safe and effective for use in a magnetic resonance imaging environment. The deflectable tip catheter is configured such that it includes a built-in antenna, such as a loopless antenna or a loop antenna. The built-in antenna permits the deflectable tip catheter to be actively tracked and/or visualized. Depending upon the specific configuration of the deflectable tip catheter, the catheter may be tracked and/or visualized as a single unit, it may be tracked and/or visualized separate and independent of other components or instruments associated with the catheter, such as pull wires, injection needles, surgical instruments, and the like. The catheters described herein include injection type catheters and/or guidance type catheters.

3 Claims, 22 Drawing Sheets



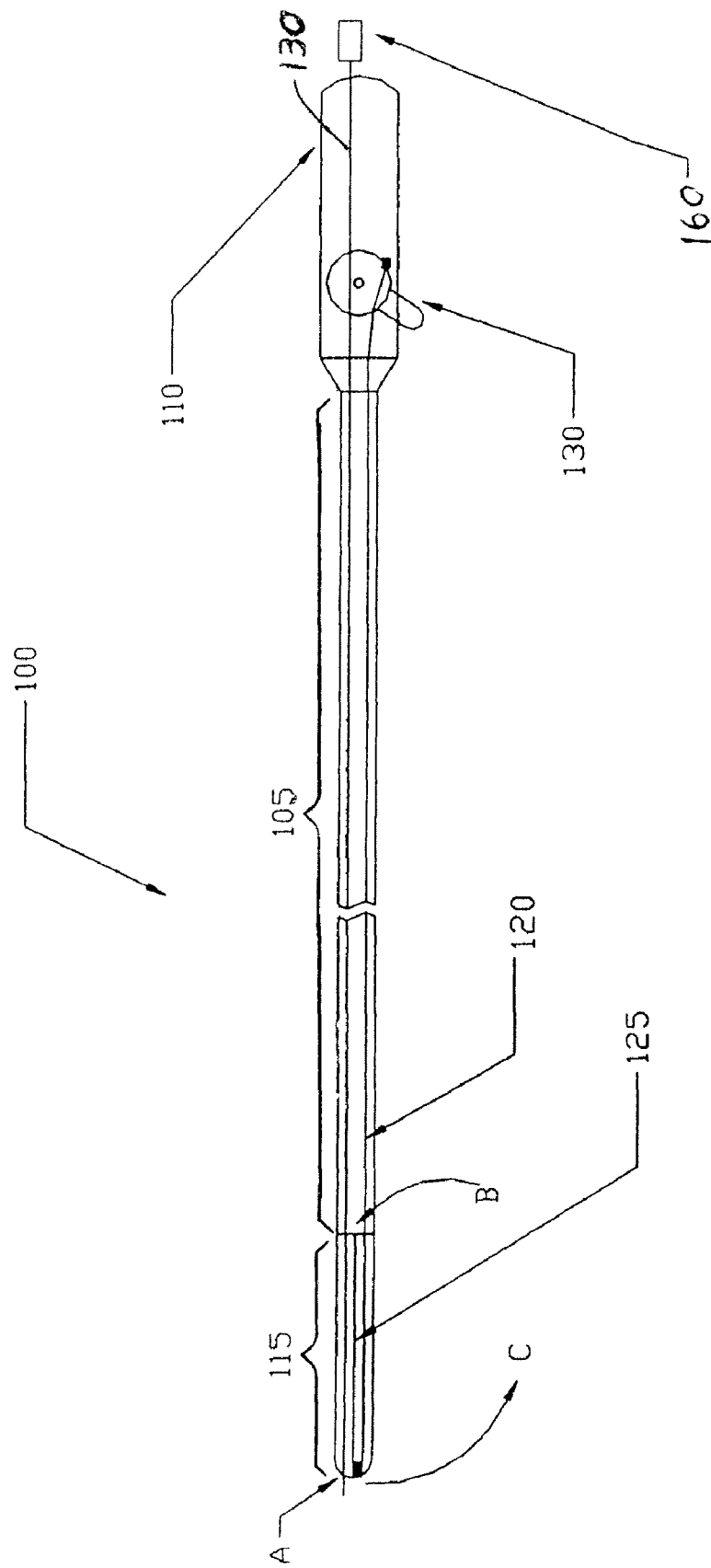
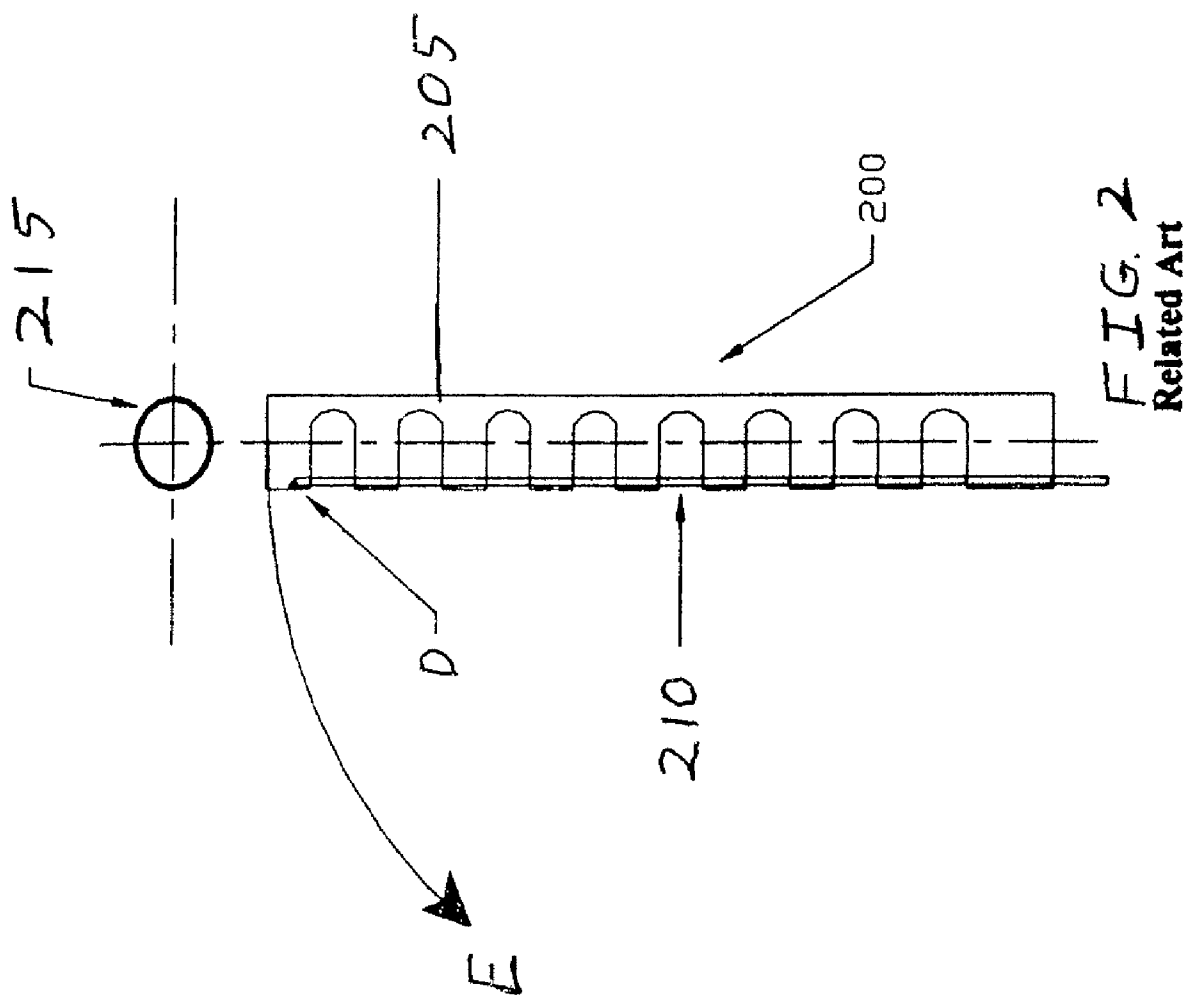


FIG. 1
Related Art



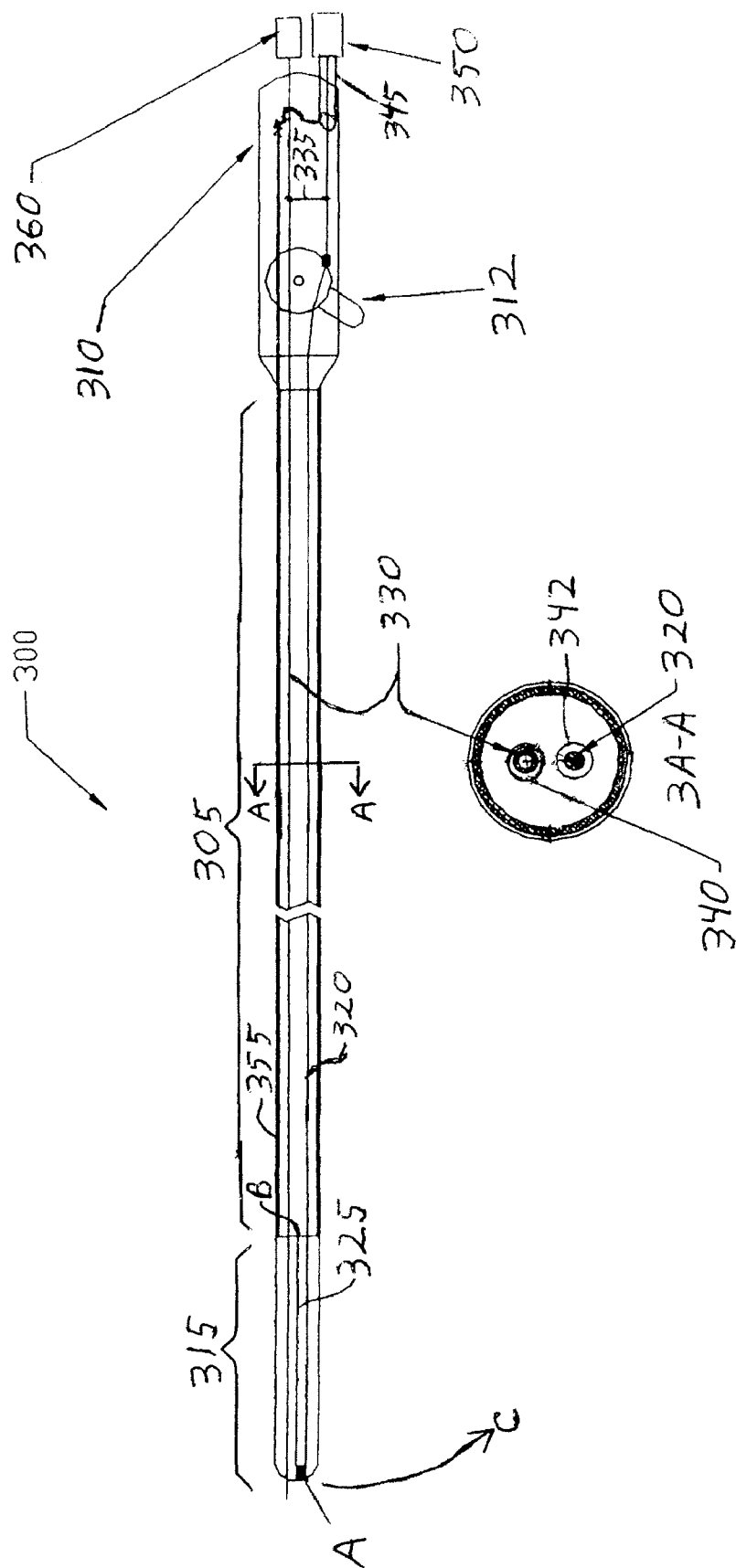


FIG. 3

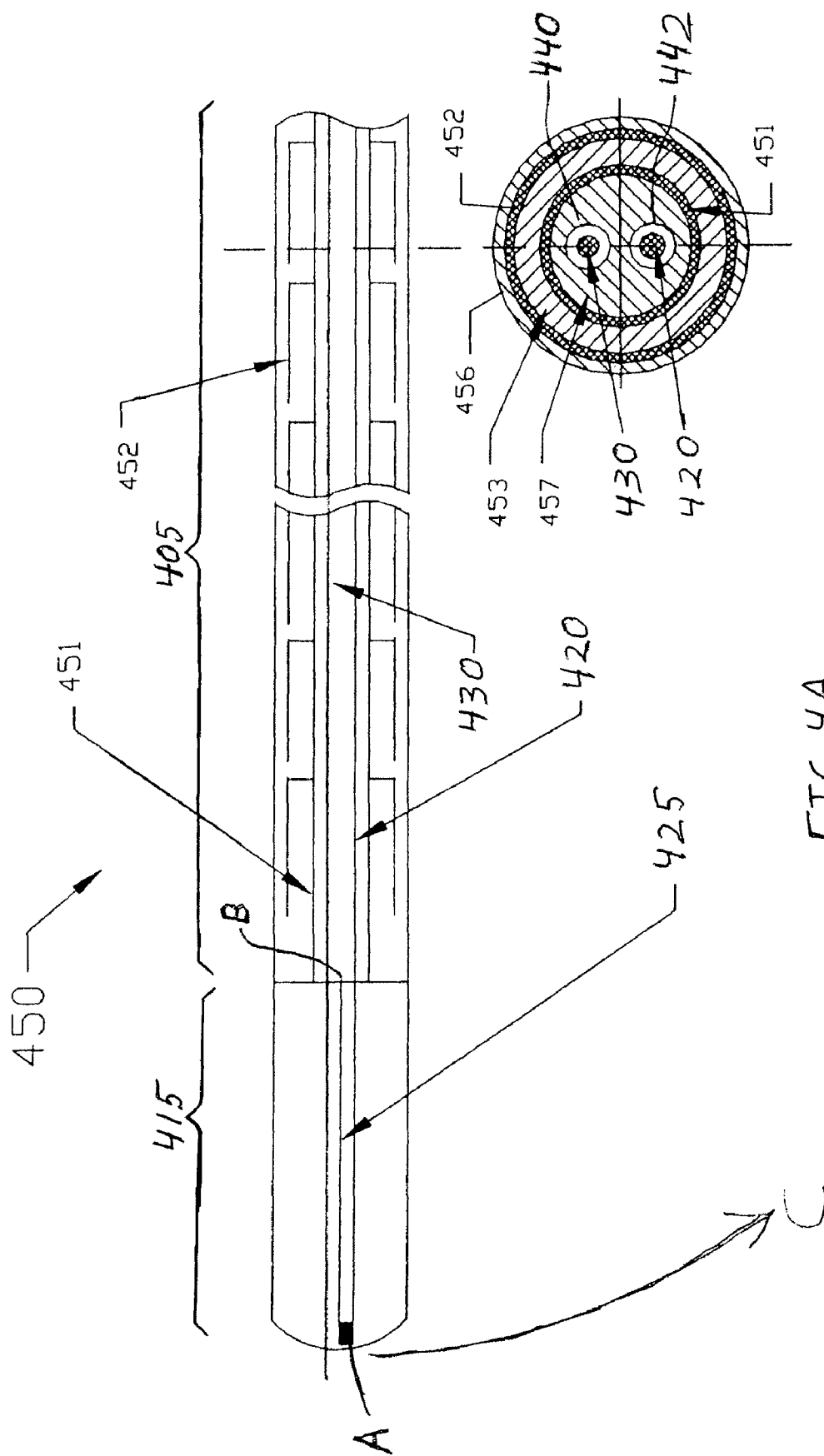


FIG. 4A

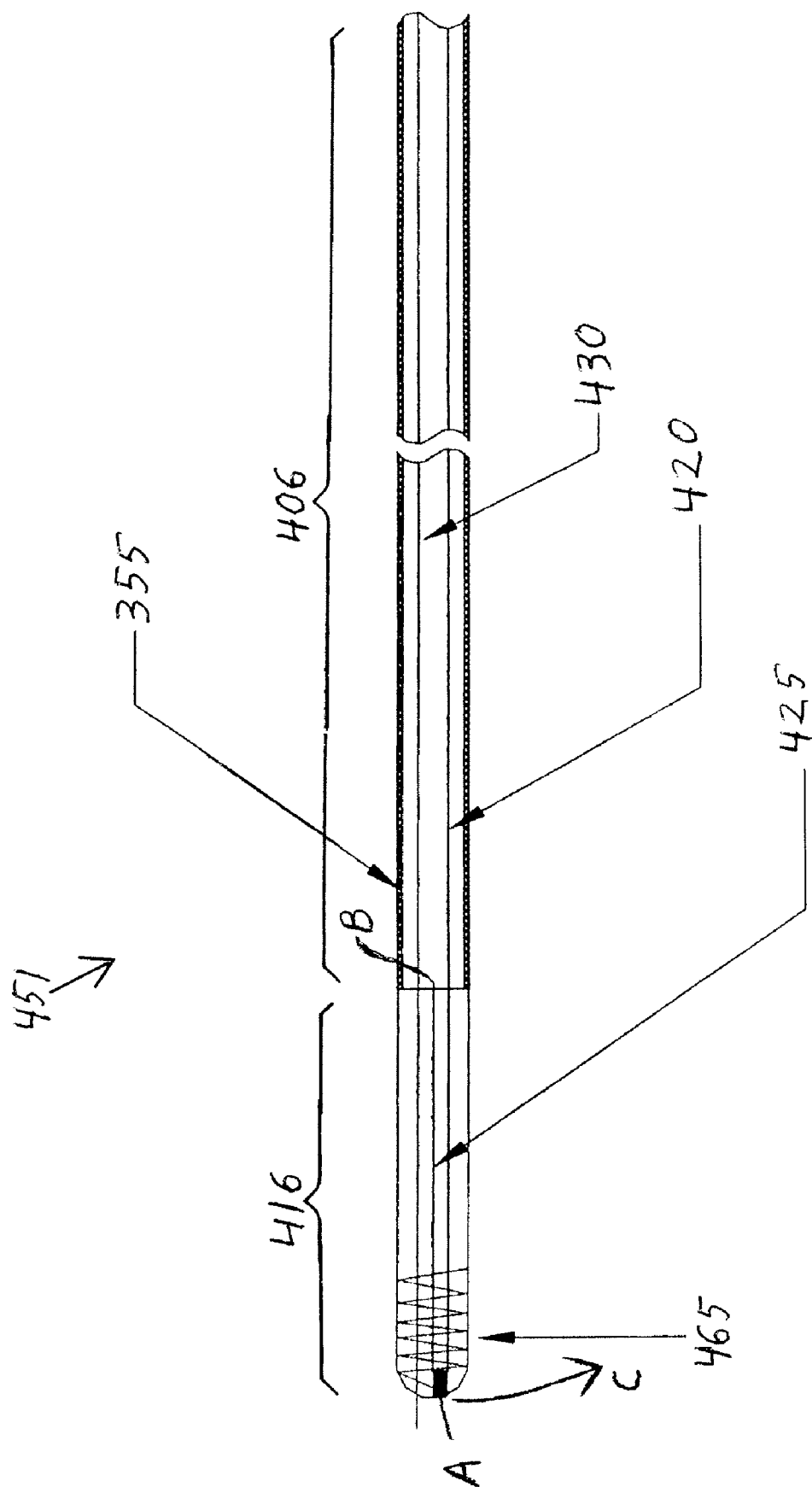
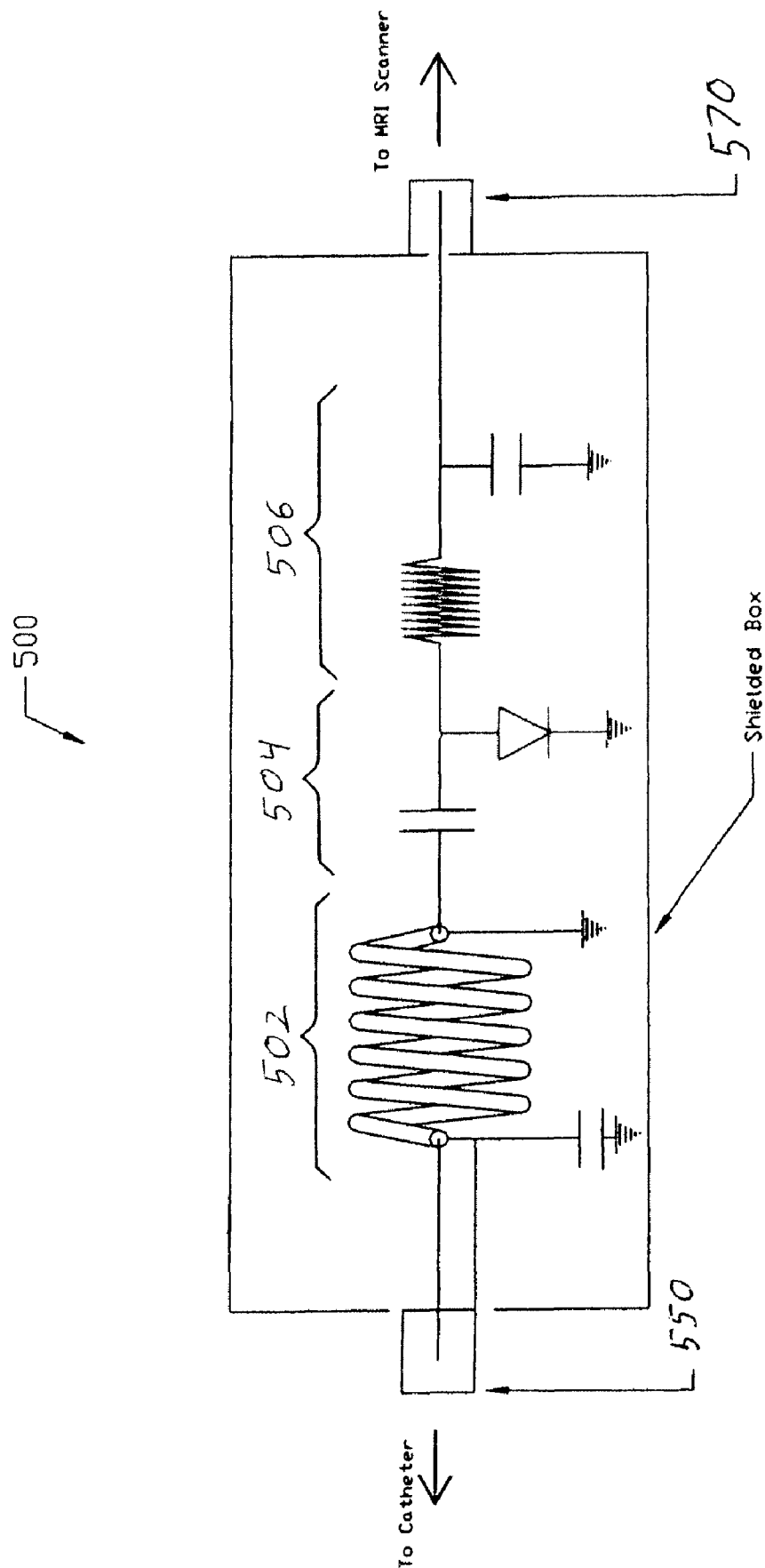
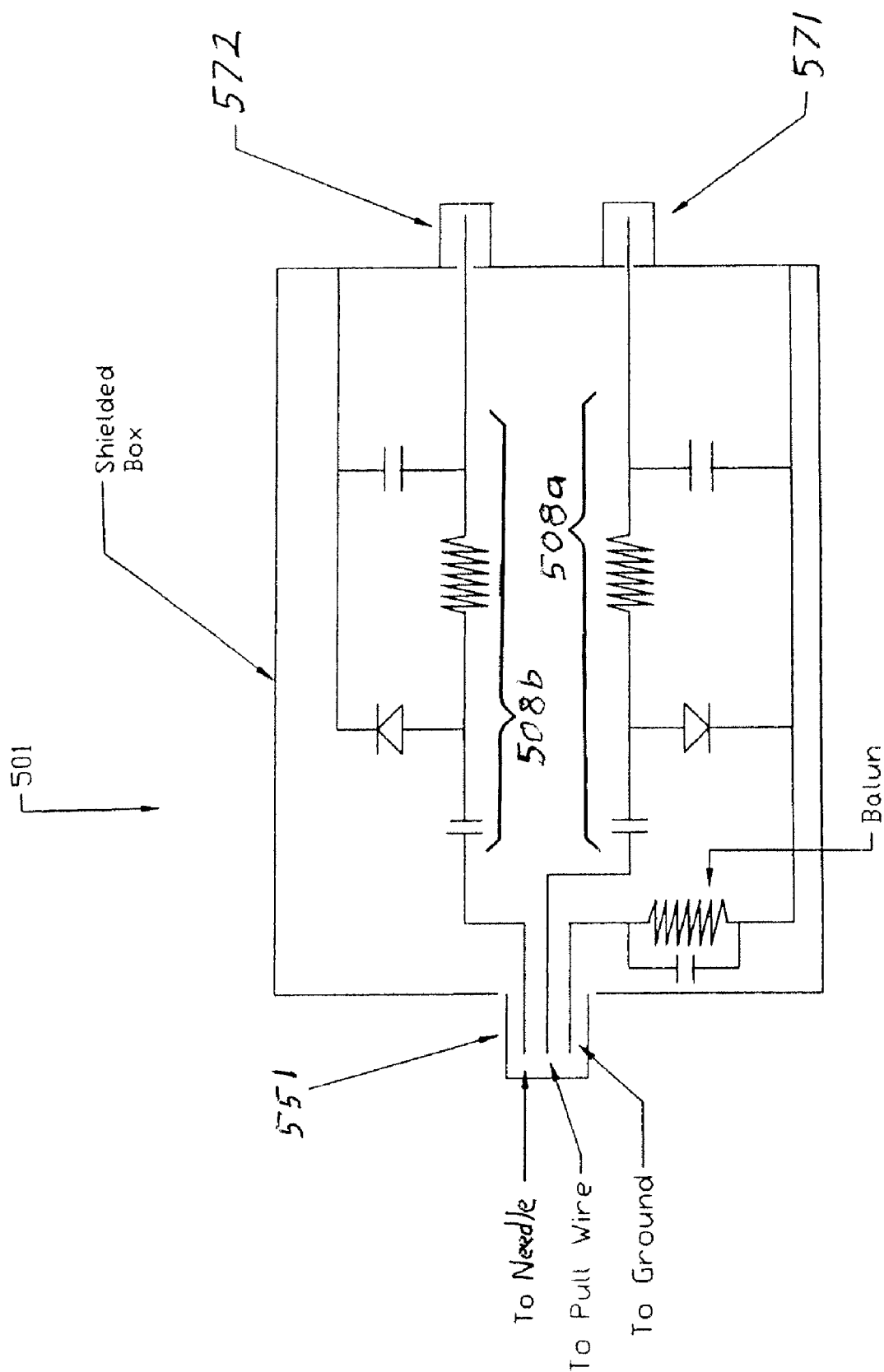


FIG. 4B





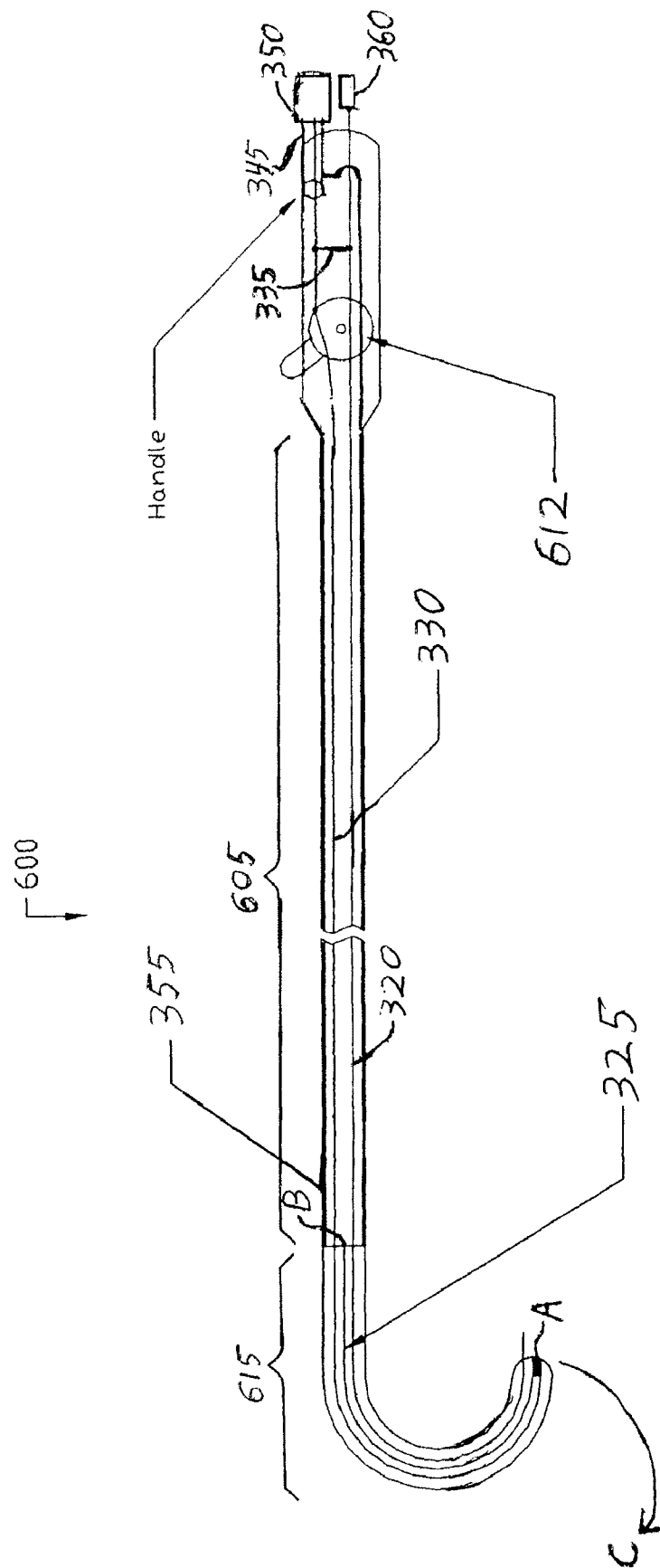


FIG. 6

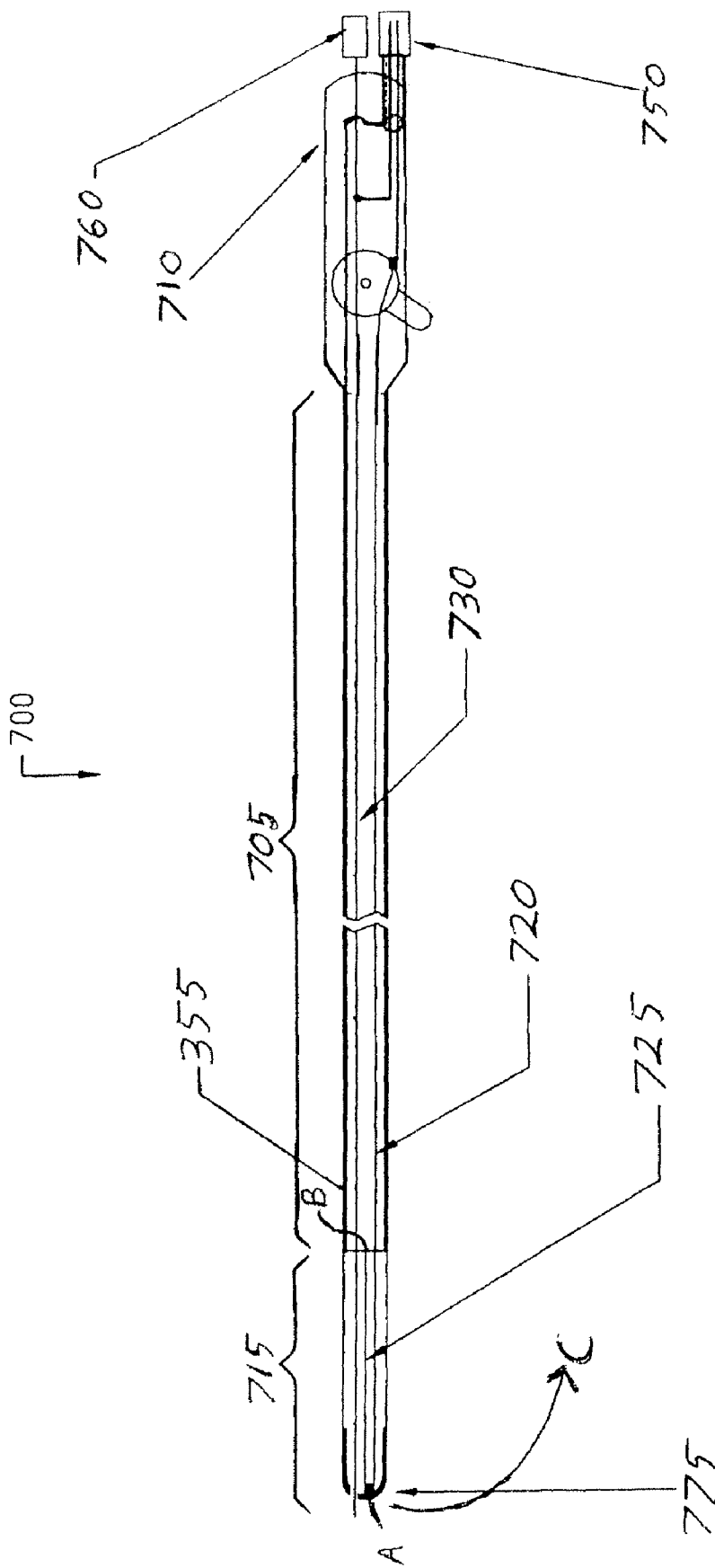


FIG. 7

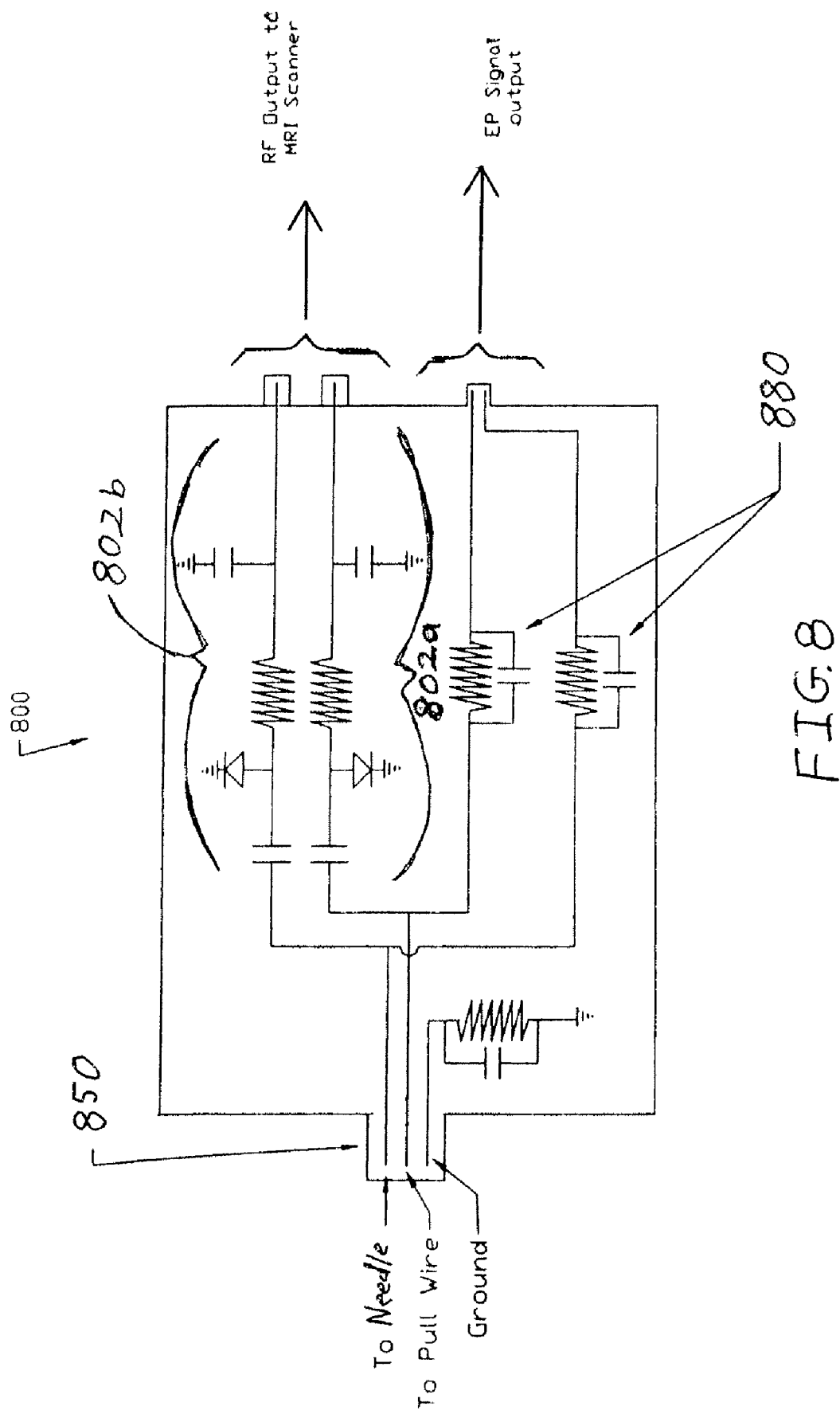


FIG. 8

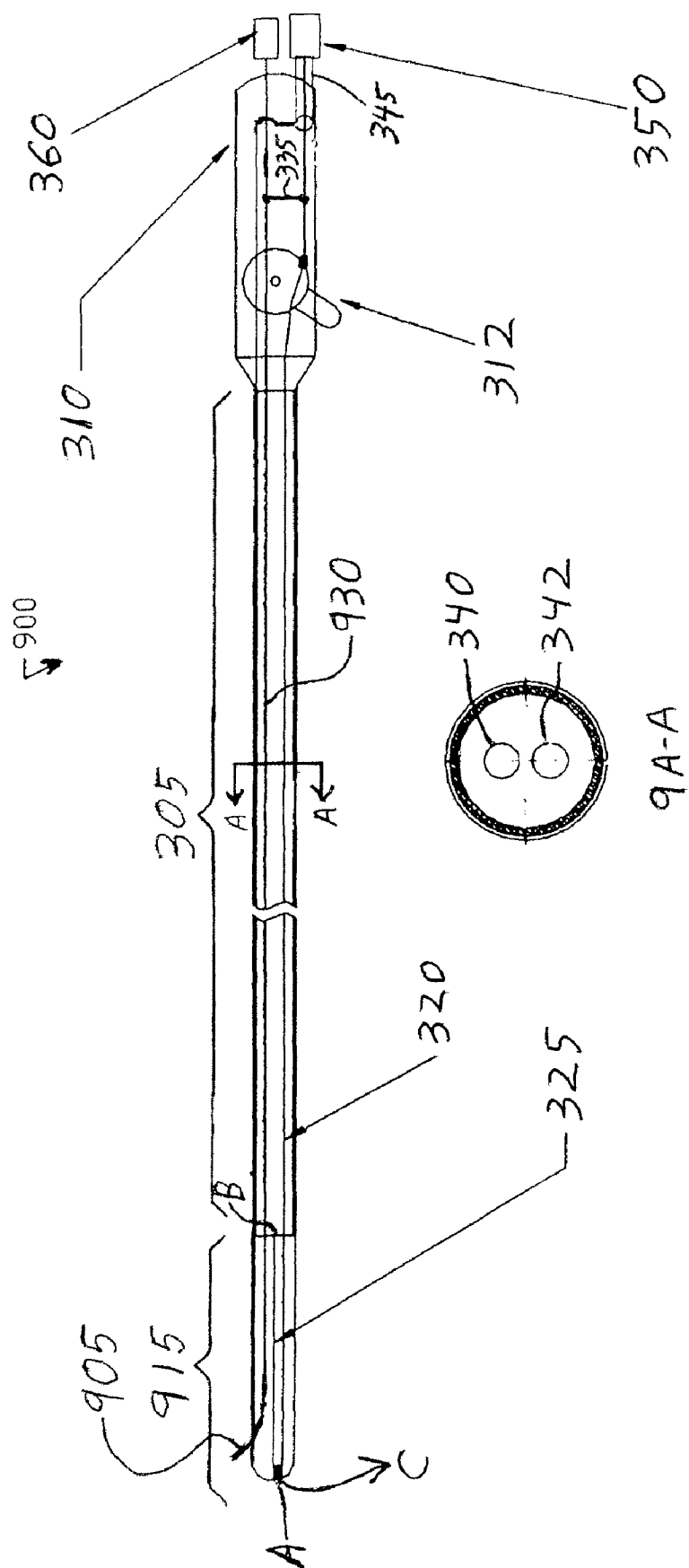


FIG. 9A

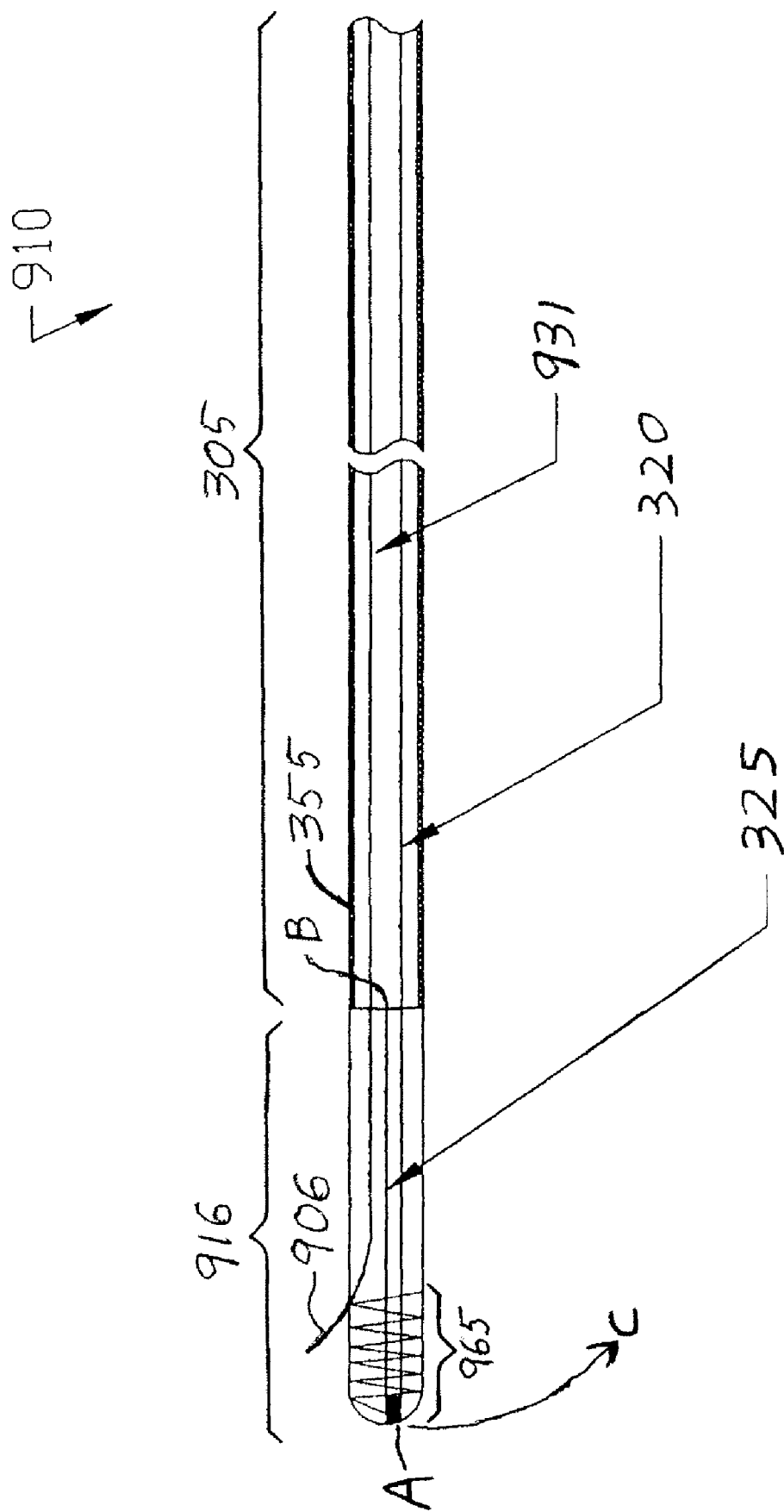


FIG. 9B

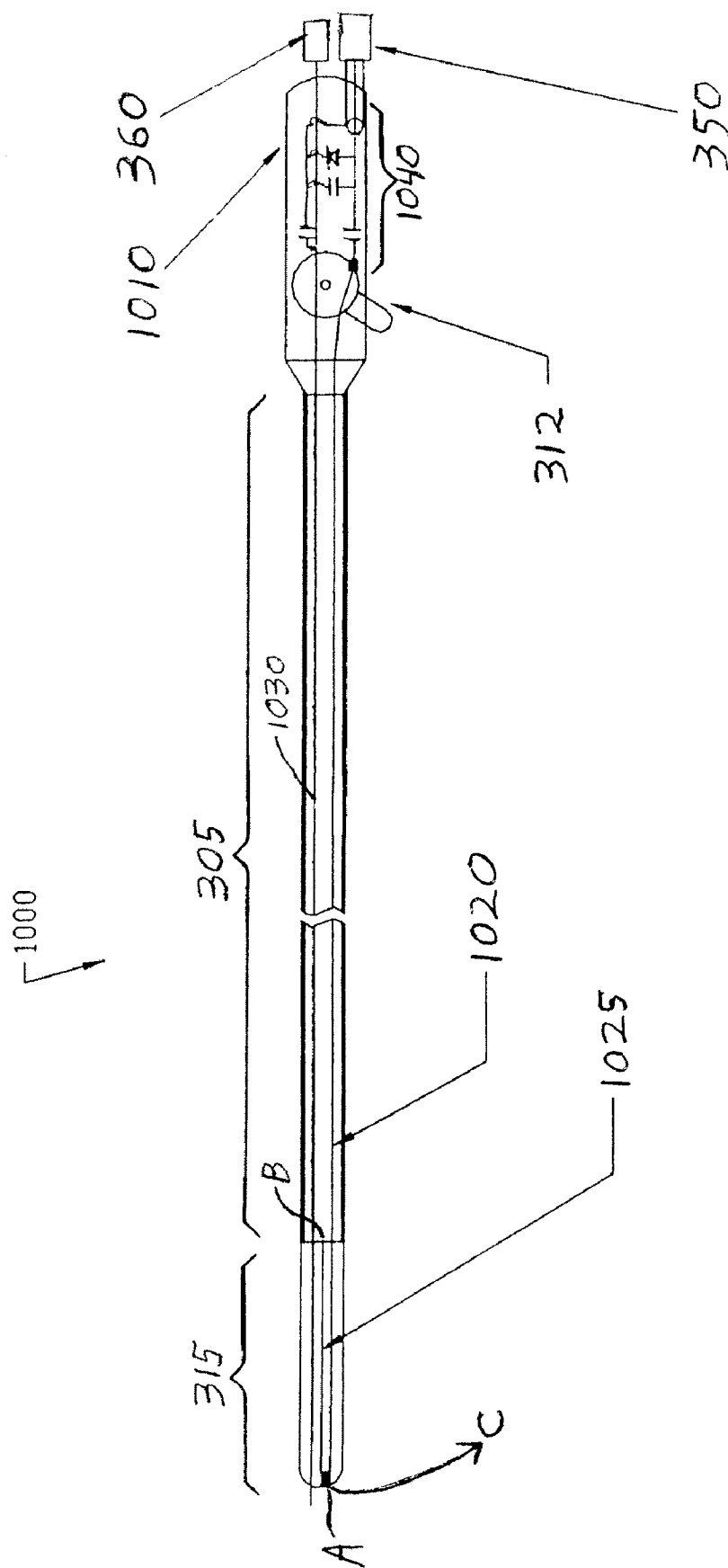


FIG. 10A

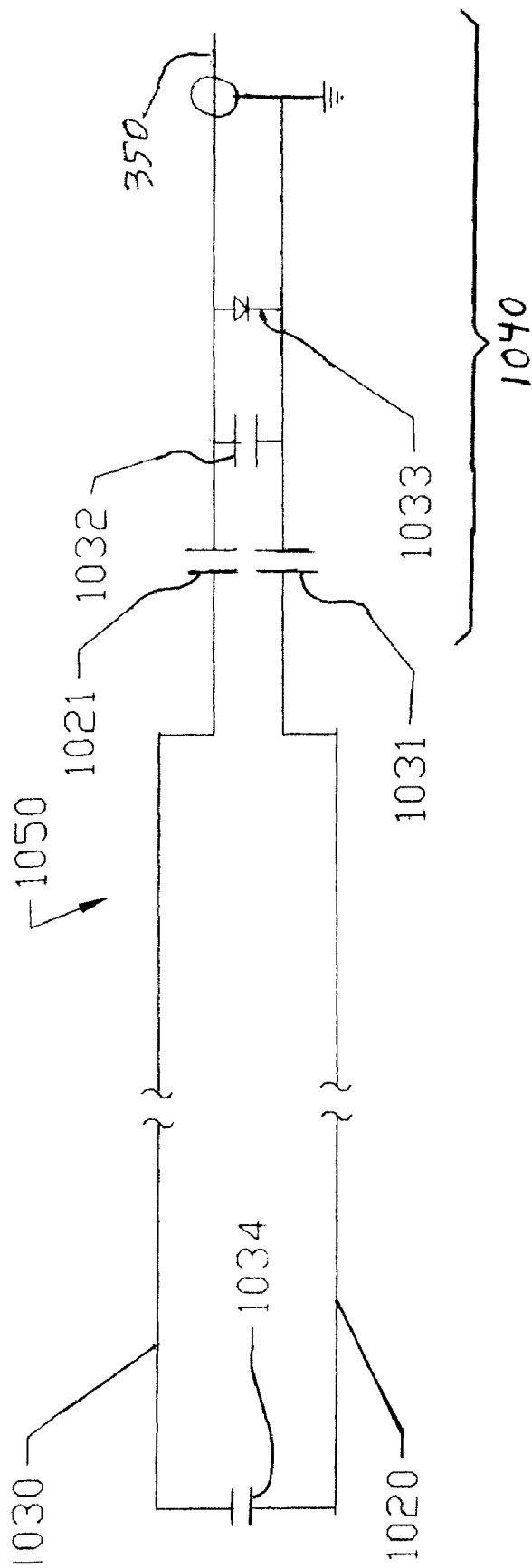


FIG. 10B

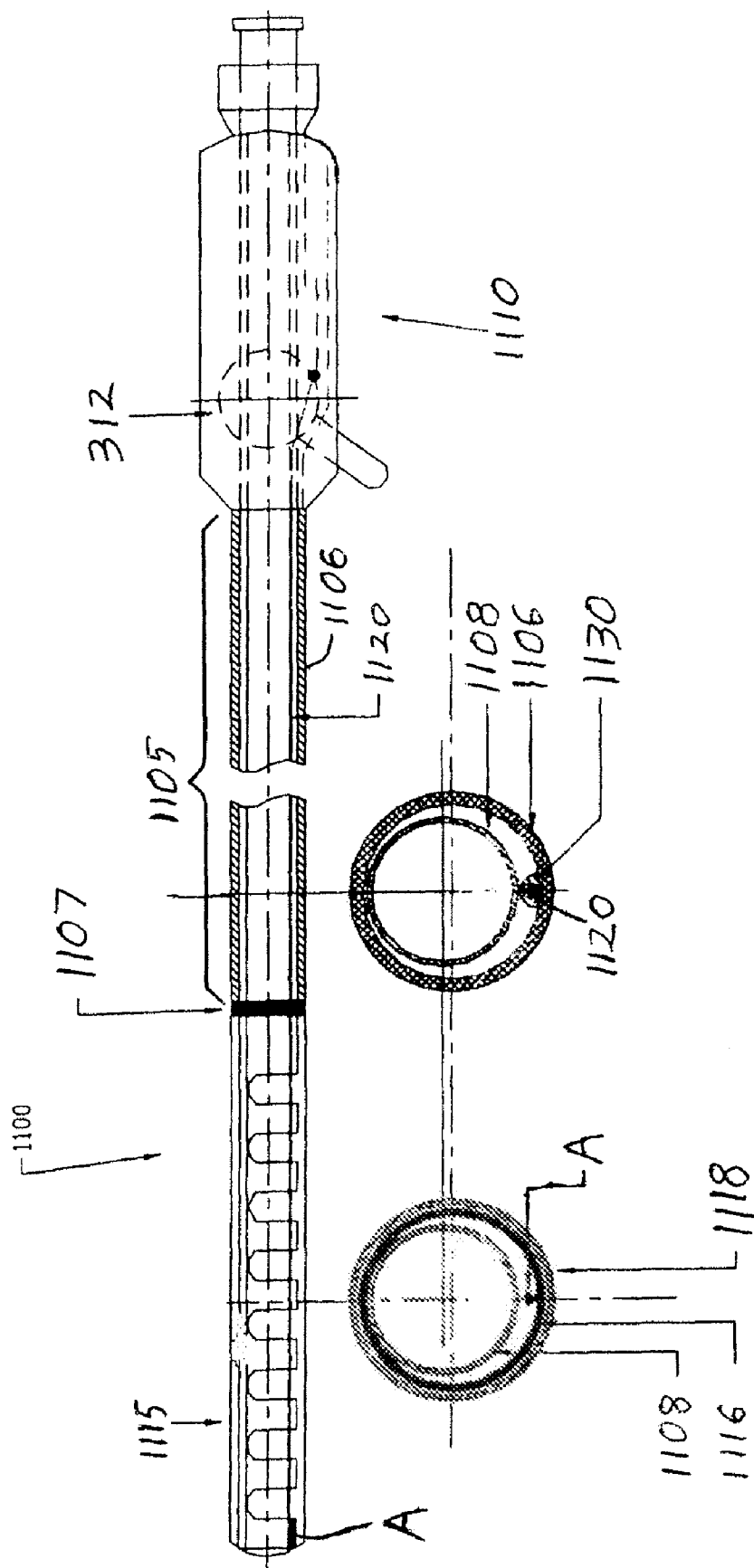


FIG. 11

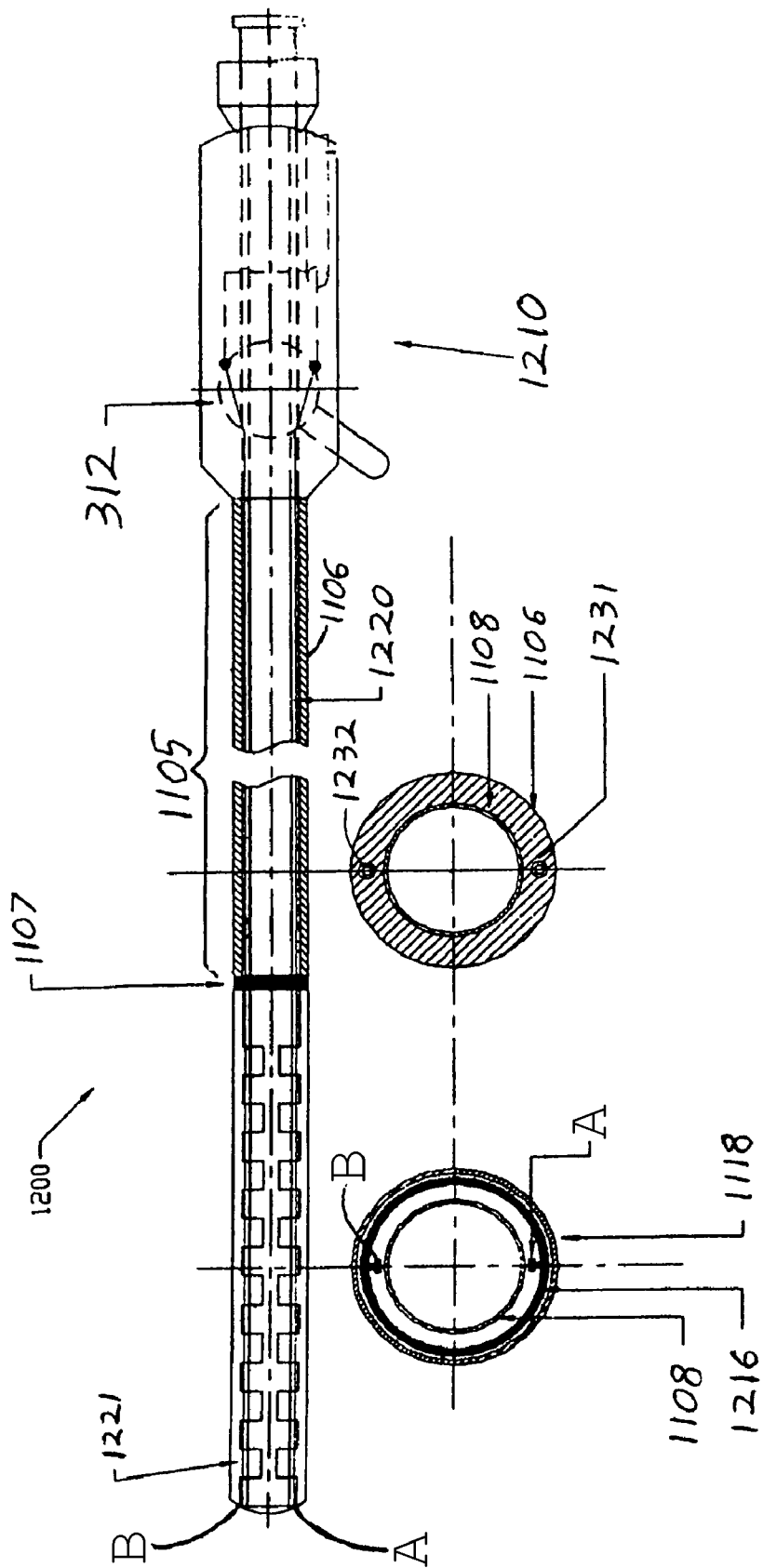


FIG. 12

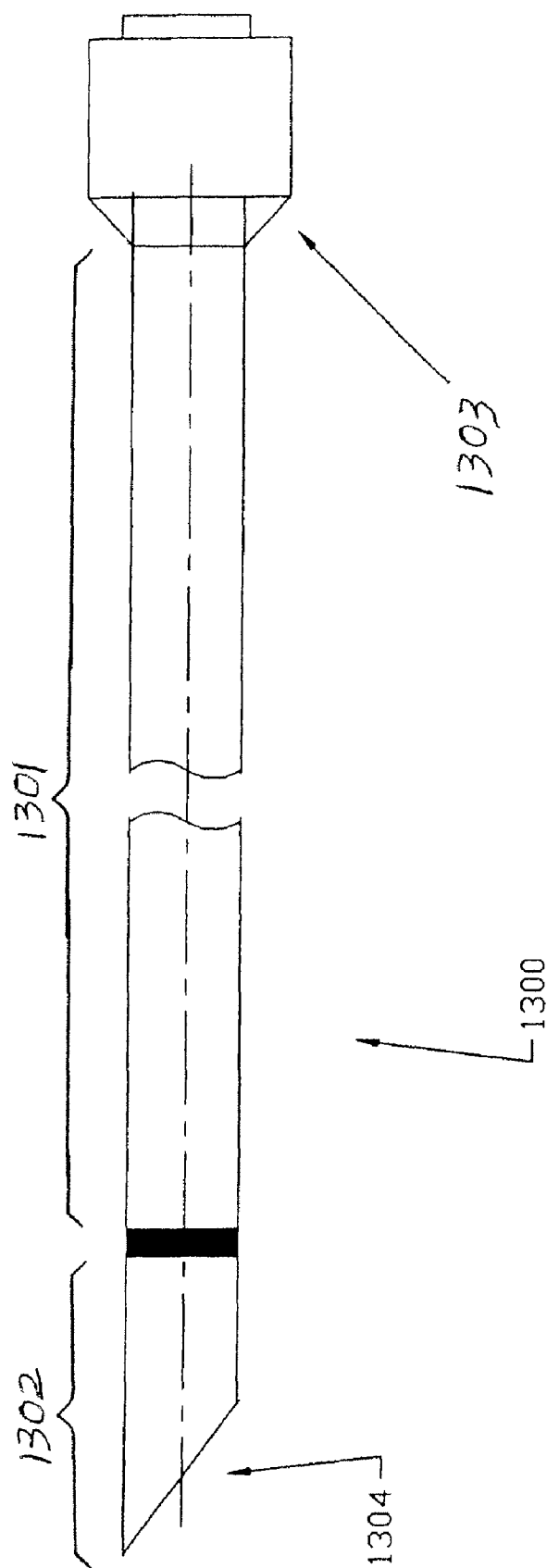


FIG. 13

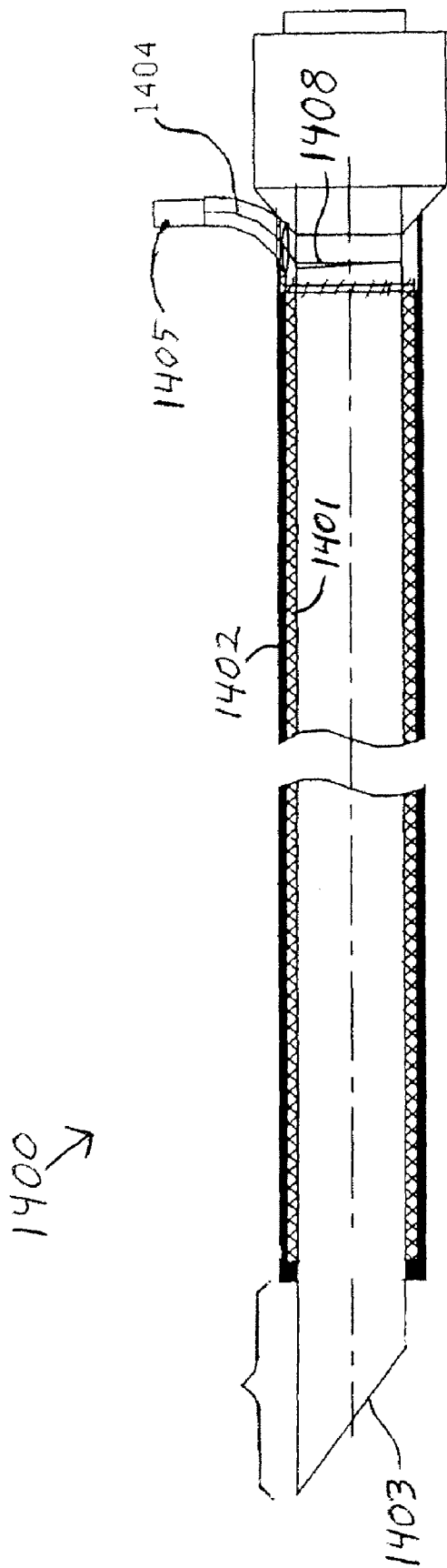


FIG. 14

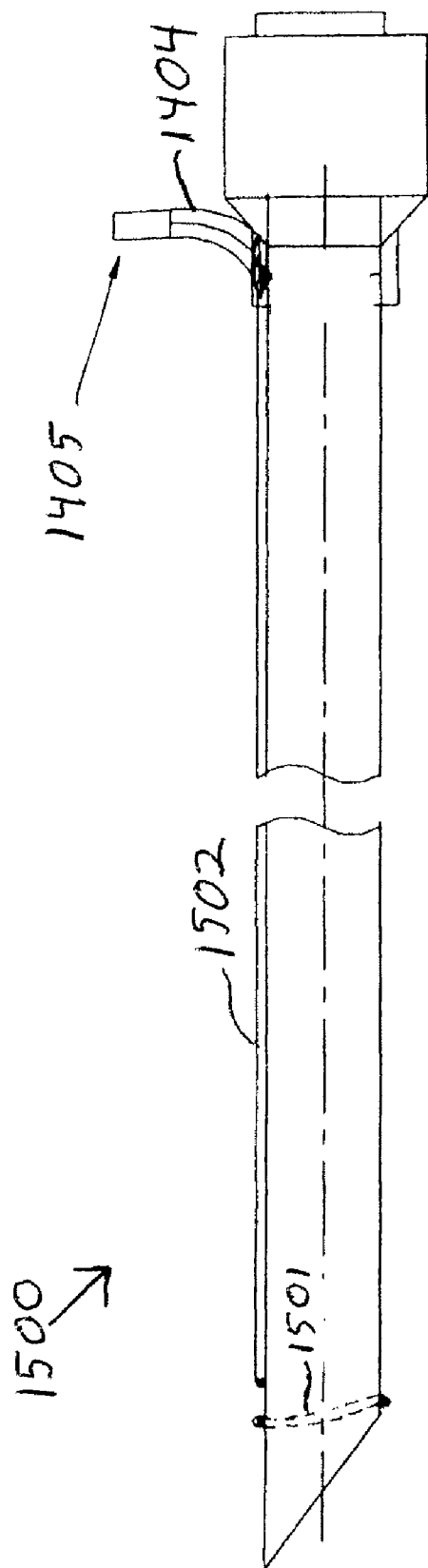


FIG. 15

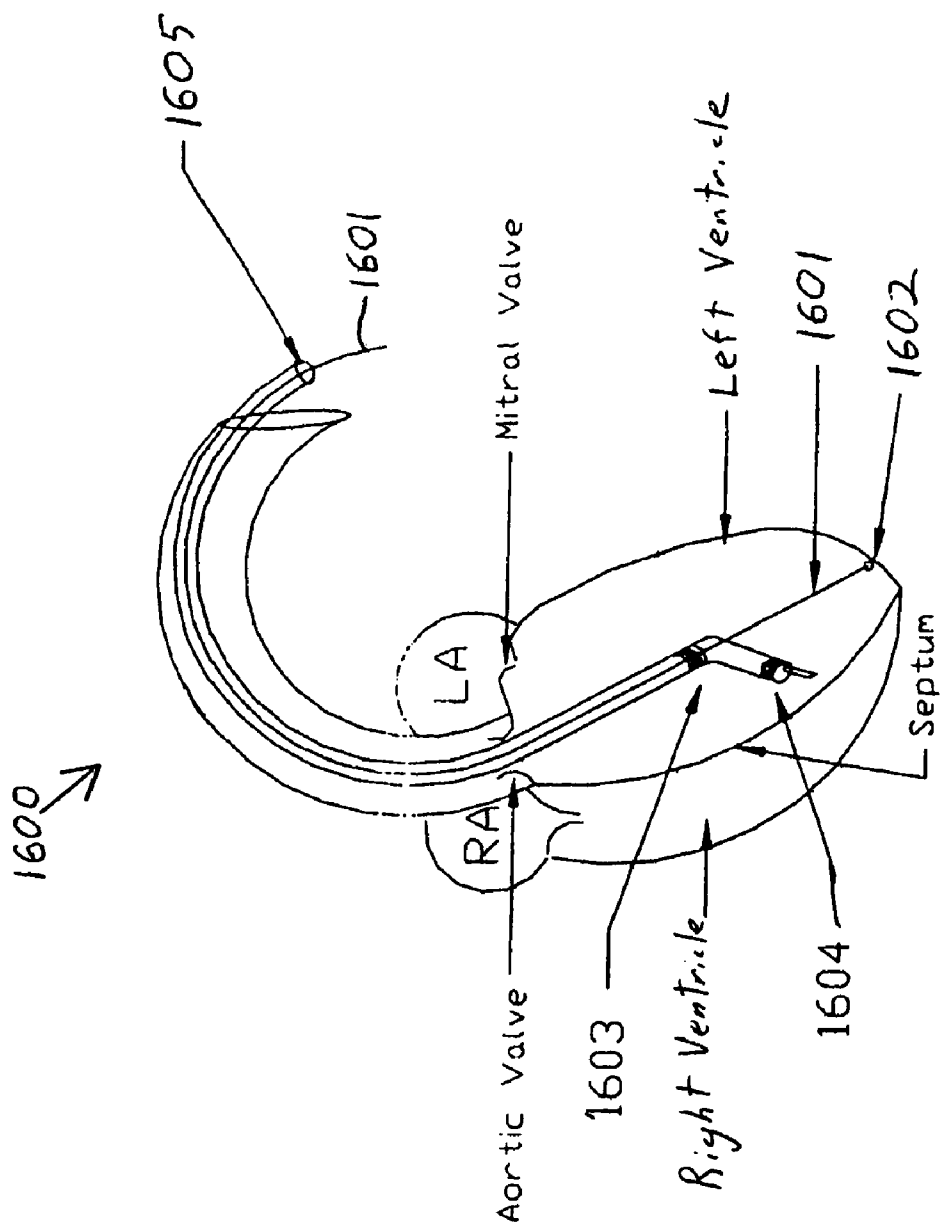


FIG. 16

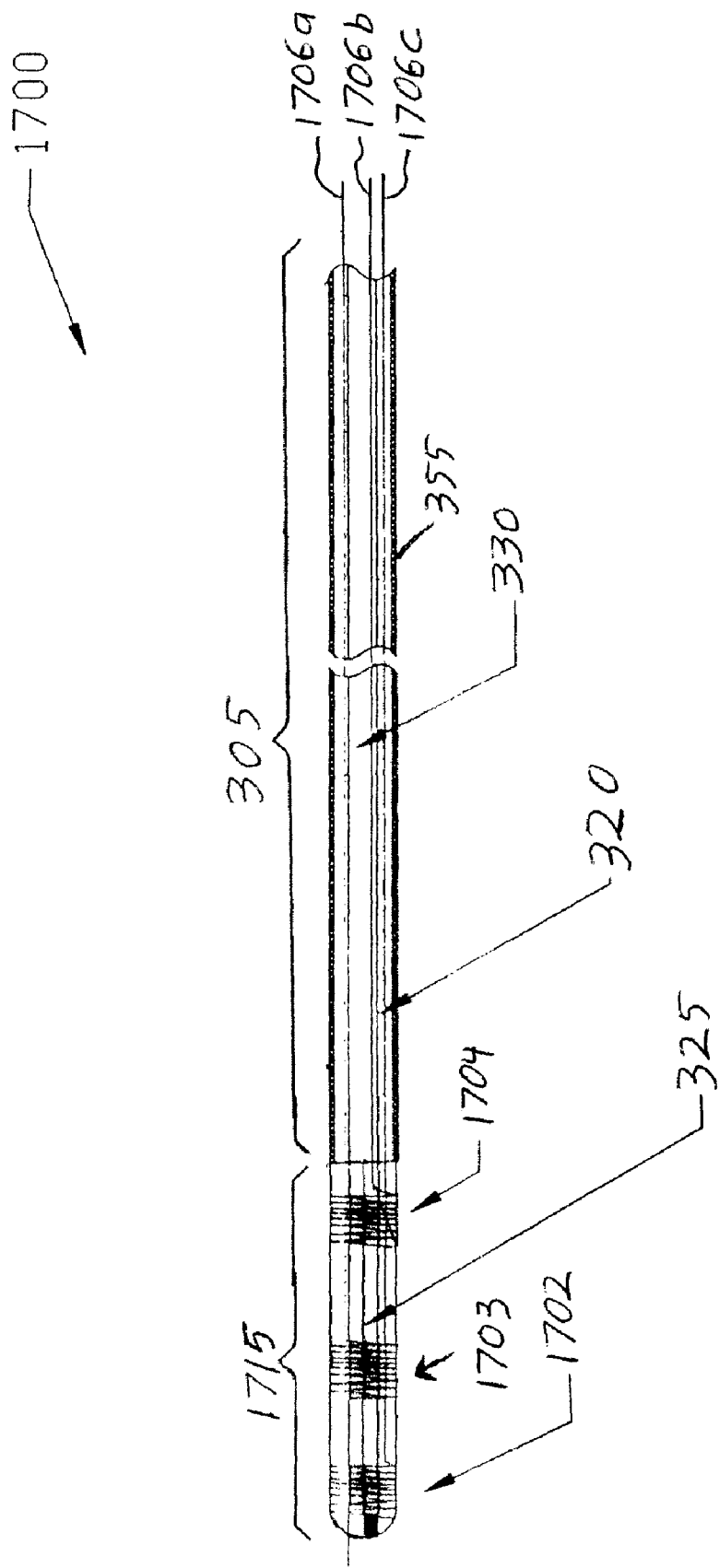


FIG. 17

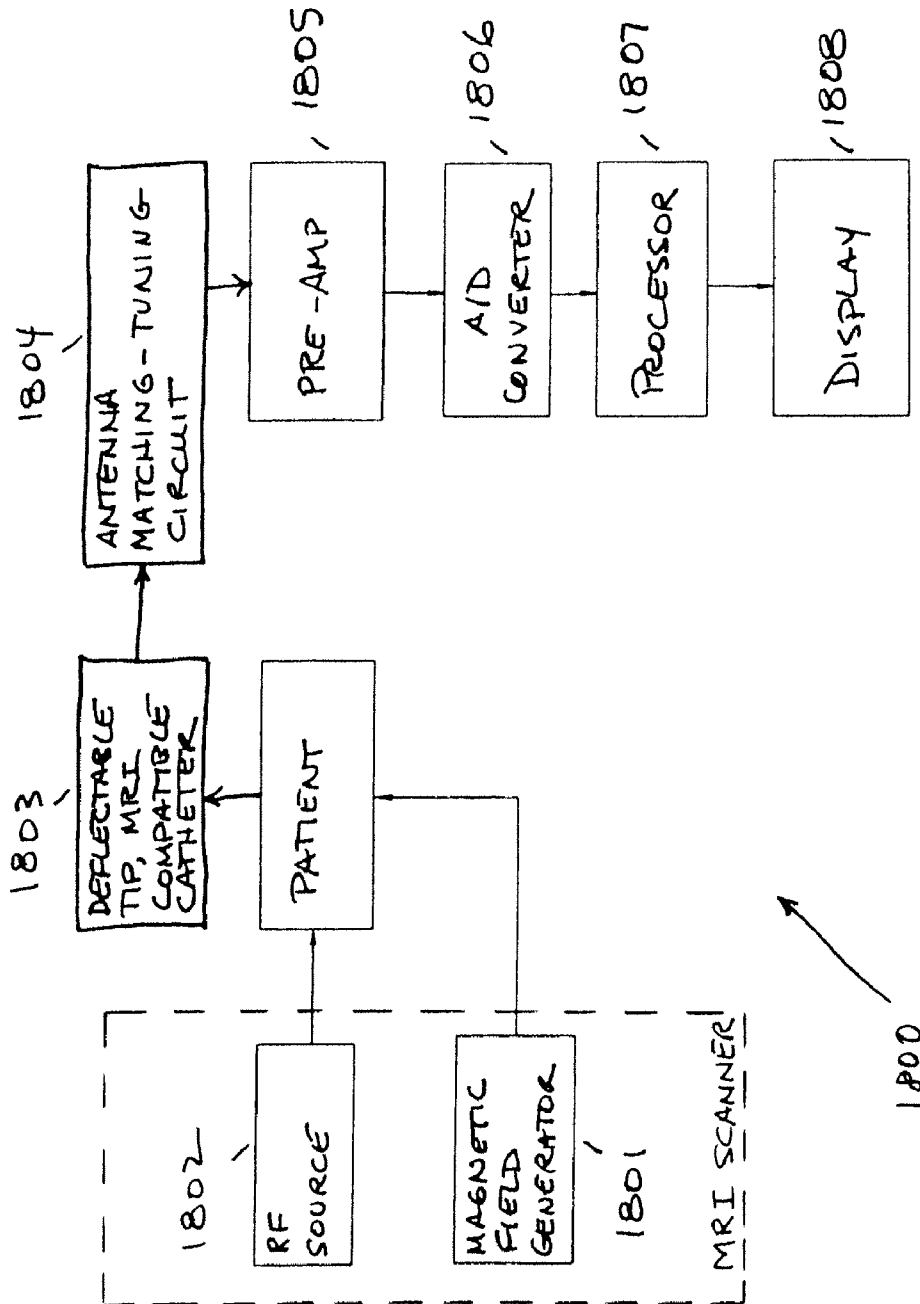


FIG. 18

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ACTIVE MRI INTRAMYOCARDIAL INJECTION CATHETER WITH DEFLECTABLE DISTAL SECTION

This application claims the benefit of, and is a divisional of, U.S. patent application Ser. No. 10/769,994, filed Feb. 3, 2004 (now U.S. Pat. No. 7,725,161), and claims the benefit of U.S. Provisional Patent Application No. 60/444,430, filed Feb. 3, 2003, the contents of each of the above-identified applications is hereby incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to catheters that have a deflectable portion. More particularly, the present invention relates to deflectable tip catheters that can be actively visualized and/or tracked in a magnetic resonance imaging (MRI) environment.

2. Discussion of the Related Art

Occlusive coronary artery disease results in myocardial infarction and deleterious left ventricular remodeling. Occlusive coronary artery disease can be treated. Treatment includes coronary balloon angioplasty, coronary artery stenting, and bypass graft surgery. However, due to the limited regenerative capacity of adult cardiomyocytes, ischemic events often result in irreversible cell injury and concurrent myocardial dysfunction, leading to congestive heart failure and death.

There is scientific evidence that delivering therapeutic agents, such as cells (e.g., stem cells), various genetic materials, growth factors, and the like, directly into the infarcted myocardial tissue may help to restore healthy tissue and normal myocardial function. Conventional interventional cardiology procedures, including the aforementioned treatments, such as balloon angioplasty, typically involve the use of a balloon catheter to dilate the occluded artery and X-ray fluoroscopy to assist the attending cardiologist guide the catheter. X-ray fluoroscopy, however, does not distinguish healthy from infarcted myocardial tissue, nor does it provide an anatomical image of the heart, where the ability to distinguish infarcted tissue from healthy tissue within an anatomical image of the heart is of vital importance to the cardiologist who is attempting to precisely deliver therapeutic agents using any one of the above-identified conventional techniques.

There are electro-anatomical mapping systems capable of providing a functional map of the cardiac anatomy; however, these systems cannot provide real-time images of the heart. An example is Biosense Webster's NOGA system, which is used in conjunction with X-ray fluoroscopy. The NOGA system employs a catheter comprising three coils and an endocardial potential measuring electrode located at the distal tip. During clinical use, three external magnets are placed at three different locations on the patient (e.g., under the patient's back and on the right and left side of the patient's chest). The cardiologist is then able to move the catheter around inside the left ventricle of the patient's heart, and, in doing so, the NOGA system measures the electrical activity at endocardial surface, as well as the motion and the location of the distal tip of the catheter. The NOGA system uses these measurements to create a three-dimensional, real-time, dynamic reconstruction of the ventricle, and assess the electrical and mechanical properties of the myocardium. The electrical potential and the motion of the ventricular wall are used, in turn, to differentiate between healthy, viable, tissue, and completely infarcted tissue. The primary drawback of

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this system is that it does not provide an anatomical image of the entire heart. It is therefore difficult to know the cardiac anatomy in which the catheter tip is located, and whether the catheter tip is apposed to the septum or the lateral wall. In addition, the procedure associated with the NOGA system is lengthy and the quality of the ventricle image is highly dependent on operator skill.

MRI is a diagnostic and imaging modality that is capable of providing a three-dimensional map, or image of the entire heart. Furthermore, MRI offers this capability without the ionizing radiation associated with other imaging modalities, such as X-ray fluoroscopy. MRI also provides real-time images with excellent tissue contrast; thus, the attending cardiologist can quickly and efficiently see the entire heart and clearly differentiate between healthy, viable, tissue and completely infarcted tissue. Ideally, MRI should be available to cardiologists for use during intervention therapy to accurately track and precisely guide the catheter to regions of infarcted myocardial tissue.

There are many types of injection catheters currently available; however, none is well suited for use in an MRI environment. For example, deflectable (i.e., steerable) tip catheters including multi-directional, bi-directional and uni-directional deflectable catheters are described in U.S. Pat. Nos. 5,487,757; 6,198,974; and 5,755,760, respectively. Injection catheters capable of delivering therapeutic agents to myocardial and other tissues are described, for example, in U.S. Pat. Nos. 5,980,516 and 6,004,295. Still further, deflectable injection type catheters are described, for example, in U.S. Pat. Nos. 6,346,099 and 6,210,362.

The various catheter designs described in the above-identified patents are not, as stated, well suited for use in an MRI environment for both procedural reasons as well as patient safety reasons. For instance, these catheters have ferromagnetic components that pose a safety hazard to the patient in a magnetic field environment, as they can cause injury to the patient, as they may move in an undesired manner due to the magnetic field. The ferromagnetic components can also cause image distortions, thereby compromising the effectiveness of the procedure. Still further, such catheters contain long metallic components, which can cause radiofrequency (RF) deposition in adjacent tissue and, in turn, tissue damage due to an extensive increase in temperature.

In addition, it would be difficult to track and/or visualize the location of the catheters described in the above-identified patents in an MRI environment. In general, there are two types of tracking in an MRI environment: active tracking and passive tracking. Active tracking is the preferred methodology. It involves incorporating a transmit and/or receive antenna into the catheter design. Because a high intensity signal is transmitted or received, active tracking provides precise location information. An example of a catheter that can be actively tracked in an MRI environment is described in U.S. Pat. No. 5,928,145. In this patent, the catheter employs a loopless antenna. Another example of a catheter that can be actively tracked in an MRI environment is described in U.S. Pat. No. 5,699,801. In this patent, the catheter does not have a deflectable tip, nor is it capable of delivering therapeutic agents to a target location, nor is it capable of deploying other surgical instruments such as forceps during a biopsy procedure.

It would be very desirable to provide attending cardiologists with a catheter design that he or she can easily steer. In addition, it would be desirable provide a catheter that can be effectively tracked and/or visualized in an MRI environment, a catheter that is safe and effective when used in an MRI environment, a catheter that can be used to effectively deliver

therapeutic agents to a target location within the patient using an injection needle, and deploy other surgical instruments such as a laser, a suturing device, forceps, a cauterization tool, and the like.

SUMMARY OF THE INVENTION

Accordingly, the present invention is directed to a deflectable tip catheter that substantially obviates the deficiencies and disadvantages associated with the related art as set forth above. More specifically, the present invention is directed to a deflectable tip catheter that can be actively tracked in an MRI environment, without excessive RF deposition (i.e., local tissue heating) and the other safety and procedural drawbacks associated with the prior related art. The present invention is also directed to a deflectable tip catheter that can be effectively used to deliver therapeutics with an injection needle and deploy other surgical instruments during procedures, such as a biopsy procedure.

It should be noted that the following detailed description portrays the various exemplary embodiments of the present invention as being particularly useful in the field of cardiology. For example, the present invention is portrayed as being particularly useful for injecting and/or delivering therapeutics to cardiac tissue. However, it will be very clear to one skilled in the art that the present invention will be equally useful for other medical procedures, including biopsy procedures, as well as procedures that involve other anatomical systems such as the brain, liver, and pancreas.

As such, one advantage of the present invention is to provide a deflectable tip catheter that can be easily and effectively visualized and tracked in an MRI environment.

Another advantage of the present invention is to provide a deflectable tip catheter that can be employed safely when used in an MRI environment.

Still another advantage of the present invention is to provide a deflectable tip catheter that is effective when used in an MRI environment and does not, among other things, distort the image, and does not cause local tissue damage due to excessive RF deposition along the length of the catheter.

Thus, in accordance with exemplary embodiments of the present invention, the aforementioned and other objectives are achieved with a deflectable tip catheter for use in an MRI environment. The deflectable tip catheter comprises a deflectable tip section and an RF antenna.

In accordance with exemplary embodiments of the present invention, the aforementioned and other objectives are also achieved with a bi-directional, deflectable tip guide catheter. The bi-directional, deflectable tip guide catheter includes a deflectable tip section, a first pull wire, and a second pull wire, where the first and second pull wires are configured to form a loop antenna.

In accordance with exemplary embodiments of the present invention, the aforementioned and other objectives are further achieved with a deflectable tip catheter that includes a deflectable tip section and an RF antenna. In addition, the catheter includes a plurality of distally located, non-magnetic, inductor loop coils.

In accordance with exemplary embodiments of the present invention, the aforementioned and other objectives are still further achieved with a MRI system. The MRI system comprises an MRI scanner, a deflectable tip catheter that is configured as an RF antenna, and an electrical connection between the deflectable tip catheter and the MRI scanner.

In accordance with exemplary embodiments of the present invention, the aforementioned and other objectives are also achieved through a magnetic resonance imaging method. The

method involves generating a magnetic field around at least a portion of a patient and transmitting RF energy over a portion of the patient exposed to the magnetic field. In addition, the method involves receiving the RF energy using an RF antenna in a deflectable tip catheter located in the patient and generating a magnetic resonance image that includes a visualization of the deflectable tip catheter in the patient.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, together with the detailed description below, set forth the various aspects and embodiment of the present invention, wherein:

FIG. 1 is a schematic diagram of a conventional, deflectable tip injection catheter **100**;

FIG. 2 is a schematic diagram of an alternative deflectable tip section **200** associated with a conventional deflectable tip catheter;

FIG. 3 is a schematic diagram of an active MRI trackable, deflectable tip injection catheter, in accordance with a first exemplary embodiment of the present invention;

FIG. 4A is a schematic diagram of a catheter having a non-deflectable portion that includes multiple RF chokes, in accordance with an alternative embodiment;

FIG. 4B is a schematic diagram illustrating an alternative deflectable tip section for an injection catheter in accordance with an alternative embodiment;

FIG. 5A is a circuit diagram of a single RF output signal matching-tuning circuit that may be employed with a deflectable tip injection catheter, in accordance with exemplary embodiments of the present invention;

FIG. 5B is a circuit diagram of a multiple RF output signal matching-tuning circuit that may be employed with a deflectable tip injection catheter, in accordance with exemplary embodiments of the present invention;

FIG. 6 is a schematic diagram of an MRI trackable, deflectable tip injection catheter that has a pre-deflected (i.e., pre-shaped), distal deflectable tip section, in accordance with a second exemplary embodiment of the present invention;

FIG. 7 is a schematic diagram of an MRI trackable, deflectable tip injection catheter that includes an endocardial potential measuring electrode, in accordance with a third exemplary embodiment of the present invention;

FIG. 8 is a circuit diagram of an interface circuit that may be used in conjunction with a deflectable tip injection catheter that has an endocardial potential measuring electrode;

FIGS. 9A and 9B are schematic diagrams of MRI trackable, deflectable tip injection catheters that include a side or lateral opening in the deflectable tip section, in accordance with a fourth exemplary embodiment of the present invention;

FIG. 10A is a schematic diagram of an MRI trackable, deflectable tip injection catheter, in accordance with a fifth exemplary embodiment of the present invention;

FIG. 10B is a schematic diagram of an interface circuit that might be used in conjunction with a deflectable tip injection catheter, in accordance with exemplary embodiments of the present invention;

FIG. 11 is a schematic diagram of a uni-directional, deflectable tip guide catheter, in accordance with a sixth exemplary embodiment of the present invention;

FIG. 12 is a schematic diagram of a bi-directional, deflectable tip guide catheter **1200**, in accordance with a seventh exemplary embodiment of the present invention;

FIG. 13 is a diagram of an injection needle that can be passively tracked in an MRI environment, for use with a deflectable tip injection catheter in accordance with exemplary embodiments of the present invention;

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FIG. 14 is a diagram of an injection needle, configured as a loop antenna, capable of being actively tracked in an MRI environment, separately and independently from the catheter, in accordance with exemplary embodiments of the present invention;

FIG. 15 is a diagram of an injection needle, configured as a loopless antenna, capable of being actively tracked in an MRI environment, separately and independently from the catheter, in accordance with exemplary embodiments of the present invention;

FIG. 16 is a schematic diagram of a deflectable tip catheter, in accordance with an eighth exemplary embodiment of the present invention;

FIG. 17 is a schematic diagram of a deflectable tip catheter, including three, non-magnetic inductor loop coils, in accordance with exemplary embodiments of the present invention; and

FIG. 18 is a schematic diagram of an MRI system, including a deflectable tip, MRI compatible catheter, in accordance with exemplary embodiments of the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

FIG. 1 is a schematic diagram of a conventional injection catheter 100 with a deflectable tip. As shown, the catheter 100 comprises a proximal portion that includes a non-deflectable section 105 and a handle 110. The catheter 100 also comprises a deflectable tip section 115. The deflection mechanism involves a pull wire 120 and an anchor wire 125, where the pull wire 120 and the anchor wire 125 are connected to each other at point A in the deflectable tip section 115, as shown. The pull wire 120 runs the length of the catheter through a lumen (not shown). The anchor wire 125 is fixed at point B where the distal end of the non-deflectable section 105 abuts the proximal end of the deflectable tip section 115. During clinical use, the attending physician (e.g., cardiologist) may actuate the deflectable tip section 115 by manipulating the deflection dial 130 on the handle 110. This action causes the pull wire 120 to move in the direction of the handle, relative to the anchor wire 125. As the anchor wire 125 is fixed, the movement of the pull wire 120 causes the deflectable tip section 115 to deflect as shown, for example, by arrow C. One skilled in the art will readily appreciate the fact that an injection needle 133, having a luer 160 at a proximal end, may run the length of the catheter 100, parallel or essentially parallel to the pull wire 120, through a second lumen (not shown), where the needle 130 is typically made of metal, polymer, or a combination of both. Again, the drawbacks associated with catheters, such as catheter 100, when employed in an MRI environment include image distortion, burns due to RF heat deposition, the inability to accurately track the position and/or location of the catheter 100 during MRI scanning.

FIG. 2 is a schematic diagram of an alternative deflectable tip section 200 associated with a conventional deflectable catheter. As shown, the deflectable tip section 200 comprises a slotted, metallic hypotube 205. Examples of catheters comprising a slotted deflectable tip section can be found in U.S. Pat. Nos. 4,898,577 and 5,030,204. In FIG. 2, a pull wire 210 is connected to the distal end of the slotted tube at point D, as shown. Moving the pull wire 210 in a proximal direction causes the deflectable tip section 200 to deflect as indicated by arrow E. Again, it will be understood by one of ordinary skill in the art that the corresponding catheter may be used as a delivery device to advance a tool such as an injection needle

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(not shown) through lumen 215 of the catheter 200 to carry out an injection and is described, for example in U.S. Pat. No. 6,102,887.

FIG. 3 is a schematic diagram of an active MRI tracking, injection catheter 300, with a deflectable tip, in accordance with a first exemplary embodiment of the present invention. More particularly, the catheter 300 is a single or uni-direction, deflectable tip MRI active injection catheter arranged as a loopless antenna with multiple cores. The catheter 300 has a proximal portion that includes a non-deflectable section 305 and a handle 310, as well as a needle 330, having a luer 360 at a proximal end. The catheter 300 also has a distal, deflectable tip section 315. In addition, catheter 300 includes a pull wire 320 and an anchor wire 325, where the pull wire 320 is run through a polymeric tube 342, as shown, and where the anchor wire 325 is connected to the pull wire 320 at point A and is fixed at point B. In this exemplary embodiment, the anchor wire 325 is a flat wire, which limits the deflection of deflectable tip section 315 to the direction indicated by arrow C. However, it will be readily understood that the anchor wire 325 may be other than a flat wire, thereby allowing for deflection in more than the one direction indicated by arrow C. Together, the pull wire 320 and the anchor wire 325 make up a first core. It should be noted that the anchor wire 325 can be made of an elastic material and it may be oval, elliptical, flat, triangular, and the like, in its cross-section. The pull wire 320 too may take on other shapes in cross-section.

The catheter 300 includes a second core. In the exemplary embodiment illustrated in FIG. 3, the second core is a needle 330, which may be employed to deliver therapeutic agents, as set forth above. The needle 330, having a luer 360 at a proximal end, runs through a needle tube 340. In a preferred embodiment, the needle 330 and the pull wire 320 run through separate tubes 340 and 342, respectively. Alternatively, the needle 330 and the pull wire 320 may run through a single tube in the distal, deflectable tip section 315. In another alternative to the first exemplary embodiment, an instrument other than or in addition to the needle 330 may be used, such as surgical forceps, where an additional instrument would preferably run through a separate corresponding tube, parallel or essentially parallel to the needle tube 340 and the polymeric tube 342.

The overall length of the catheter 300 might range from approximately 10 cm to approximately 200 cm, where the length of the distal, deflectable tip section 315 may range in length from 0.5 cm to 30 cm, though a length between 1 cm and 6 cm is more common. The proximal, non-deflectable portion 305 might have a length of approximately 10 cm to 199 cm. These lengths are intended to be illustrative and not limiting in any way as to the present invention. As one of skill in the art will appreciate, the length of any catheter in accordance with the various embodiments of the present invention can and will vary depending on the intended use and application for which the catheter is being employed.

As shown in FIG. 3, the needle 330 and the pull wire 320 are electrically connected, for example, at electrical connection 335 in the handle 310, where the pull wire 320 and the needle 330 together serve as the cores of a loopless catheter antenna. The loopless catheter antenna is connected to an interface/decoupling circuit, also referred to as a matching-tuning circuit, such as the circuits illustrated in FIG. 5A or 5B, via a coaxial cable 345 and BNC (e.g., a micro BNC) connector 350. The matching-tuning circuit tunes the antenna to the appropriate frequency so the catheter 300 may be actively tracked within an MRI environment. The catheter antenna and the matching-tuning circuit are connected to the MRI

scanner by a coaxial cable. The matching-tuning circuits in FIGS. 5A and 5B will be described in greater detail below.

The non-deflectable portion 305 of catheter 300 is covered by a braided tube 355, which acts as an RF shield for the loopless antenna. The braiding is preferably made from MRI compatible material, such as nitinol, tungsten, MP35N, copper, or other like materials. Alternatively, the non-deflectable portion 305 may be covered by a shield made from flexible MRI compatible hypotubing, where the hypotubing may be laser cut at different locations along its length, or heat-treated to modify the mechanical properties, so as to make the tubing flexible.

As stated, the proximal end of the catheter 300 includes a handle 310. The handle 310 houses, among other features, a deflection dial 312. The deflection dial 312 is part of the deflection mechanism. Manipulation of the deflection dial 312 causes the pull wire 320 to move relative to the anchor wire 325 which, in turn, causes the distal, deflectable tip section 315 to deflect under the constraint of anchor wire 325, for example, in the direction indicated by arrow C. The matching-tuning circuits 500 and 501 illustrated in FIGS. 5A and 5B may be located in the handle of the deflectable tip catheter 300, in which case, the handle of the catheter will be directly connected to the MRI scanner via a coaxial cable.

FIG. 4A is a schematic diagram of a catheter 450 having a non-deflectable portion 405 that includes the added safety feature of multiple RF chokes 452, in accordance with an alternative to the first exemplary embodiment illustrated in FIG. 3. This alternative embodiment may be particularly useful in the event the non-deflectable portion 405 of the catheter is excessively long, and there is added concern over heat build-up along this portion of the catheter 450. As shown in FIG. 4A, the non-deflectable portion 405 has primary shielding 451 and secondary shielding 452, where the secondary shielding 452 has a length that is less than one-quarter wavelength ($\lambda/4$) and is connected to the primary shielding 451 at one end. At the other end, there may be a capacitor (not shown) located between the primary shielding 451 and the secondary shielding 452, or simply a stray capacitance resulting from the close proximity of the primary and secondary shielding, where there is a primary insulation layer 453 between the primary shielding 451 and the secondary shielding 452. In addition, the secondary shielding 452 is, as shown, discontinuous. There is also a secondary insulation layer 456, located radially outside the secondary shielding 452. In a preferred embodiment, there is dual lumen tubing 457 running the length of the catheter 450, where a first lumen 442 is for pull wire 420, and the other lumen 440 is for a surgical instrument, such as a needle 430.

It will be apparent that the needle 430 can extend beyond the distal deflectable tip 415, for example, in order to deliver or inject a therapeutic agent (e.g., cells, drugs, genetic material, other biological materials, and the like) into tissue during a clinical procedure. The mechanism for manipulating the needle 430 may include a spring mechanism (not shown) for injecting the needle 430 into tissue. The spring mechanism may be located in the distal, deflectable tip section 415 or in the handle (not shown, similar to 310). The mechanism for operating the needle 430 may also include a luer (not shown, similar to luer 360 which facilitates the attachment of a syringe (not shown) containing the therapeutic agent that is to be delivered to the tissue.

FIG. 4B is a schematic diagram illustrating an alternative distal, deflectable tip section 416 for the injection catheter 451 of FIG. 4B. As shown, the catheter 451 includes, in the distal, deflectable tip section 416, a pull wire 421 and an anchor wire 426. As was the case for the embodiment illus-

trated in FIG. 3, the anchor wire 426 is connected to the pull wire 421 at point A in the deflectable tip section 416 and fixed at a point B, where the proximal end of the deflectable tip section 416 meets the distal end of the non-deflectable portion 406. The catheter 451 also includes an MRI compatible (i.e., non-magnetic), insulated metallic wire 465 connected to the pull wire 420 or the needle 430, where the metallic wire 465 is coiled backwards upon itself, as shown. The coiled wire 465 increases the MRI signal intensity associated with the distal tip of the catheter 451. Thus, the deflectable tip 416 is more visible as compared to the rest of the catheter in the MRI image, making it easier for the attending physician to locate and track the catheter 451.

FIG. 5A is a circuit diagram of a matching-tuning circuit 500 that may be employed if the needle 330 and the pull wire 320 are electrically connected or shorted at the proximal end in the handle section, as shown, for example, by electrical connection 335 in FIG. 3. In a preferred embodiment, matching-tuning circuit 500 includes a balun 502, which prevents shield currents induced on the connecting coaxial cable (i.e., between the matching-tuning circuit 500 and the MRI scanner) from being transmitted to the catheter 300; decoupling circuitry 504, which decouples/detunes the catheter when the MRI scanner is transmitting RF energy, thus preventing excessive RF deposition along the length of the catheter 300; and matching-tuning circuitry 506, which tunes the loopless antenna associated with catheter 300 to the operating frequency of the MRI scanner (not shown), for example, 64 MHz at 1.5 Tesla.

If the needle 330 and the pull wire 320 are electrically connected, such as by electrical connection 335, there is but one RF output signal associated with the loopless antenna, as shown by the single coaxial cable 345. Thus, the matching-tuning circuit 500 has but one electrical connection through the BNC connector 550, where the BNC connector 550, in FIG. 5A, connects with the BNC connector 350 in FIG. 3. The matching-tuning circuit 500 also has a BNC connector 570, which is electrically connected to the MRI scanner, via a coaxial cable (not shown). As there is but one RF output signal, the MRI scanner cannot separately and independently track the pull wire 320 (i.e., cannot separately and independently track the catheter, which serves as the first core of the loopless antenna) and the needle 330 (i.e., the second core of the loopless antenna).

FIG. 5B is a circuit diagram of a matching-tuning circuit 501 that may be employed if the needle 330 and the pull wire 320 are not electrically connected. As shown, matching-tuning circuit 501 has a decoupling and matching-tuning circuit 508a for the pull wire 320 and a separate decoupling and matching-tuning circuit 508b for the needle 330. In addition, the matching-tuning circuit 501 includes a BNC connector 551 with multiple insulated cores or a multi-pin connector, a BNC connector 571 and a BNC connector 572. BNC connector 551 contains three separate electrical conductors: one for the needle 330, one for the pull wire 320, and one that serves as a ground connection. BNC connector 571 is electrically connected to the MRI scanner via a coaxial cable (not shown), and the electrical conductor associated with the BNC connector 571 carries the output signal associated with the pull wire 320. Similarly, BNC connector 572 is electrically connected to the MRI scanner via a coaxial cable (not shown), and the electrical conductor associated with the BNC connector 572 carries the output signal associated with the needle 330. As there are two separate output signals, one for the needle 330 and one for the pull wire 320, the MRI scanner can separately and independently track the position and location of the needle 330 and the pull wire 320. As the pull wire 320 always

remains inside the catheter **300**, it will be understood that tracking the position and location of the pull wire **320** equates to tracking the position and location of the catheter **300**.

FIG. **6** is a schematic diagram of an injection catheter **600** in accordance with a second exemplary embodiment of the present invention. As shown in FIG. **6**, the distal, deflectable tip section **615** is pre-shaped into a relatively small radius, so the catheter **600** can more easily traverse through, for example, the aortic valve without causing damage. The catheter **600** is typically advanced into the left ventricle through the femoral artery and across the aortic arch through the aortic valve. Once in the left ventricle, the attending physician can manipulate the deflection dial **612** to deflect the tip of the catheter **600**. To facilitate the retraction of the catheter **600** from the left ventricle, the attending physician may straighten the distal, deflectable tip section **615**, as indicated by arrow **A**, by manipulating the deflection dial **612** appropriately.

FIG. **7** is a schematic diagram of an injection catheter **700** in accordance with a third exemplary embodiment of the present invention. In this embodiment, the catheter **700** includes an electrode **775** built into the distal end of the deflectable tip section **715**. This electrode **775** may be used to measure the electrical potential of adjacent tissue (e.g., endocardial tissue). Although the catheter **700**, illustrated in FIG. **7**, has but one electrode **775**, it will be apparent to those skilled in the art that it would be feasible to employ more than a single electrode.

FIG. **8** is a circuit diagram of an exemplary matching-tuning circuit **800** that may be used in conjunction with injection catheter **700** illustrated in FIG. **7**. As shown, matching-tuning circuit **800**, like matching-tuning circuit **501** in FIG. **5B**, has separate RF input leads for the pull wire **720** and the needle **730**. A multi-pin connector **750** may connect to a corresponding multi-pin connector **850** of the matching tuning circuit **800**. In addition, there are separate decoupling and matching-tuning circuits **802a** and **802b** for the pull wire **720** and the needle **730**, respectively. Accordingly, the MRI scanner will be able to separately track the position and location of the catheter **700** (i.e., by tracking the position and location of the pull wire **720**) and the needle **730**. The matching-tuning circuit **800** also includes RF blocking circuitry **880**. The RF blocking circuitry **880** filters out any RF components associated with the MRI system so that those components are not coupled to the electrical potential output signal lines. Thus, the Electrical Potential signal output will more accurately reflect the electrical potential of the tissue adjacent to the distal end of the deflectable tip section **715** of catheter **700**.

In the embodiments described above, the needle, as stated previously, is preferably made of MRI compatible metal, e.g., nitinol, MP35N, titanium, tantalum, gold, platinum, various non-ferromagnetic alloys, and the like. In addition, the needle may be selectively heat-treated; for example, the distal end of the needle may be heat treated, such as the last 10 cm of the needle. By heat-treating the distal end of the needle, the distal end of the needle can be adjusted for stiffness and made more flexible than the proximal portion of the needle. This makes it easier for the attending physician to advance the needle into adjacent tissue (e.g., myocardial tissue) particularly when the distal tip of the catheter is deflected. The needle may also be coated with a hydrophilic or hydrophobic coating on the inside and/or outside to enhance injection rates and reduce the shear stress experienced by cells being injected through the needle. Still further, the outer surface of the needle may be electroplated using a conducting metal, such as gold, silver, copper or the like, to enhance the RF and/or the electrical potential signal associated with the needle.

In the embodiments described above, the injection catheters employ but one needle. However, it will be evident that more than one needle may be employed, where each would serve as a separate core for the loopless antenna. The attending physician would, of course, have the ability to advance each needle individually, where each needle may contain a different therapeutic agent.

In each of the embodiments described above, the needle projects through the distal end of the deflectable tip section of the injection catheter. However, FIGS. **9A** and **9B** are schematic diagrams of an injection catheter **900** and an injection catheter **901**, respectively, in accordance with a fourth exemplary embodiment of the present invention, wherein the injection needle **930**, **931** project through a side or lateral opening **905**, **906** in the deflectable tip section **915**, **916** of the catheters **900**, **901**, respectively, rather than an opening in the distal end of the deflectable tip section of the catheter. But for the side or lateral needle openings **905**, **906** injection catheters **900**, **901** have the same, or substantially the same, configuration as injection catheter **300** and injection catheter **451**, as illustrated in FIG. **3** and FIG. **4B**, respectively. Alternatively, the injection catheter **900**, **901** may contain one or more needles and have multiple needle outlets through which the attending physician may advance a needle, including an opening in the distal end of the deflectable tip section **915**, **916**, as well as one or more lateral openings. Similarly, needles may be concentrically placed one inside the other and advanced by the attending physician in a telescopic fashion.

Side or lateral needle openings may be quite beneficial during certain procedures. For example, a catheter as illustrated in FIG. **9A** or **9B** may be advanced into a coronary artery. The needle may then be advanced more easily through a side or lateral opening, in the deflectable tip section, through the arterial wall and into the adjacent myocardium to enable delivery of a therapeutic into the tissue. Such a catheter would also be useful in a vascular bypass procedure.

There are many additional features associated with the catheter needle that may be incorporated into the various embodiments of the present invention. For example, the catheter may have a mechanism, preferably located on or near the handle of the catheter, for locking the needle in place, releasing the needle from a locked position, and controlling the extent of needle insertion into adjacent tissue. For example, it may be useful to lock the needle in a retracted position to prevent the accidental injection of a therapeutic agent.

FIG. **10A** is a schematic diagram of an injection catheter **1000**, in accordance with a fifth exemplary embodiment of the present invention. In this embodiment, the needle **1030** and the pull wire **1020** serve as parallel wires of an elongated loop antenna, rather than a loopless antenna. The matching-tuning circuit **1040** for decoupling and tuning the loop antenna is shown as being located in the handle **1010** of the injection catheter **1000**. However, the matching-tuning circuit could be externally located, like the previous embodiments described above.

FIG. **10B** is a schematic diagram that more clearly depicts a matching-tuning circuit **1040** that might be used in conjunction with the injection catheter **1000**. The circuit **1040** includes an electrical connector or lead **350** for the pull wire **1020** and the needle **1030**, a series capacitor **1021**, a series capacitor **1031**, a parallel capacitor **1032**, and a PIN diode **1033**. There may also be a series capacitor **1034** at the distal end of the inductor loop, or there may be stray capacitance induced by the close proximity of the two conductors and the dielectric therebetween. The parallel capacitor **1032** and the PIN diode **1033** serve as the decoupling circuitry. It will be

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understood, however, that other matching-tuning circuit configurations may be employed with the catheter **1000**.

The exemplary embodiments described herein below, involve deflectable guide catheters. In general, the guide catheters covered by these embodiments comprise a proximal, non-deflectable shaft and a distal, deflectable tip section. Referring now to FIG. **11**, the distal, deflectable tip section **1115** of a guide catheter **1100** preferably includes outer tubing **1118** and, within the outer tubing **1118**, thin walled hypotubing **1116**, made from a superelastic MRI compatible metal/alloy, such as nitinol, MP35N, and the like. The hypotubing **1116** is slotted (i.e., it has cut-outs) on at least one side, similar to that which is illustrated in FIG. **2**. The diameter of the lumen associated with a guide catheter **1100** is relatively large to accommodate the one or more medical instruments passing therethrough. The slotted hypotubing **1116** provides greater deflectability where the diameter of the distal, deflectable tip section **1115** is, as stated, relatively large.

In accordance with the guide catheters in the exemplary embodiments described below, the proximal, non-deflectable shaft portion is preferably covered by braided or non-braided tubing. If braided tubing is used, the braiding material will be a MRI compatible metal, for example, nitinol, tungsten, titanium, tantalum, MP35N, or a non-metal, such as Kevlar. Moreover, these guide catheters may have an inner tubing **1108** running the length of the catheter, where the lumen of this inner tubing would accommodate the aforementioned medical instruments. The inner tubing **1108** will be made from a suitable, MRI compatible material that also facilitates the movement of the one or more medical instruments (e.g., Teflon).

FIG. **11** is a schematic diagram of a uni-directional, deflectable tip guide catheter **1100**, in accordance with a sixth exemplary embodiment of the present invention. As set forth above, the deflectable tip guide catheter **1100** includes a proximal, non-deflectable shaft **1105**, a handle **1110**, and a distal, deflectable tip section **1115**. The non-deflectable shaft **1105** is covered, in this embodiment, by braided tubing **1106**, where the braiding is made from an MRI compatible material. The distal, deflectable tip section **1115** contains a slotted hypotube **1116**. The distal, deflectable tip section **1115** is electrically isolated from the braid **1106** by an insulating strip **1107**. In addition, the guide catheter **1100** includes a pull wire **1120**. In the non-deflectable shaft **1105**, the pull wire **1120** runs along the inside of the braided tubing **1106**, within a pull wire tube or lumen **1130**, thus creating an eccentric coaxial cable. In the distal, deflectable tip section **1115**, the pull wire **1120** runs along the inner wall of the slotted hypotube **1116**, and is attached thereto at point A', as shown. In this sixth exemplary embodiment, the braided tubing **1106** and the pull wire **1120** together form a loopless antenna. A matching-tuning circuit, such as the one shown in FIG. **5A**, may be used to decouple and tune the loopless antenna and to provide a single RF output signal for the MRI scanner, so the catheter **1100** can be actively tracked and/or visualized.

Further regarding the guide catheter **1100**, the braided tubing **1106** and the pull wire **1120** may, alternatively, be configured so as to form an elongated loop antenna, rather than a loopless antenna. In accordance with this alternative embodiment, the braid of the braided tubing **1106** is electrically connected to the proximal end of the slotted hypotube **1116**, whereas the insulated pull wire **1120** is connected to the distal end of the slotted hypotube **1116**. Both the pull wire **1120** and the braiding of the braided tubing **1106** are connected to the core and the shielding of a coaxial cable (not shown) at the proximal end of the catheter, for example, in the handle of the catheter, wherein an interface circuit, such as the matching-

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tuning circuit shown in FIG. **10B**, is employed to decouple and tune the loop antenna, and to generate and forward an RF output signal to the MRI scanner so that the catheter **1100** can be actively tracked and/or visualized.

FIG. **12** is a schematic diagram of a bi-directional, deflectable tip guide catheter **1200**, in accordance with a seventh exemplary embodiment of the present invention. The guide catheter **1200** is substantially similar to the guide catheter **1100**, illustrated in FIG. **11**, except that guide catheter **1200** has two pull wires **1220** and **1221** that pass within pull wire lumens **1231** and **1232**, rather than one pull wire, where the pull wires **1220** and **1221** are attached to the inner wall of the slotted hypotube **1216** at points A and B, respectively, to facilitate bi-directional deflection. In addition, the two pull wires **1220** and **1221** are electrically configured to form a loop antenna. Although not shown in FIG. **12**, an interface circuit, such as the matching-tuning circuit **1040** in the handle of catheter **1000**, illustrated in FIG. **10**, may be employed to decouple and tune the loop antenna, and to provide an RF output signal for the MRI scanner so the catheter **1200** can be actively tracked and/or visualized. It will be understood, however, that the two pull wires **1220** and **1221** could be configured, in the alternative, to form a loopless antenna.

The guide catheters **1100** and **1200**, described above, can, of course, be modified such that they may be employed as injection catheters. This may be achieved, for example, by incorporating an injection needle into the guide catheter assembly, where the injection needle can be actively tracked and/or visualized by providing a corresponding, separate RF path between the needle and the MRI scanner via an interface circuit. Alternatively, the needle may also be passively tracked.

FIG. **13** is a diagram of an injection needle **1300** that can be passively tracked in an MRI environment. As shown, needle **1300** has a proximal, polymeric tube section **1301**, a distal section **1302** (comprised, for example, of metal), and a luer **1303**. The distal section **1302** is made of an MRI compatible metal, and it includes a beveled tip **1304**. The luer **1303** is used to attach a syringe that may contain a therapeutic agent. The length of the needle **1300** will approximate $\frac{1}{4}$ wavelength (λ), for example, 10 cm for a 1.5 Tesla system). In addition, the needle **1300** may be insulated or un-insulated. Preferably, there would be some calibrated indicator on the handle, for example, that reflects the extent to which the needle **1300** is deployed in the patient tissue. The primary advantage realized by the use of needle **1300** is that the proximal polymeric section **1301** does not generate any significant heat, which might otherwise pose a safety hazard for the patient.

FIG. **14** is a diagram of an injection needle **1400** that is capable of being actively tracked, separately and independently from the guide catheter. As shown, the needle **1400** has a proximal section, where the proximal section is covered by an inner shielding layer **1401**, and where the inner shielding **1401** is covered by an outer insulating layer **1402**. The needle **1400** also has a distal tip portion **1406** with a beveled edge **1403**. The distal tip portion **1406** is made from an MRI compatible metal, and it includes a polymeric insulating sheath (not shown). Together, the shielding layer **1401**, the outer insulating layer **1402**, and the polymeric insulating sheath (not shown) prevent the needle **1400** from generating a significant amount of heat, which might otherwise pose a safety hazard for the patient. In addition, the needle **1400** has a built-in loop antenna **1408**, which is connected to an interface circuit via one or more electrical leads **1404** through a BNC connector **1405**. It is this built-in antenna that allows the needle **1400** to be actively tracked and/or visualized separate

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and independent of guide catheter in which the needle **1400** is contained. It should be noted that the needle **1400** may be coated with an insulating polymeric dielectric layer, e.g., polyimide, polyurethane lacquer, and the like, on the inside.

FIG. **15** is a diagram of an injection needle **1500** that is capable of being actively tracked, separately and independently from the guide catheter. It differs from the injection needle illustrated in FIG. **14** in that injection needle **1500** is configured as a loopless antenna **1502**, rather than a loop antenna **1408**.

It is of particular importance to be able to track and/or visualize the distal tip of the injection needle. Thus, the needles described above may include a thin metallic wire **1501** coiled around the distal tip. This will increase the intensity of the RF signal associated with the distal tip of the needle, thereby making the distal tip of the needle more visible under MRI.

The ability to identify and select the geometric plane in which the catheter lies during an MRI procedure is quite important, as it allows the attending physician to then more rapidly and precisely identify and prescribe image slices of interest that are associated with or intersect this plane. U.S. Pat. No. 6,687,530, which is incorporated herein by reference, proposes a methodology for tracking the location of individual coils located along the length of a catheter, in three-dimensional space, using MRI, and acquiring an image in or associated with the geometric plane defined by the location of the coils. This technique then permits an attending physician to identify the geometric plane and, thereafter, select and visualize imaging slices relative to that geometric plane. A catheter in accordance with exemplary embodiments of the present invention will now be described for use with an MRI system that employs the capability provided by this or similar methodologies.

FIG. **16** is a diagram of a deflectable tip catheter **1600**, that includes three individual inductor loop coils, in accordance with an eighth exemplary embodiment of the present invention, wherein the basic structure and design of the deflectable tip catheter **1600** may take the form of any one of the catheters described in the previous exemplary embodiments, with the addition of a guidewire lumen **1605**. The deflectable tip catheter **1600** has, in addition to those catheters described above, a guidewire **1601**, which is made from a relatively stiff, MRI compatible material. Attached to or connected to the distal tip of the guidewire **1601** is an inductor loop coil **1602**. The attending physician will advance the guidewire **1601** into the left ventricle or other anatomical structure of interest, as shown in FIG. **16**. The attending physician then advances the deflectable tip catheter **1600** over the guidewire **1601**, where the guidewire **1601** runs through a guidewire lumen **1605**. There are two additional inductor loop coils **1603** and **1604** located at the deflectable tip section of the catheter **1600**. More specifically, coil **1603** is located at the fulcrum, or point of deflection, and coil **1604** is located at the distal tip of the catheter **1600**.

Each of the three inductor loop coils **1602**, **1603** and **1604** are electrically connected to a corresponding coaxial cable (not shown) so that the MRI system using, for example, the aforementioned software, can identify the location of the three inductor loop coils **1602**, **1603**, and **1604** in three dimensional space within the anatomical structure of interest, track the geometric plane through the anatomical structure of interest defined by the location of the three coils **1602**, **1603**, and **1604**, and generate an image slice relative to the geometric plane as specified by the attending physician. Once the attending physician has positioned the distal tip of deflectable catheter **1600** so that it is pointing towards the region of

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interest, the physician may advance the injection needle into, for example, the myocardial tissue to deliver a therapeutic agent.

FIG. **17** is a schematic diagram of a deflectable tip catheter **1700**, including three, non-magnetic inductor loop coils, in accordance with an alternative to the eighth exemplary embodiment described above. As shown, the three inductor loop coils **1702**, **1703**, and **1704** are built into the distal, deflectable tip section **1715**. Each of the inductor loop coils **1702**, **1703**, and **1704** are electrically connected to a corresponding center conductor **1706a**, **1706b**, and **1706c**, respectively, of a coaxial cable (not shown), so that the MRI scanner, through, for example, software as described above, can individually identify the position and/or location of each coil in three dimensional space and, there from, acquire an image associated with the geometric plane defined by the position of the three coils. This information will assist the attending physician in guiding or steering the catheter **1700** into a desired location and/or position.

These individual loop coils could be coiled circumferentially around the diameter of the catheter, on the outside or inside of the catheter tubing. In addition, the coils may be placed inside the distal tip, or other locations, and oriented in the x, y and z planes, i.e., orthogonal to one another. The aforementioned tracking methodology could be implemented to track the position and location of the coils.

FIG. **18** is a diagram of an MRI system **1800** in accordance with exemplary embodiments of the present invention. The MRI system **1800** of FIG. **18** includes a magnetic field generator **1801**, for establishing a magnetic field on the patient, and an RF source **1802** for emitting RF signals to at least a portion of the patient disposed within the magnetic field. Of particular importance, the MRI system **1800** employs a deflectable tip, MRI compatible catheter **1803**, in accordance with the present invention, such as any of the deflectable tip catheters described herein above. In addition, the MRI system **1800** includes an interface circuit **1804**. The specific antenna interface circuit that is employed will, of course, depend on the deflectable tip, MRI compatible catheter **1803** that is employed, as set forth above. The RF signals received by the antenna in the deflectable tip MRI compatible catheter **1803** and the antenna interface circuit **1804** are then amplified by the pre-amplifier **1805**, and converted from analog to digital by the A/D converter **1806**. The digital signals are then provided to the processor **1807**, which employs hardware and/or software, as discussed above) to generate MRI information relating to the patient, as well as the position and location of the deflectable tip, MRI compatible catheter **1803** and, in accordance with certain embodiments described above, the position and location of any surgical instrument or instruments contained in the catheter **1803** (e.g., the position and location of an injection needle). The MRI information is then displayed in the form of a MR image on display **1808**, so that the attending physician can visualize and more effectively steer the catheter **1803** to or within the anatomical structure of interest.

It will be apparent to those skilled in the art that various modifications and variations of the exemplary embodiments described above can be made without departing from the spirit or scope of the present invention. Thus, it is intended that the present invention cover these modifications and variations provided they come within the scope of the appended claims and the equivalents thereof.

What is claimed is:

1. A method of injecting a therapeutic agent into target intramycocardial tissue during a magnetic resonance imaging

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(MRI)-guided interventional procedure using an intramyocardial catheter having an injection needle, comprising:

intraluminally inserting a distal end of the intramyocardial catheter into a heart of a patient during the MRI-guided procedure, wherein the intramyocardial catheter comprises a deflectable tip section having a predetermined length and a pull wire within the deflectable tip section, and wherein the pull wire is configured as a catheter antenna;

obtaining a first RF output signal from the catheter antenna in the heart of the patient;

tuning the first RF output signal from the catheter antenna using a first matching-tuning circuit to track the catheter antenna during the MRI-guided interventional procedure;

tracking the catheter antenna in the heart of the patient during the MRI-guided interventional procedure;

deflecting the deflectable tip section of the catheter in the heart to steer a distal end of the deflectable tip section toward a target intramyocardial location using the pull wire based on MRI images generated from the tracked catheter antenna;

advancing an injection needle from the deflectable tip section of the catheter toward the target intramyocardial location, wherein the injection needle comprises an injection needle antenna;

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obtaining a second RF output signal from the injection needle antenna in the heart of the patient;

tuning the second RF output signal from the injection needle antenna using a second matching-tuning circuit, different from the first matching-tuning circuit, to track the injection needle antenna during the MRI-guided interventional procedure;

tracking the injection needle antenna in the heart of the patient during the MRI-guided interventional procedure;

injecting a therapeutic agent from the injection needle into tissue at the target intramyocardial location,

wherein positions and locations of the catheter antenna and the injection needle antenna are separately and independently tracked to visualize the deflectable tip section of the catheter in the heart of the patient separately and independently of the injection needle on MRI images generated during the MRI-guided interventional procedure.

2. The method of claim 1, further comprising detecting electrical potential of adjacent tissue using an electrode on the deflectable tip of the catheter.

3. The method of claim 1, wherein tracking comprises active tracking.

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