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### INTRAVASCULAR LITHOTRIPSY CATHETER

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#### Abstract

An intravascular lithotripsy catheter can include a sheath, first and second insulated wires, and a carrier. The first and second insulated wires can include exposed portions of an electrically conductive member and can be wound around the sheath. Exposed portions of the first and second insulated wires that form an emitter can be circumferentially offset from each other and can be longitudinally offset from each other. The carrier can encase the first and second insulated wires and the sheath and can comprise a plurality of carrier openings aligned with the exposed portions of the first and second insulated wires. The catheter can electrically connect to an energy generator that is operable to cause a spark to travel longitudinally along the catheter and circumferentially around the catheter between the exposed portions.

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## Background/Summary

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application are hereby incorporated by reference under 37 CFR 1.57 for all purposes and for all that they contain.

### TECHNICAL FIELD

[0002] The present disclosure relates generally to intravascular lithotripsy catheters. More specifically, the present disclosure relates to multiple intravascular lithotripsy catheter implementations and associated systems that can selectively control the firing of one or more emitters.

### BACKGROUND

[0003] An intravascular lithotripsy (IVL) catheter may be used to treat calcified lesions within the cardiovascular system. IVL catheters can be used to enhance the effectiveness of percutaneous cardiovascular interventions in cases where heavily calcified lesions present challenges for traditional treatment methods. An IVL catheter can include a balloon, which when inflated with a saline solution, can deliver mechanical pressure waves to break up and/or modify calcified lesions, making it easier to dilate an artery during balloon angioplasty and/or stent placement procedures.

### SUMMARY

[0004] The systems, methods, and devices described herein each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of this disclosure, several non-limiting features will now be discussed briefly.

[0005] Described herein are an improved IVL catheter implementations and systems that can safely deliver one or more sonic pressure waves (hereinafter “sonic waves”) within blood vessels of a cardiovascular system.

[0006] Disclosed herein is an intravascular lithotripsy system configured to modify calcified plaque within a blood vessel of a subject. The system can comprise: a sheath comprising a lumen configured to receive a guidewire; at least three insulated wires; and an energy generator. Each of the at least three insulated wires can comprise at least two exposed portions spaced from one another along a length of the insulated wire, wherein the at least three insulated wires are helically wound around an outer surface of the sheath and independently electrically connected with the energy generator, the exposed portions of the at least three insulated wires defining a plurality of emitters spaced from one another along a length of the sheath and independently operable by the energy generator. The energy generator can induce a spark via each of the plurality of emitters.

[0007] In some implementations, the plurality of emitters comprises: a first emitter defined by a first exposed portion of a first one of the at least three insulated wires and a first exposed portion of a second one of the at least three insulated wires; a second emitter defined by a second exposed portion of the first one of the at least three insulated wires and a first exposed portion of a third one of the at least three insulated wires; and a third emitter defined by a second exposed portion of the second one of the at least three insulated wires and a second exposed portion of the third one of the at least three insulated wires.

[0008] In some implementations, each of the at least three insulated wires is configured to form at

least one of the plurality of emitters with each of the other at least three insulated wires.

[0009] In some implementations, the plurality of emitters are formed from the at least three insulated wires without any other insulated wires.

[0010] In some implementations, the at least three insulated wires comprises at least four insulated wires, wherein the plurality of emitters comprises more emitters than the at least four insulated wires.

[0011] In some implementations, the at least three insulated wires does not include a dedicated return wire.

[0012] In some implementations, the energy generator is configured to drive voltage on the at least three insulated wires independently to cause each of the at least three insulated wires to transition between operating at least as a live wire conducting current from the energy generator or as a return wire conducting current to the energy generator.

[0013] In some implementations, the system comprises a balloon around at least a portion of the sheath and configured to be expanded with a conductive fluid configured to conduct a sonic wave originating from a spark.

[0014] In some implementations, the system comprises a carrier encasing the at least three insulated wires and the sheath, the carrier comprising carrier openings aligned with the exposed portions of the at least three insulated wires.

[0015] Disclosed herein is an intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject. The intravascular lithotripsy catheter can comprise a sheath, a first insulated wire, a second insulated wire, and a carrier. The sheath can comprise a lumen configured to receive a guidewire, wherein a longitudinal axis of the intravascular lithotripsy catheter extends through the lumen. The first insulated wire can be wound around and can contact an outer surface of the sheath. The first insulated wire can comprise an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member. The second insulated wire can be wound around and can contact the outer surface of the sheath. The second insulated wire can be arranged adjacent the first insulated wire and can comprise an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire. The exposed portion of the second insulated wire can be circumferentially offset from the exposed portion of the first insulated wire by an angle originating at the longitudinal axis. The exposed portion of the second insulated wire can be longitudinally offset from the exposed portion of the first insulated wire by a longitudinal distance extending along the intravascular lithotripsy catheter parallel to the longitudinal axis. The carrier can encase the first and second insulated wires and the sheath. The carrier can comprise: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire. The intravascular lithotripsy catheter can be configured to be electrically connect to an energy generator that is operable to cause a spark to travel longitudinally along the intravascular lithotripsy catheter and circumferentially around the intravascular lithotripsy catheter between the exposed portions of the first and second insulated wires.

[0016] In some implementations, the carrier comprises an inner surface configured to contact the first and second insulated wires and an outer surface opposite the inner surface, wherein the intravascular lithotripsy catheter is configured such that the spark travels from the exposed portion of the first insulated wire, through the first carrier opening, above the outer surface of the carrier, through the second carrier opening, and to the exposed portion of the second insulated wire.

[0017] Disclosed herein is an intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject. The intravascular lithotripsy catheter can comprise a sheath

configured to receive a guidewire through a lumen of the sheath, a longitudinal axis extending through the lumen of the sheath, a first insulated wire, a second insulated wire, and a carrier. The first insulated wire can comprise an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member. The second insulated wire can be arranged adjacent the first insulated wire and can comprise an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire. The first and second insulated wires can be wrapped around the sheath. The exposed portion of the second insulated wire can be arranged at a different longitudinal location than the exposed portion of the first insulated wire relative to said longitudinal axis relative to said longitudinal axis. The exposed portion of the second insulated wire can be arranged at a different angular location than the exposed portion of the first insulated wire relative to a plane defined normal to said longitudinal axis.

[0018] Disclosed herein is an intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject. The intravascular lithotripsy catheter can comprise a sheath with a lumen configured to receive a guidewire, a longitudinal axis extending through the lumen of the sheath, a first insulated wire, a second insulated wire, and a carrier. The first insulated wire can comprise an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member. The second insulated wire can be arranged adjacent the first insulated wire and can comprise an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire. The first and second insulated wires can be wrapped around the sheath. A transverse cross-section through the intravascular lithotripsy catheter that is perpendicular to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire. A longitudinal cross-section through the intravascular lithotripsy catheter that is parallel to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire.

[0019] Various combinations of the above and below recited features, embodiments, implementations, and aspects are also disclosed and contemplated by the present disclosure.

[0020] Additional implementations of the disclosure are described below in reference to the appended claims and/or clauses, which may serve as an additional summary of the disclosure.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Various implementations will be described hereinafter with reference to the accompanying drawings. These implementations are illustrated and described by example only, and are not intended to limit the scope of the disclosure. In the drawings, similar elements may have similar reference numerals.

[0022] FIG. 1 illustrates an example implementation of a system that can be used to modify calcified lesions in blood vessels of a patient.

[0023] FIG. 2A is an example block diagrams of a cardiac synchronization system.

[0024] FIG. 2B is an example block diagram of a cardiac synchronization system with individually wired electrodes.

[0025] FIG. 2C-2F illustrate example graphs of asymmetric energy that may be emitted by an IVL catheter.

[0026] FIG. 3A illustrates an example side-view of a helically wound electrode pair as part of an IVL catheter.

[0027] FIG. 3B-3E illustrate example geometric shapes for a recessed channel as part of an IVL catheter.

[0028] FIG. 4A illustrates an example cross-sectional view of an embedded electrode pair as part of an IVL catheter.

[0029] FIGS. 4B-4E illustrate example geometric shapes for a notch as part of an IVL catheter.

[0030] FIG. 5A illustrates an example perspective view of an IVL catheter with conductive wires helically wound around a carrier.

[0031] FIG. 5B illustrates an example perspective view of a conductive wire helically wound around a carrier.

[0032] FIG. 5C illustrates an example perspective view of a helically wound conductive wire.

[0033] FIG. 5D illustrates an example implementation of ring electrodes as part of a helically wound electrode pair.

[0034] FIG. 5E illustrates a cross-sectional view of a conductive wire and a ring electrode.

[0035] FIG. 5F illustrates an example implementation of an IVL catheter with variable-pitch helically wound insulated wires.

[0036] FIG. 6 illustrates an example implementation of an IVL catheter having one or more valves.

[0037] FIG. 7 illustrates an example implementation of a an IVL catheter having one or more valves.

[0038] FIG. 8A illustrates an example implementation of a CTO IVL catheter.

[0039] FIG. 8B illustrates an example implementation of a distal end of a CTO IVL catheter.

[0040] FIG. 9A illustrates an example perspective view of a dual-balloon IVL catheter.

[0041] FIG. 9B illustrates an example cross-sectional view of a dual balloon IVL catheter.

[0042] FIG. 9C illustrates an example cross-sectional view of a dual balloon IVL catheter in a blood vessel.

[0043] FIG. 10 illustrates an example implementation of a balloon-less IVL catheter.

[0044] FIG. 11 illustrates an example implementation of a balloon-less IVL catheter.

[0045] FIG. 12A illustrates an example perspective view of an eccentric IVL catheter.

[0046] FIG. 12B illustrates an example implementation of an eccentric IVL catheter.

[0047] FIG. 12C illustrates an example cross-sectional view of an eccentric IVL catheter balloon.

[0048] FIG. 13A illustrates an example implementation of a double occluding balloon IVL catheter.

[0049] FIG. 13B illustrates an example implementation of a double occluding balloon IVL catheter in a blood vessel.

[0050] FIGS. 14A-14B depict an example implementation of a system for indicating the effectiveness of sonic pressure waves on a calcified lesion.

[0051] FIG. 15 depicts an example method for synchronizing emitted energy from an IVL catheter according to an example implementation.

[0052] FIGS. 16A-16C are side views of various portions of an example IVL catheter.

[0053] FIG. 17A is a schematic diagram illustrating insulated wires of an IVL catheter with electrodes forming emitters.

[0054] FIG. 17B is a schematic diagram illustrating insulated wires of an IVL catheter with electrodes forming emitters.

[0055] FIG. 17C is a cross-section view of an example IVL catheter with insulated wires having electrodes forming emitters.

[0056] FIG. 18A is a side view of a portion of an example IVL catheter.

[0057] FIG. 18B is a schematic diagram illustrating insulated wires of an IVL catheter with electrodes forming emitters.

[0058] FIG. 19 is a flowchart of an example process of making an IVL catheter or portions thereof.

DETAILED DESCRIPTION

[0059] The present disclosure will now be described with reference to the accompanying figures, wherein like numerals may refer to like elements throughout. The following description is merely illustrative in nature and is in no way intended to limit the disclosure, its application, or uses. Furthermore, the devices, systems, and/or methods disclosed herein can include several novel features, no single one of which is solely responsible for its desirable attributes or which is essential to practicing the devices, systems, and/or methods disclosed herein. Additionally, the structures, systems, and/or devices described herein may be embodied as integrated components or as separate components.

[0060] Some aspects and/or implementations have been described in connection with the accompanying drawings. The scale of the figures is not limiting, since dimensions and proportions other than what are shown are contemplated and are within the scope of the disclosed invention. Distances, angles, etc. are merely illustrative and do not necessarily bear an exact relationship to actual dimensions and layout of the devices illustrated. Components can be added, removed, and/or rearranged. Further, the disclosure herein of any particular feature, aspect, method, property, characteristic, quality, attribute, element, or the like in connection with various embodiments can be used in all other embodiments set forth herein. Additionally, any methods described herein may be practiced using any device suitable for performing the recited steps. Various steps within a method may be executed in different order without altering the principles of the present disclosure.

[0061] Several medical procedures have been developed to modify and/or treat calcified lesions in blood vessels. In the context of cardiovascular interventions, these procedures aim to make the calcified plaque more amenable to subsequent treatments, such as balloon angioplasty and stent placement. Some common methods for modifying a calcified lesion include rotational atherectomy, balloons (e.g., cutting, scoring, high-pressure and/or the like), excimer laser atherectomy, and/or intravascular lithotripsy (IVL), for example.

[0062] Each method has certain advantages and/or pitfalls. For example, rotational atherectomy (e.g., via a rotator device) involves the use of a high-speed rotational device to abrade and remove calcified plaque. A rotator device can be equipped with a diamond-coated burr that rotates at high speeds to grind away the calcifications. A rotator process can provide one or more benefits, such as for example, by preparing a vessel wall for subsequent angioplasty.

[0063] However, the use of a rotator has several downsides, including a risk of dissection, where the high-speed rotational devices can potentially cause vessel dissection (e.g., a tear in the arterial wall) if not used carefully, especially in the presence of heavily calcified lesions. Further, rotational action of the rotator device can generate plaque debris or micro-particles. Plaque debris may be released into the bloodstream causing further complications including possible downstream occlusions. In some cases, a rotator device may not completely modify a calcified lesion as some heavily calcified lesions may be resistant to modifications. Additionally, the use of rotational blades may extend procedural time, exposing patients and physicians to prolonged safety risks associated with percutaneous procedures.

[0064] Another conventional method includes the use of several types of balloons, such as a cutting balloon, a scoring balloon, and/or a high-pressure balloon. Cutting balloons can modify calcified lesions by the use of small blades and/or microsurgical blades mounted on the balloon's surface. When a balloon is inflated, these blades create inclusions in calcified plaque, allowing for better vessel expansion during angioplasty. In some cases, a high-pressure balloon can be used. A high-pressure balloon has a rigid structure allowing for greater force during inflation to modify calcified lesions. While balloons may be effective in some context, high-pressure balloons may still carry the risk of vessel dissection or rupture if applied excessively. Scoring balloons, can pose challenges in achieving uniform scoring, potentially leaving some areas untreated. Furthermore, these balloons may generate plaque debris. Additionally, balloons may be structurally rigid, limiting a physician's ability to navigate the balloon through arteries, reducing the reachability of the balloon and versatility depending on the location of a calcified lesion.

[0065] Excimer laser atherectomy is a conventional technique using laser energy to vaporize and ablate calcified plaque. The laser energy is delivered through optical fibers within the catheter, breaking down the calcifications into smaller particles. Common issues associated with the use of a laser can include arterial perforation, where the laser's ablative action may weaken the arterial wall, increasing the risk of intended perforations. The laser may generate plaque debris and/or micro particles as described above. Further, lasers may be ineffective at ablating extremely dense calcifications. Additionally, lasers can have a limited depth of penetration when attempting to modify deep and/or extensive calcifications. Further the cost of using a laser and/or the necessary equipment associated with the use of lasers can be expensive in comparison to other methods.

[0066] An IVL catheter employs sonic waves to disrupt and modify calcified plaque by introducing the IVL catheter to, for example, a coronary artery through, a guiding catheter (guidewire). The IVL catheter can include a balloon, positioned within or adjacent to calcified plaque. A balloon can be inflated (typically with a conductive solution such as saline and/or the like), such that fluid within the balloon serves as a medium for sonic waves generated by one or more emitters within the IVL catheter. Emitters can include electrodes (e.g., wherein an electrical arc across a spark gap results in sonic waves), lasers emitting energy causing sonic waves, and/or mechanical means such as acoustic pressure causing sonic waves. Sonic waves are translated from electrode pairs, through saline, and to the outer surface of the balloon, where the energy is transferred to the walls of blood vessels. Sonic waves can generate fractures within calcified plaque, destroying the rigid structure of calcifications.

[0067] Unlike a few of the example methods for modifying calcified lesions mentioned above (e.g., rotational atherectomy, cutting balloons, scoring balloons, high-pressure balloons, excimer laser atherectomy, and/or the like), an IVL catheter can fracture associated plaque while reducing the risk of causing serious trauma to the surrounding vessel walls, as the energy source is generated within a balloon. Moreover, an IVL catheter can reduce the likelihood of particles in the bloodstream as the primary energy source is not applied directly to the vessel wall. Additionally, IVL catheters can provide a physician with more precise control over dissipated energy, thus reducing procedure time.

[0068] However, IVL catheters do suffer from performance issues that must be optimized to enhance procedural safety and efficacy. For example, emitter configurations within an IVL catheter may not optimally direct energy (e.g., sonic waves) to a specific location, resulting in poor and/or nonexistent directional control of sonic waves, dispersed energy densities, and prolonged procedures for physicians and patients alike. IVL catheters may emit energy radially, axially, longitudinally, and/or in all directions, dispersing the energy to targeted calcified lesions and/or non-targeted areas. Thus, procedural time may increase as physicians may not be able to effectively target an area having, for example, non-symmetrical calcified plaque (e.g., calcifications not uniformly distributed around the circumference of a vessel). Further, in some scenarios, when electrode pairs are not optimized to transfer energy to a specified target location, a physician may be required to generate an excessive number of sonic waves while attempting to fracture calcified plaque.

[0069] Ineffective treatment as described can increase the possibility of exceeding a IVL catheter's lifespan, increase heat generated by the IVL catheter in a blood vessel, and/or expose a patient to greater health risks associated with excessive electrical arcing (e.g., a spark when using electrodes). If, in the event that an IVL catheter's lifespan is exceeded during a procedure, the IVL catheter must be removed and replaced, thus prolonging a procedure and increasing safety and health risks to a patient. Further, the lifespan of an IVL catheter can be limited in certain circumstances when an electrode pair generates an arc in one direction. For example, when a mono-phasic energy source is used as part of an IVL catheter, electrical arcs across electrode pairs may result in burns and/or scarring at the surface of one electrode, reducing the useable life of the IVL catheter. Moreover, mono-phasic energy can induce muscular contraction leading to heart attacks.

[0070] In addition to issues associated with controlling the directionality of sonic waves, conventional IVL catheter designs may inefficiently control one or more characteristics of sonic waves. Depending on the size, shape, and location of calcified plaque, a physician may require a sonic wave having varying characteristics. Specifically, a physician may desire to alter the intensity, duration, and/or frequency of a sonic wave to optimize IVL catheter performance during a procedure. Further, conventional IVL catheters may lack the ability to alter the origin of sonic waves within the IVL catheter. For example, a physician may seek to generate sonic waves from one or more electrode pairs within the IVL catheter, to fracture a targeted grouping of calcified plaque, while seeking to prevent sonic waves generated from other electrode pairs. Conventional IVL catheter designs do not facilitate the selectivity and control that physicians desire because electrode pairs and/or each electrode within an IVL catheter may not be individually wired to an energy generation source (e.g., individually electrically connected and/or the like), nor are the electrode pairs and/or electrodes multiplexed at an associated energy source.

[0071] Conventional IVL catheter designs may be too rigid and/or too large (e.g., increased cross-sectional area) to reach and treat all the desired calcified lesions. In some scenarios, an overly rigid IVL catheter may not be able to reach highly tortuous and/or heavily calcified vessels, small vessels where navigational challenges exist, areas associated with bifurcated lesions where a single vessel divides into two branches, proximal lesions located near the origin of proximal part of the coronary arteries, and/or areas where the IVL catheter must cross occluded segments. For example, conventional manufacturing techniques for an IVL catheter can result in an excessively rigid catheter when polyethylene terephthalate (PET) tubing is used with one or more sections of the carrier and/or sheath. In some examples, manufacturers include PET tubing between electrode pairs, to protect the associated wiring from damage, however, the use of PET tubing increases the rigidity of the IVL catheter, limiting the usefulness and range of locations accessible by the IVL catheter. Further, conventional methods of manufacturing an IVL catheter may place electrode pairs outside and/or adjacent to the sheath, increasing the cross-sectional area of an IVL catheter, thus preventing the catheter from fitting into, for example, occluded segments.

[0072] Conventional IVL catheters may limit the number of pulses a physician may emit (e.g., a cycle count), as electrical arcing occurring during each pulse may slowly degrade and/or erode the surface of an electrode within an electrode pair. For example, a physician may be limited to 300 pulses during a procedure with conventional IVL catheters. Pulse limitations may result in “pulse rationing,” where a physician elects to limit a number of pulses for a first calcified lesion, regardless of the effectiveness of the pulses on the first calcified lesion, in order to conserve pulses for subsequent calcified lesions. Physicians may pulse ration to reduce the number of procedures a patient may endure, reduce costs associated with having to replace an IVL catheter during a procedure, and/or as covered by a patient's medical insurance. Regardless of the reasoning, a patients may not obtain the most effective treatment due to the limited cycles associated with conventional IVL catheters.

[0073] In summary, inefficiencies associated with conventional catheters may result in ineffective treatment for a patient from low energy densities, high-energy emissions, increased procedural times, and/or broad applications of sonic waves to modify plaque, in the same way a sledgehammer relies on a user's physical strength and control to modify concrete. Whereas in contrast, one or more IVL catheters as disclosed herein can provide functionality, efficiency, longevity, and/or precision analogous to a jackhammer, by applying a targeted energy source to plaque, to quickly modify plaque while reducing risk to a patient. The issues associated with conventionally manufactured IVL catheters, and their associated systems can be overcome by one or more IVL catheter implementations and associated system designs incorporating one or more of the features as described herein. For example, an IVL catheter can be created that is flexible and/or small enough to allow physicians to navigate the IVL catheter into a broad range of desired locations within the body. An IVL catheter can maximize its useful life while efficiently targeting and



fracturing calcified lesions by individually wiring electrodes to an energy generation source, incorporating a multiplexed energy generator to selectively energize electrode pairs, and/or by providing an energy source that enables a physician to configure one or more characteristics of the emitted energy (e.g., mono-phasic and/or bi-phasic pulses, changing the intensity, duration, and frequency of emitted energy, and/or the like). Further, an IVL catheter can optimize procedural time and/or procedural efficiency by controlling the directionality of sonic waves based on one or more electrode pair configurations as described herein.

[0074] The present disclosure includes example implementations and methods using an IVL catheter and/or system, to treat calcified lesions in blood vessels. Blood vessels can include arterial or venous vasculature. Blood vessels can include coronary vessels (e.g., proximal to the heart and/or that supply blood to the heart) or peripheral blood vessels (e.g., distal to the heart such as in the arms or legs). Treating calcified lesions, deposits, plaque, build-up, etc. can include modifying said deposits. Modifying deposits etc. can refer to changing a physical structure of said deposits such as fragmenting, disintegrating, cracking, breaking, dissolving, rupturing, etc. said deposits. IVL catheters can be used in percutaneous interventions, which are procedures performed to treat blockages or narrowing in the blood vessels, such as coronary interventions or peripheral interventions. For example, a guidewire may be threaded through the vascular access site (e.g., femoral and/or radial artery) and navigated to the blood vessel treatment site with a guidewire under fluoroscopic guidance via one or more markers. An IVL catheter can be advanced over the guidewire to the site of the calcified lesion. Once in position, an IVL catheter can be activated, producing sonic waves to disrupt calcium deposits, making the deposits more manageable for subsequent interventions. Example embodiments of IVL catheters and/or one or more associated systems and/or subsystems are described below with reference to the figures.

[0075] FIG. 1 illustrates an example implementation of a system **100** that can be used to modify lesions in blood vessels of a patient. A system **100** can include an IVL catheter **101** in electrical communication with an energy generator **150**. An IVL catheter **101** can include a proximal end **33** and a distal end **34**. An IVL catheter **101** can be percutaneously inserted into a patient's artery by a physician. An IVL catheter **101** can be positioned in an artery where one or more calcified lesions exist. Once in position, a physician may generate one or more electrical arcs, originating from an energy generator **150** to modify a calcified lesion of a patient.

[0076] An IVL catheter **101** can include a balloon **111**. A balloon **111** can have a composition including a high-quality polymer such as for example, polyethylene and/or polyamide and/or any other suitable composition. Balloon **111** can be, for example, transparent and/or opaque. A balloon **111** can have a distal end **34** and a proximal end **33**. A balloon **111** can include a central portion, extending longitudinally along a carrier **112** from a proximal **33** to a distal end **34**. In some examples, balloon **111** can be radially symmetric along a first axis A.sub.1. A balloon **111** may have a seal **114** at a distal end and/or a seal **113** at a proximal end. Seal **113** and/or **114** can be, for example, an ultraviolet adhesive. Seal **113** and/or **114** can prevent a balloon **111** from moving axially, longitudinally, and/or radially along a carrier **112**, and/or prevent loss of a solution (e.g., conductive fluid) within the balloon **111** during a procedure. In some implementations, a balloon **111** may be inflated (e.g., expanded) with a solution such as saline at a proximal end **33**. Further, a balloon **111** can be deflated at a proximal end **33**. In some implementations a balloon **111** can be deflated in less than three seconds. Inflation and/or deflation times for a balloon **111** may vary depending on, for example, a number of source wires **124** and/or common wires **123** (e.g., wires including a common ground) utilized as part of an IVL catheter **101**. As mentioned above, a conductive solution can be used to translate one or more sonic waves from electrode pairs **120** to an outer wall of a balloon **111**. In some examples, a conductive solution can enhance one or more sonic waves produced by electrode pairs **120**. For examples, increasing and/or decreasing the conductivity of the conductive solution can concentrate and/or disperse one or more sonic waves produced by electrode pair **120**.

[0077] A balloon **111** may deliver medication (e.g., a drug) to a target area. A surface of a balloon **111** may be coated with a drug. When a balloon **111** coated with a drug is inflated, the balloon **111** may deliver medication to a target area (e.g., cells of a blood vessel). In some cases a balloon **111** may be coated with a medication to treat, among other things, edema. Edema is a swelling, which may be caused by an IVL catheter during a procedure. Swelling may reduce the effectiveness of treatment and/or access to certain calcified lesions at a down-stream location in a blood vessel. In some examples, when a balloon **111** is coated with a drug to treat edema, the likelihood of success during a procedure can be drastically improved.

[0078] A balloon **111** can include one or more shapes as described herein. In some examples, a balloon **111** is cylindrical as depicted in FIG. 1. However the balloon **111** can be another shape such as semi-compliant and/or non-compliant shape (e.g., the balloon **111** may conform to irregularities of a blood vessels and/or remains in a given shape when inflated) along a first axis A1. A length **130** of a balloon **111** can vary based on, for example, the number of electrode pairs **120**, electrode pair spacing **26**, a spark gap **125**, a location of one or more calcified lesions, and/or the like. In some implementations a balloon **111** can have a length **130** of about 60 mm, while in some implementations the length **130** of the balloon **111** can be approximately 58 mm. In some implementations, a balloon **111** can have an outer diameter of approximately mm, however the outer diameter can be more or less. An IVL catheter **101** can include one, two, three or more balloons **111**. In some implementations, the IVL catheter **101** may not include a balloon **111**.

[0079] An IVL catheter **101** can further include a carrier **112**. A carrier **112** can be a flexible, elongated shaft centered along a first axis A1. A carrier **112** can facilitate the advancement and positioning of an IVL catheter **101** within a blood vessel. A cross-sectional area of a carrier **112** can have, for example, a circular, square, rectangular, hexagonal, conical, and/or any other shape along a plane intersecting a first axis A1 and/or a second axis A2 (e.g., an asymmetrical shape along a first axis A1 and/or a second axis A2). A carrier **112** can include a solid composite material. In some examples a carrier **112** can be created by a first layered composite material and a second composite material. In some examples a carrier **112** can be created with multiple layers. A carrier **112** can have a hollow channel (e.g., a lumen) extending longitudinally along a first axis A1. A hollow channel of a carrier **112** can support a guidewire **118**. A guidewire **118** can assist a physician in positioning an IVL catheter **101** in a blood vessel, by allowing a carrier **112** to advance over the guidewire **118**. In some implementations, a carrier **112** can have an outer diameter of approximately 0.018" although dimensions may vary depending on intended use.

[0080] An IVL catheter **101** can include electrode pairs **120**. An IVL catheter **101** (e.g., as part of a system **100**) can generate electrical arcing between two or more electrode pairs **120**. Electrical arcing in turn generates sonic waves, transmitting energy to an outer wall of a balloon **111** to modify calcified lesions. Electrode pairs **120** can be coupled to a carrier **112** along a first axis A1. Electrodes as part of electrode pairs **120** as illustrated in FIG. 1, can be ring electrodes, however electrode pairs **120** (and/or an individual electrode of electrode pairs **120**) may be any type and/or a combination of electrode types as described and/or illustrated herein. Electrodes as part of electrode pair **120** can be one or more of, and/or a combination of gold, platinum-iridium alloy, stainless steel, a nickel-titanium alloy, and/or the like. In some examples, electrode pair **120** is not adjacent to a hollow channel of a carrier **112** (e.g., not adjacent to a lumen).

[0081] Emitter spacing **126** (e.g., the spacing between two emitters) can be for example, approximately 10 mm. In another example implementation, emitter spacing **126** can be more and/or less than 10 mm depending on, for example, the intensity and/or concentration of sonic waves desired in a given location along an IVL catheter **101**. FIG. 1 depicts four electrode pairs **120**, however, in one implementation, an IVL catheter **101** can have five electrode pairs **120**. In some implementations, emitter spacing **126** can be 11.5 mm between a first and second electrode pair, 10.5 mm between a second and third electrode pair, 9.5 mm between a third and fourth electrode pair, and/or 7.5 mm between a fourth and fifth electrode pair, beginning at a distal end **34** and/or a

proximal end **33**. In some examples, one or more electrodes of an electrode pair **120** can have a width of approximately 1 mm, although the width of electrodes can vary depending on the intensity and/or concentration of sonic waves desired.

[0082] Electrode pairs **120** can have a spark gap **125**. A spark gap **125** may be a space between two electrodes in an electrode pair **120** (e.g., on a first and second side of, for example, a first axis A1 and/or a second axis A2), that facilitates a controlled electrical arc (e.g., electrical discharge) when electrical energy is applied to one or more electrode pairs **120**. In some implementations, a spark gap **125** can be 1 mm. In some implementations a spark gap **125** can be 0.5, 1, 2, 3, 4, 5, and/or more mm. In some implementations a spark gap **125** can vary from one electrode pair **120** to another electrode pair **120**. Further, a spark gap **125** can be more or less than 1 mm depending on the desired intensity and/or concentration of desired pressure sonic waves at a given location in an IVL catheter **101**. Advantageously, a spark gap **125** can be designed to direct sonic waves toward a calcified plaque as described below.

[0083] Electrode pairs **120** can further include a common wire **123** and source wires **124**. Wire **123** and/or **124** can be electrically connected to one or more electrodes of an electrode pair **120** and to an energy generator **150**. Wires **123** and/or **124** can carry electrical energy from an energy generator **150** to an electrode pair **120** to generate an electrical arc across spark gap **125**. In some implementations, a system **100** can include individual wires **123** and/or **124** for each electrode in an electrode pair **120**, enabling an energy generator **150** to individually control each electrode pair **120** (e.g., an N×2 configuration where “N” is the number of electrode pairs **120**). However, individually wiring each electrode pair **120** may result in an increased diameter of the overall dimensions of an IVL catheter **101**, as two wires may be fitted in the IVL catheter **101** for each electrode pair **120**. Advantageously, an N×2 configuration can be used to selectively generate a spark gap **125** between any two electrodes within an IVL catheter **101**. In some implementations, a system **100** can have one common wire **123** and individual source wires **124**, as depicted in FIG. 1. For example, one electrode of each electrode pair **120** can be individually wired to an energy generator **150**, and a second electrode of each electrode pair **120** can be electrically connected together with a common wire **123** (e.g., an N+1 configuration where “N” is the number of electrode pairs **120**).

Advantageously, wiring electrode pairs **120** in an N+1 configuration can reduce the number of wires **123** and/or **124** within an IVL catheter **101** in comparison to individually wired electrode pairs **120** as mentioned above. For example, the number of wires **123** and/or **124** decreases for a number of electrode pairs **120** as one moves from a proximal end **33** to a distal end **34** of an IVL catheter **101**, as depicted in FIG. 1. In addition to a reduced overall diameter for an IVL catheter **101**, an N+1 wiring configuration enables an energy generator **150** to individually control each electrode pair **120** as only one of the electrodes are individually wired, via source wire **124**, to an energy generator **150** as further described with reference to FIGS. 2A-2B below. As illustrated in FIG. 1, common wire **123** and/or source wires **124** can be routed outside the carrier **112**. In some implementations, wire **123** and/or **124** can be routed within (e.g., beneath an outer surface, embedded, and/or the like) a carrier **112**.

[0084] An IVL catheter **101** can further include markers **116**. Markers **116** can be used during a procedure to help a physician visualize and position IVL catheter **101**. Markers **116** can be radiopaque markers that can be visible under fluoroscopy and/or X-ray imaging. Further, markers **116** can be alignment markers used to position IVL catheter **101** accurately within specific anatomical landmarks to the target calcified lesion within a blood vessel. Markers **116** can be positioned at a distal end **34**, a proximal end **33** and/or at any other part of an IVL catheter **101**. Further, there can be one or more markers **116**, each positioned at varying locations within an IVL catheter to assist a physician in alignment and treatment such as on a carrier **112**, a balloon **111**, and/or any other area.

[0085] An IVL catheter **101** may include an indicator **117**. An indicator **117** can be a check valve, a pressure sensor, a flow indicator, temperature sensor, and/or another sensor to determine a change

in state of an IVL catheter **101**. An indicator can be coupled to an inner surface, an outer surface, and/or within an inner surface of a balloon **111**. Alternatively and/or optionally an indicator **117** may be at another location within a system **100** such as positioned along the carrier **112**, as part of and/or along a proximal seal **114** and/or a distal seal **113**, as part of an energy generator **150**, coupled to a hollow channel as defined by the carrier **112**, along a inflation lumen (depicted as part of FIG. **14A-14B**), and/or the like.

[0086] An indicator **117** may sense a change in state, (e.g., a physical property) such as a change in pressure, flow, temperature, motion (e.g., a vibration), volume, and/or the like, of one or more components of an IVL catheter **101**. In some examples, the indicator **117** may detect a pressure change in the balloon **111**. A balloon **111** may experience a pressure fluctuation once a calcified lesion is successfully broken. As an illustrative example, during a successful treatment of a calcified lesion by an IVL catheter **101**, a balloon **111** may expand in volume, and thus experience a pressure decrease within the balloon **111**. Indicator **117** may sense a pressure drop within the balloon **111** once the volume of the balloon **111** increases. The indicator **117** may therefore indicate to a user, that an IVL procedure successfully modified a calcified lesion. Additionally and/or optionally, an indicator **117** may sense a change in pressure and/or flow of conductive fluid within a balloon **111** due to a ruptured balloon **111**.

[0087] A system **100** can further include an energy generator **150**. An energy generator **150** can provide electrical energy (e.g., current) to electrode pairs **120** as mentioned above. Additionally, the energy generator **150** can generate one or more electrical patterns by changing the frequency, pulse width, amplitude, pulse polarity, pulse shape and/or phase of one or more pulses transmitted to electrode pairs **120** to further alter the intensity, duration, and/or directionality of one or more sonic waves to modify a calcified lesion. In some implementations, an energy generator **150** can transmit electrical energy to electrode pairs **120** at a minimum rate of approximately 5 Hz. In some implementations, an energy generator **150** can transmit electrical energy to electrode pairs **120** at a minimum rate less than and/or more than 5 Hz (e.g., 1, 2, 3.5, 10 Hz and/or the like). As further described with reference to FIGS. **2A-2B**, an energy generator **150** can selectively emit energy to one or more electrode pairs **120** based on, for example the use of a multiplexer and/or can be used along with additional devices to improve patient safety by synchronizing a patient's cardiac rhythm with one or more IVL generated sonic waves.

[0088] FIGS. **2A-2B** are an example block diagrams of a cardiac synchronization system **200A** and/or **200B**. As illustrated in FIG. **2A**, a cardiac synchronization system **200A** can be used to improve the safety and efficacy of an IVL procedure. A cardiac synchronization system **200A** can include an IVL catheter **201A**, energy generator **250**, cardiac rhythm unit **260**, and a patient **270**. An IVL catheter **201A** can be electrically connected to an energy generator **250** via wires **223** and/or **224**. An IVL catheter **201A** can be configured to receive electrical energy from an energy generator **250** in response to a physician's request to generate sonic waves in the IVL catheter **201A**. An energy generator **250** can be in further communication with a cardiac rhythm unit **260**. For example, the cardiac rhythm unit **260** can transmit data (e.g., via wired and/or wirelessly) associated with a cardiac rhythm of a patient **270** to energy generator **250**.

[0089] As mentioned above, during an IVL procedure, electrical arcs may be generated in an IVL catheter **201A**. Sonic waves created from electrical arcs are used to modify calcified lesions. In some procedures, an IVL catheter **201A** can be positioned in close proximity to the heart of a patient **270** and/or other electrically sensitive organs. Advantageously, timing electrical arcs in an IVL catheter **201A** according to a cardiac rhythm of a patient **270** during an IVL procedure can mitigate certain health risks.

[0090] An IVL catheter **201A** can be the same and/or similar to IVL catheter **101** as described with reference to FIG. **1** and/or any of the additional configurations as mentioned herein. In some examples, an IVL catheter **201A** can have electrode pairs **220** (e.g., electrode pair **220\_1**, **220\_2**, **220\_n**), each electrode pair **120** can include at least two electrodes (e.g., **E\_1\_1** and/or **E\_1\_2** for

electrode pair **220\_1**). Electrode pairs **220** can be configured in an N+1 configuration as mentioned in above and as illustrated in FIGS. **1-2A**. In some implementations, electrode pairs **220** can be electrically connected via wires **223** and/or **224**, in another configuration (e.g., in parallel, series, individually wired, and/or the like). In some examples, electrode pairs **220** are electrically connected to a multiplexer **255** via wires **223** and/or **224**. In some examples, electrode pairs **220** are electrically connected to another component such as arc generator **254**.

[0091] An IVL catheter **201A** can include an indicator **217**. Indicator **217** can be the same as and/or similar to an indicator **117** of FIG. **1**. An indicator **217** can include, for example, a check valve, a pressure sensor, a flow indicator, temperature sensor, motion sensor, and/or another sensor to determine a change in state of an IVL catheter **201A**. An indicator **217** may indicate to a user, that an IVL procedure successfully modified a calcified lesion, that a balloon **111** has ruptured, and/or the like.

[0092] A cardiac rhythm unit **260** can transmit (e.g., wirelessly and/or wired) information associated with a patient **270** cardiac rhythm to, for example, an energy generator **250**. Further, a cardiac rhythm unit **260** can transmit a discrete signal based on one or more triggering events associated with a patient **270** cardiac rhythm to an energy generator **250**. A cardiac rhythm unit **260** can be any device designed to monitor and/or determine one or more characteristics of a patient **270** cardiac rhythm including but not limited to: a heart rate, P waves (electrical activity associated with the upper chambers), QRS complex (lower chambers of the heart), PR interval (the time between the beginning of the P wave and the start of the QRS complex), QT interval (time between the start of the QRS complex to the end of the T wave), T wave (ventricular repolarization), and/or the like. In some examples, the cardiac rhythm unit **260** can be an AccuSync® 72 ECG trigger monitor. In some examples, a cardiac rhythm unit **260** can detect an R-wave signal and in response, transmit a discrete signal to an energy generator **250** based on one or more triggering events associated with the R-wave signal.

[0093] A cardiac synchronization system **200A** can include an energy generator **250**. An energy generator **250** can include a controller **251**, memory **252**, a communication unit **253**, an arc generator **254**, and/or a multiplexer **255**. An energy generator **250** can transmit electrical energy to electrode pairs **220** of an IVL catheter **201A**.

[0094] An energy generator **250** can include a controller **251**, memory **252**, and/or a communication unit **253**. An energy generator **250** can store information obtained by a controller **251** in memory **252**. Examples of information stored in memory **252** can include operational data such as electrical patterns, a counter to determine a lifespan of an IVL catheter **201A** based on the emitted energy from energy generator **250**, and/or information associated with cardiac synchronization (e.g., a threshold and/or the like). In some examples, a counter can generate an alert after the counter determines that an IVL catheter **201A** exceeded a threshold number of pulses (e.g., 100, 200, 300, and/or more pulses). Additionally, an energy generator **250** includes a communication unit **253**. A communication unit **253** can transmit and/or receive data from, for example, a cardiac rhythm unit **260**. For example, a communication unit **253** may receive data representing a cardiac rhythm of a patient **270**, and/or a discrete signal from a cardiac rhythm unit **260**. A discrete input can be, for example, representative of a timeframe enabling an energy generator **250** to transmit electrical energy to an IVL catheter **201A**. Additionally and/or optionally, a discrete signal can disable an energy generator **250** from emitting electrical energy to the IVL catheter **201A**.

[0095] A controller **251** can determine one or more electrical characteristics of electrical energy transmitted to electrode pairs **120**. For example, a controller **251** can determine the frequency, amplitude, pulse width (e.g., duty cycle), pulse shape, pulse polarity, and/or phase of one or more electrical pulses as created by the arc generator **254**. A controller **251** can change one or more electrical characteristics based on, for example, an input from a user (e.g., a physician conducting an IVL procedure). A controller **251** can change electrical characteristics of energy transmitted to

an IVL catheter **201A** based on a user's input regarding one or more aspects of a calcified lesion such as the location, quantity, and/or concentration of a calcified lesion. In some examples, a controller **251** can determine an electrical pattern as created by an arc generator **254**. An electrical pattern can include a pulse width, an amplitude, a frequency, pulse shape, pulse polarity, a duration, and/or the like. In some examples, an electrical pattern can be linear, a random burst, a square wave, a triangle wave. An electrical pattern can further include selectively emitting energy to one or more electrode pairs **220**. For example, a controller **251** can instruct a multiplexer **255** to select one or more channels based on, for example a desired electrical pattern as described herein.

[0096] Additionally and/or alternatively, a controller **251** can determine whether to emit a monophasic pulse and/or a biphasic electrical pulse. In some examples, a controller **251** can instruct the arc generator **254** to emit a monophasic pulse, where the polarity of one electrode in electrode pairs **220** is positive and/or another electrode in electrode pairs **220** is negative. In a monophasic pulse, the current creating an arc traveling in one direction, from a first electrode (e.g., E\_1\_1) to a second electrode (e.g., E\_1\_2). Consequently, a monophasic pulse can create weld spots on the surface of one electrode. Over time, these weld spots may reduce the control and/or directionality of sonic waves, increase component degradation, and/or cause premature electrode failure.

[0097] Advantageously, a controller **251** can instruct an arc generator **254** to generate biphasic pulses. Biphasic pulses deliver electrical energy in two phases, a positive phase and/or a negative phase. Thus current (and/or electrical arcs) flowing through an electrode pair **220** can alternate between positive and/or negative. A biphasic pulse can increase reliability and/or lifespan of an IVL catheter **201A** as weld spots are less likely to accumulate on one electrode. In some implementations, a controller **251** can instruct an arc generator **254** to combine one or more patterns based on a user input. For example, a controller **251** can instruct an arc generator **254** to create an electrical pattern having a monophasic pulse, a biphasic pulse, a frequency, pulse width, amplitude, phase, pulse shape, and/or the like, to increase the reliability and/or lifespan of an IVL catheter **201A**.

[0098] In some examples, a controller **251** can instruct an arc generator **254** to generate asymmetric pulses (e.g., biphasic pulses where a positive pulse and/or a negative pulse are asymmetric with respect to one another). Asymmetric pulses can include varying rise and/or fall times (e.g., a slope), varying energy levels, and/or the like, for a positive and/or negative pulse. Advantageously, asymmetric pulses may increase the longevity of electrode pairs **120**, and thus increase the lifespan of an IVL catheter **101**, as erosion and/or pitting resulting from arcing may be more evenly distributed, and/or heat may be efficiently dissipated in comparison to symmetric pulse patterns.

[0099] An asymmetric pulse may be characterized by different energy levels on a positive and/or on a negative portion of a biphasic pulse. As an illustrative example, a positive pulse may include a larger voltage difference (e.g.,  $\Delta V$ ) and/or a longer pulse width in comparison to a negative pulse. As another example, a negative pulse may have a shorter  $\Delta V$  for a longer duration than a positive pulse. In some examples, an asymmetric pulse can have multiple  $\Delta V$ s and/or differing rise and/or fall times for positive and/or negative pulses. As an illustrative example, a positive pulse can be characterized by a first  $\Delta V$  for a first duration at a first slope, and a second  $\Delta V$  for a second duration at a second slope, while a negative pulse can be characterized by a third  $\Delta V$  for a third duration at a third slope, and a fourth  $\Delta V$  for a fourth duration at a fourth slope.

[0100] Additionally and/or alternatively, a controller **251** can determine and/or adjust an energy level for positive and/or negative pulses of an asymmetric pulse based on an estimated amount of heat generated by the arc generator **254**. For example, a controller **251** may generate a first pulse and/or set of pulses having approximately a 10  $\mu s$  pulse width and adjust the pulse width accordingly based on a calculated heat generation and/or dissipation associated with an electrode pair **220** (e.g., as an illustrative example and not meant to be limiting, based on a spark gap **125**, **325**, **425**, **525** and/or the like). A controller **251** may calculate heat dissipation based on, among

other factors, an area of the body receiving treatment, the number and/or frequency of pulses, the type of arc generator **254**, the type, position, quantity, composition and/or another property associated with electrode pairs **220**, and/or the like.

[0101] In some examples, a controller **251** can instruct an arc generator **254** to emit energy such that an electric field is generated at and or near an electrode pair **220**. In some examples, the controller **251** may instruct a first electrode and a second electrode to emit energy to cause an electric field according to one or more electrical characteristics associated with increasing the efficacy of a medication into an arterial wall via reversible electroporation. An electric field may be controlled such that sonic pressure waves do not result from a spark gap. In some examples, an electric field may be applied to endothelial cells during a procedure. An electric field may increase the efficacy of a medication from, for example, a drug-coated balloon **111** of FIG. **1** as described herein.

[0102] In some implementations, a controller **251** can instruct an arc generator **254** to emit electrical energy to electrode pairs **220** at and/or near the resonance frequency of plaque within an artery, to efficiently facilitate the modification of plaque. Plaque, like any item in the physical world, has a resonance frequency. When plaque is subjected to an external force at a resonance frequency (e.g., sonic waves from an IVL catheter such as **101**, **201A**, **201B**, and/or the like), the plaque exhibits maximum vibrational amplitudes by absorbing and/or storing energy, resulting in significant oscillations inevitably modifying the plaque. In some examples, a resonance frequency is determined by inherent characteristics of plaque (e.g., mass, stiffness and/or the like). In some examples, a controller **251** can instruct an arc generator **254** to emit electrical energy at the resonance frequency of plaque (e.g., approximately 54 Hz). In some examples, a controller **251** can instruct an arc generator **254** to emit electrical energy having a resonance frequency range from approximately 10 Hz to 55 Hz. In some examples, a controller **251** can instruct an arc generator **254** to emit electrical energy at the resonance frequency of plaque, wherein the frequency is greater than 5 Hz. However, the controller **251** can instruct the arc generator **254** to emit electrical energy at a resonance frequency greater than and/or less than 5 Hz (e.g., 1, 2, 6.5, 10.1, and/or the like). In some examples, a controller **251** can instruct an arc generator to emit electrical energy having one or more electrical patterns including a resonance frequency, a pulse width, an amplitude, a pulse polarity, a pulse shape and/or a phase as described herein.

[0103] Additionally and/or optionally, a controller **251** can instruct an arc generator **254** to emit electrical energy that may include one or more of and/or a combination of features and/or electrical characteristics as described herein. As an illustrative example, a controller **251** can instruct an arc generator **254** to emit a biphasic and/or asymmetric pulse shape wherein a positive pulse is associated with a first energy level and a negative pulse is associated with a second energy level.

[0104] In some examples, a controller **251** can receive an input from a cardiac rhythm unit **260**. Based on a received input from a cardiac rhythm unit **260**, a controller **251** can determine one or more periods to enable and/or disable electrical energy to an IVL catheter **201A**. A controller **251** can analyze one or more characteristics of a cardiac rhythm including: a heart rate, P waves (electrical activity associated with the upper chambers), QRS complex (lower chambers of the heart), PR interval (the time between the beginning of the P wave and/or the start of the QRS complex), QT interval (time between the start of the QRS complex to the end of the T wave), T wave (ventricular repolarization), and/or the like. In some examples, when an IVL catheter **201A** is located within close proximity to the heart (e.g., coronary arteries, coronary veins, and/or the like), a controller **251** can determine, based on the cardiac rhythm received from a cardiac rhythm unit **260**, that an arc generator **254** should be disabled. In some examples, a controller **251** can ignore requests from a user (e.g., a physician) to generate one or more arcs in an IVL catheter **201A** based on a patient **270** cardiac rhythm.

[0105] In some examples, a controller **251** can determine whether to transmit electrical energy to electrode pairs **220** located at a distal and/or proximal end of an IVL catheter **201A** while

preventing the transmission of electrical energy to other electrode pairs **220**, based on the received cardiac rhythm. For example, a controller **251** can instruct multiplexer **255** to transmit electrical energy to electrode pair **220\_1** while further instructing multiplexer to prevent transmission of electrical energy to electrode pair **220\_2**. In some examples, a controller **251** can instruct the multiplexer **255** to select one or more channels to increase the concentration of sonic waves at a specific location within a blood vessel.

[0106] In some examples, a controller **251** can indicate the state of an IVL catheter (e.g., whether a procedure was successful) based on an indicator **217**. For example, a controller **251** may receive an input from an indicator **217**, which may measure a state of an IVL catheter **201A**, (e.g., a physical property) such as a change in pressure, flow, temperature, motion (e.g., a vibration), volume, and/or the like. In some examples, the controller **251** may determine that the pressure within an IVL catheter **201A** has changed based on a change in a volume of a balloon (e.g., balloon **111** of FIG. 1). In some examples, the controller **251** may indicate that an IVL procedure successfully modified a calcified lesion based on a detected pressure fluctuation as described with reference to FIGS. **14A-14B**.

[0107] An energy generator **250** can further include an arc generator **254**. An arc generator **254** can create one or more electrical pulses based on, for example, an instruction from controller **251**. Arc generator **254** can create an electrical arc pattern having one or more characteristics such as a monophasic pulse, a biphasic pulse, a frequency, pulse width, a symmetric and/or asymmetric pulse shape, amplitude, phase, and/or the like. An arc generator **254** can transmit one or more arc patterns to, for example, multiplexer **255**. Additionally and/or alternatively, arc generator **254** can be wired directly to one or more electrode pairs **220** and/or transmit one or more arc patterns directly to electrode pairs **220**. Further, arc generator **254** can generate one or more arc patterns simultaneously. For example, an arc generator **254** can transmit a first arc pattern and/or a second arc pattern to a multiplexer **255**, such that a first set of electrode pairs **220\_1** create sonic waves based on a first arc pattern, and/or a second set of electrode pairs **220\_2** create sonic waves based on a second arc pattern.

[0108] An energy generator **250** can further include a multiplexer **255**. A multiplexer **255** can include any number of channels corresponding to the number of electrode pairs **220** associated with an IVL catheter **201A** (e.g., one, two, three, four, or more). A multiplexer **255** can receive instructions from a controller **251**, and/or in response, select one or more electrode pairs **120** to generate arcs in accordance with a controller **251** determined arc pattern. A multiplexer **255** be configured to select one or more electrode pairs **220** based on, for example, a desired concentration of sonic waves at a target location in a blood vessel, and/or the like.

[0109] To induce a spark, energy generator **250**, under control of the controller **251**, can drive the wires **223B**, **224B** with voltage such as between 1000V and 5000V, between 1000V and 4000V, between 1000V and 3000V, between 1000V and 2000V, between 2000V and 4000V, between 1500V and 3000V, between 1500V and 2500V, or between 2000V and 3000V, or any value therebetween. The voltage provided by the energy generator **250** can be the difference in voltage between two wires or the absolute value of the voltage driven on a single wire. The wires **223B**, **224B** can have an impedance of thousands of Ohms depending on the implementation, which may increase with smaller electrode surface area. The energy generator **250** can drive the wires **223B**, **224B** at the voltage for a duration between 1  $\mu$ s and 50  $\mu$ s, between 1  $\mu$ s and 40  $\mu$ s, between 1  $\mu$ s and 30  $\mu$ s, between 1  $\mu$ s and 20  $\mu$ s, between 1  $\mu$ s and 10  $\mu$ s, between 1  $\mu$ s and 5  $\mu$ s, between 5  $\mu$ s and 50  $\mu$ s, between 10  $\mu$ s and 50  $\mu$ s, between 20  $\mu$ s and 50  $\mu$ s, between 30  $\mu$ s and 50  $\mu$ s, between 40  $\mu$ s and 50  $\mu$ s, between 1  $\mu$ s and 25  $\mu$ s, between 25  $\mu$ s and 50  $\mu$ s, or any value therebetween. The time during which the energy generator **250** drives the voltage may depend inversely on the voltage such that a higher voltage requires a shorter time duration and vice versa. For example, the energy generator **250** can drive the wires **223B**, **224B** at 1500V for 50  $\mu$ s to induce a spark or can drive the wires **223B**, **224B** at 3000V for somewhere between 1  $\mu$ s and 10  $\mu$ s to induce a spark. Driving the



wires **223B**, **224B** under such conditions can results in hundreds of milliamps of current drawn from the energy generator **250** to the wires **223B**, **224B**.

[0110] The impedance between electrodes in an emitter (e.g., between 1 and 10 Ohms) may be less than the impedance of the wires themselves such that when a spark forms between electrode pairs it can result in an increased current draw (e.g., 30 A-40 A) from the energy generator **250** for a few additional microseconds (e.g., 4  $\mu$ s-10  $\mu$ s) at the same voltage output.

[0111] In some examples, one or more components and/or functions of the cardiac synchronization system **200A** can be combined. For example, arc generator **254** and/or multiplexer **255** can include one or more components designed to generate arc patterns and/or select electrode pairs **220** in response to one or more instructions received from controller **251**. Additionally and/or alternatively, an energy generator **250** and/or a cardiac rhythm unit **260** can be combined into one and/or more units that may determine one or more aspects of a patient **270** cardiac rhythm and/or determine whether to enable/disable the transmission of electrical energy to one or more electrode pairs **220**, and/or transmit electrical energy to the electrode pairs **220**.

[0112] FIG. 2B is an example implementation of a cardiac synchronization system **200B** having an IVL catheter **201B** with individually wired electrode pairs **220**. One or more components of a cardiac synchronization system **200B** can be the same and/or similar to that of cardiac synchronization system **200A**. As depicted in FIG. 2B, a cardiac synchronization system **200B** can be in electrical communication with electrode pairs **220\_1**, **220\_2**, and/or **220\_n** of an IVL catheter **201B**. In some implementations, each electrode within an electrode pair (e.g., electrodes E\_1\_1 and/or E\_1\_2 of electrode pair **220\_1**) can be individually wired via wires **223B** and/or **224B** to, for example, multiplexer **255**. Advantageously, a cardiac synchronization system **200B** can have each electrode wired (e.g., via wires **223B** and/or **224B**) individually to a multiplexer **255**, to generate a spark gap between any two electrodes. For example, in some implementations, a spark gap can exist between electrodes E\_1\_1 and/or E\_1\_2, while in some implementations a spark gap can exist between E\_1\_1 and/or E\_2\_1. Additionally and/or alternatively, a spark gap can exist between electrode pairs E\_1\_1 and/or E\_2\_1 while a second spark gap exists between E\_1\_2 and/or E\_2\_2. In some implementations, multiplexer **255** can selectively transmit a mono-phasic and/or bi-phasic pulse between any combination of electrodes such that an electrical arc travels in one or more direction across a spark gap.

[0113] FIGS. 2C-2F illustrate example graphs **200C-200F** of pulse patterns that may be generated by an energy generator **250**. The example graphs **200C-200F** are illustrative examples of pulse patterns and are not meant to limit the scope of this disclosure. In some examples, a controller **251** may instruct an energy generator **250** to emit one or more pulses having a rise time and/or fall time similar to pulse examples illustrated in graphs **200C-200F**. Additionally and/or optionally, a controller **251** may instruct an energy generator **250** to emit pulses having a different energy level, frequency, intensity, duration and/or the like than what is depicted in graphs **200C-200F**.

[0114] Graph **200C** illustrates an example of a symmetric pulse pattern. A symmetric pulse pattern as depicted in graph **200C** may generate substantially equal amounts of energy for a positive pulse and a negative pulse via the same and/or similar waveforms (e.g., pulses, step functions, energy levels, and/or the like).

[0115] Example graphs **200D-200F** illustrate asymmetric pulse patterns. As described above, asymmetric pulse patterns can include varying rise and/or fall times (e.g., a slope), a biphasic pulse including varying energy levels based on polarity, and/or the like. Advantageously, asymmetric pulses may increase the longevity of electrode pairs **220**, and thus increase the lifespan of an IVL catheter **201A**, as erosion and/or pitting resulting from arcing may be more evenly distributed, and/or heat may be efficiently dissipated in comparison to symmetric pulse patterns.

[0116] Graph **200D** illustrates an example of an asymmetric pulse that generates an equal amount of energy for both a positive and negative pulse. For example, although a positive pulse may have a higher intensity (e.g., voltage) for a shorter duration in comparison to a negative pulse, the total

energy emitted by a positive pulse and a negative pulse may be equal and/or substantially equal as the total area above and below 0 volts is approximately equal. Graphs **200E**, **200F** illustrate examples of asymmetric pulses having different intensities, durations, and/or energy levels. [0117] Although graphs **200D-200F** depict positive pulses followed by negative pulses, this is not meant to be limiting. For example, a negative pulse may be emitted from electrode pairs **220**, followed by a positive pulse. Additionally and/or optionally, pulses do not necessarily have to alternate. For example, one, two, three and/or more negative and/or positive pulses may succeed a first pulse. As an illustrative example, a first negative pulse may be succeeded by an additional negative pulse, and then a positive pulse. Advantageously, generating a bi-phasic pulse pattern (e.g., with positive pulses and a negative pulses) and/or an asymmetric pulse pattern can reduce the likelihood of inducing muscular contractions. Accordingly, the systems and devices described herein can implement intravascular lithotripsy near the heart without risking inducing a heart attack.

[0118] One or more example emitter implementations as part of an IVL catheter are described herein with reference to FIGS. **3A-3E** and/or **4A-4E**. Example implementations of emitters can be used as part of, for example, IVL catheter **101**, **201A**, **201B**, and/or in any other example implementation of an IVL catheter as described herein.

[0119] One or more components of an IVL catheter (e.g., emitters, wires, balloon, carrier, and/or the like) can be configured to optimize sonic waves to modify a calcified lesion. Optimizing the intensity and/or directionality of sonic waves can provide physicians and/or patients alike with several benefits. For example, an efficiently operating IVL catheter generates less heat, thereby reducing a blood vessel's exposure to higher temperatures. An efficient IVL catheter can decrease the pulse counts required to modify calcified lesions, thus reducing overall procedure times. Further, an efficient IVL catheter can modify calcified lesions located at multiple locations within a blood vessel without requiring replacement, thus increasing the efficacy of a procedure. An IVL catheter can optimize the directionality and/or intensity of sonic waves by, for example, positioning electrodes at a distal end, a proximal end, within a carrier, and/or outside a carrier. Further, a shape and/or size of electrodes, a spark gap, and/or the configuration of one or more locations of an electrode pair and/or associated wiring can result in a smaller, lighter, more flexible, and/or hence more efficient IVL catheter as described herein.

[0120] FIG. **3A** is an example side view of a helically wound electrode pair **320**. Electrode pair **320** can be electrically similar and/or the same as electrode pair **120** of FIG. **1**. In some examples, an IVL catheter, such as IVL catheter **101** and/or **201A**, **201B**, and/or the like, can have one or more electrode pairs **320** electrically connected to an energy generator **250** to create an arc within an IVL catheter.

[0121] In some examples, carrier **312** can be the same and/or similar to carrier **112** of FIG. **1**. For example, carrier **312** can have a solid core and/or a hollow channel along a first axis A1. A carrier **312** can be configured with a hollow channel to support, for example a guidewire (e.g., guidewire **118** of FIG. **1**) therethrough. A carrier **312** can have an inner surface **312\_1** and an outer surface **312\_2**. The carrier **312** can have a volume between the inner surface **312\_1** and an outer surface **312\_2** that can house electrodes **321** and/or **322**. The inner surface **312\_1** of a carrier **312** can form, for example, a lumen along a first axis A1. The outer surface **312\_2** can have one or more recessed channels **328**. In some examples, carrier **312** can have a recessed channel **328** as shown in cross section of electrode pair **320** (e.g., a cross-section along a plane intersecting a first axis A1. For example, carrier **312** can have a recessed channel **328** beginning at a proximal end **34** and/or ending at a distal end **33**. In some examples, a recessed channel **328** can create a helix around a carrier **312**.

[0122] A recessed channel **328** can have a first height  $h_{sub.1}$  of approximately 0.02 to 0.1 mm. A first height  $h_{sub.1}$  of a recessed channel **328** can be measured from one or more wires **323** and/or **324** to an outer surface **312\_2** of the carrier. In some examples, a first height  $h_{sub.1}$  more and/or

less than 0.03 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.4, 1 and/or the like). A recessed channel can have a second height h.sub.2 measured from one or more wires **323** and/or **324** to the inner surface **312\_1**. The second height h.sub.2 can be approximately 0.02 to 0.06 mm. In some examples, the second height h.sub.2 can be more and or less than approximately 0.02 to 0.06 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.3, 1, 2, and/or more). In some examples, a recessed channel **328** can have a distance d.sub.1 of approximately 0.25 to 0.07 mm. In some examples, a distance d.sub.1 of a recessed channel **328** can be more and/or less than 0.25 to 0.07 mm (e.g., 0.01, 0.1, 0.2, 0.3, 1, 2, and/or more). A first height h.sub.1 and a second height h.sub.2 can determine, for example, the depth of a recessed channel **328** and/or a proximity of wires **323** and/or **324** to an inner surface and/or the outer surface **312\_2** of a carrier **312**. In some examples, a recessed channel **328** has a varying first height h.sub.1 and/or distance d.sub.1 depending on the number of conductive wires **323** and/or **324** included in the recessed channel **328**. In some examples, a recessed channel **328** has a reduced first height h and/or distance d.sub.1 at a distal end of the carrier **312** in comparison to a proximal end. In some implementations, a recessed channel **328** can have one or more geometric shapes as depicted in FIGS. 3A-3E.

[0123] Advantageously, insulated conductive wires **323** and/or **324** can be beneath (e.g., embedded, below, and/or the like) a recessed channel **328** of carrier **312** and/or an outer surface **312\_2** of a carrier **312**, to optimize the directionality and/or control of sonic waves generated by an electrode pair **320**. Positioning wires **323** and/or **324** beneath a recessed channel and/or an outer surface **312\_2** can, in some cases, reduce an overall diameter of an IVL catheter as measured along a first axis A1. Moreover, an arc between electrode **321** and/or **322** of electrode pair **320** can generate sonic waves within the recessed channel **328**, (e.g., beneath the outer wall and/or spaced inward from an outer surface) of the carrier **312**, thus directing sonic waves outward towards a targeted lesion in a blood vessel. Further, a carrier **312** can have a spark gap **325**. A spark gap **325** can be, for example, a notch exposing electrode **321** and/or **322**. In some examples, carrier **312** can include a spark gap **325** for each electrode pair **320**. In some examples, a first spark gap **325** can be positioned on a distal end **34** of a second axis A2, while a second spark gap **325** can be positioned on a proximal end of a second axis A2. Further, a carrier **312** can include a plurality of spark gaps **325** positioned longitudinally, helically, and/or radially along a first axis A1 and/or a second axis A2 of the carrier **312**.

[0124] Electrode pair **320** can include insulated conductive wires **323** and/or **324** (hereinafter “wire” **323** and/or **324**). Wire **323** and/or **324** can be in electrical communication with, for example an energy generator **250** as illustrated in FIG. 2A-2B. Wire **323** and/or **324** can be a 36 AWG wire (e.g., copper wire insulated with one or more insulating materials). In some examples the wire gauge of wire **323** and/or **324** can be more and/or or less than 36 AWG (e.g., 34, 35, 37, 38, 39, and/or the like). In some examples, wire **323** can be a first wire gauge while wire **324** can be a second wire gauge. Although FIG. 3A depicts one of wire **323** and/or **324**, additional implementations can include multiple wires **323** and/or **324**. For example, wire **323** and/or **324** can be configured in an N+1 configuration as described herein, to selectively transmit electrical energy to one or more electrode pairs **320**. In some configurations, electrode pair **320** can be wired in another configuration such as in parallel, series, individually wired (e.g., such as system **200B** of FIG. 2B), and/or the like.

[0125] In some examples, electrode pair **320** can include a first electrode **321** and/or a second electrode **322**. Electrodes **321** and/or **322** can be for example, a part of wire **323** and/or **324** including a portion where the insulation has been removed to expose a conductor. In some examples, the conductor can be copper wire. In some examples, electrodes **321** and/or **322** can be electrodes welded to the conductor of wire **323** and/or **324**. Electrodes **321** and/or **322** can have a spark gap **325** therebetween. A spark gap **325** can be, for example, 1 mm. However, spark gap **325** can be wider and/or narrower depending on the configuration. For example, FIG. 3A depicts electrodes **321** and/or **322** in similar locations along wire **323** and/or **324** respectively. Electrode

**321** and/or **322** can be positioned proximally **33** and/or distally **34** along wire **323** and/or **324** to increase and/or decrease spark gap **325** as necessary. In some examples, an electrode pair **320** can include multiple sets of electrodes **321**, **322**, and/or spark gaps **325** along a recessed channel **328** of carrier **312**. In some examples, a recessed channel can have one or more geometries as depicted in FIGS. 3A-3E below.

[0126] Although FIG. 3A depicts electrodes **321** and/or **322** proximate to one another, in some implementations, electrodes **321** and/or **322** can be separated, and/or beneath the outer surface **312\_2** of the carrier **312**, (e.g., in a volume between the inner surface **312\_1** and an outer surface **312\_2**). For example, electrode **322** may be located proximate to an inner surface **312\_1** of a carrier **312**, while electrode **321** may be located proximate to an outer surface **312\_2** of the carrier **312**. In some examples, electrodes **321**, and/or **322** can be individually wired as described with reference to FIG. 2B to facilitate individual control of one or more electrodes, to selectively generate an arc between any two electrodes.

[0127] As mentioned above, an IVL catheter having a large outer diameter as measured along a second axis A2 may not be able to navigate one or more occluded segments in a blood vessel, thus limiting the IVL catheter's use. To expand the applicability of an IVL catheter, one design choice may reduce the overall diameter of the IVL catheter. However, as the diameter of an IVL catheter is decreased, so too may the structural integrity of the IVL catheter decrease. In some examples, an IVL catheter's outer diameter can be reduced to a point where the IVL catheter becomes too flexible, to the point where physicians are unable to navigate the IVL catheter into a desired blood vessel. Advantageously, to overcome this problem, wire **323** and/or **324** may be wrapped in a helical shape around the carrier **312**, to increase the overall rigidity of an IVL catheter while reducing the overall diameter of the IVL catheter. Wire **323** and/or **324** can be wrapped around a carrier **312** along a first axis A.sub.1, beginning at a proximal end **33** and/or ending at a distal end **34**. In some examples, insulated conductive wire **323** and/or **324** can be wrapped in a helical shape around a carrier **312** as described above and/or wrapped along the outer surface **312\_2** the carrier.

[0128] FIGS. 3A-3E illustrate examples of additional geometric shapes for a recessed channel **328** of electrode pair **320**. In some examples, a recessed channel **328** can have the same shape throughout a carrier **312**. In some implementations a recessed channel **328** can have a varying shape. In some implementations, a carrier **312** can include one or more recessed channels **328** and/or the like, by removing a volume between an outer surface **312\_2** and an inner surface **312\_1**. For example, a recessed channel **328** can be created when a proximal sidewall of a carrier **312** has a first geometric shape, while a distal sidewall of the carrier **312** has a second geometric shape. FIGS. 3A-3E are a few examples of additional geometric shapes for a recessed channel and are not meant to be limiting. Other shapes and/or a combination of one or more shapes not illustrated in FIGS. 3A-3E may be implemented. Advantageously, a recessed channel **328**, **328a**, **328b**, **328c**, **328d**, and/or the like can be implemented by a system (e.g., **100**, **200A**, **200B**, and/or the like) to efficiently control the directionality and/or concentration of emitted energy as the result of one or more electrical arcs between two electrodes (e.g., electrodes **321** and/or **322**).

[0129] FIG. 3B illustrates an example electrode pair **320a** having a recessed channel **328a** as part of a carrier **312a**. In some examples, a recessed channel **328a** can have a distance d.sub.1 along an outer surface **312a\_2** that is less than a distance of spark gap **325** and/or less than a distance of the recessed channel **328a** proximate to an inner surface **312a\_1**. In some examples, the distance d.sub.1 can be less than and/or the same as a distance of spark gap **325** along an outer surface **312a\_2**. In some examples, a carrier **312a** can form a recessed channel **328a** by removing a portion of the outer surface **312a\_2**. As depicted in FIG. 3B, a carrier **312a** can form a recessed channel **328a** having a substantially angled sidewall on a proximal **33** and/or distal **34** end of a second axis A2.

[0130] FIG. 3C illustrates an example electrode pair **320b** having a recessed channel **328b** as part of a carrier **312b**. The recessed channel **328b** can have a substantially convex sidewall on a

proximal **33** and/or distal **34** end along a second axis A2. In some examples, a recessed channel **328b** can have a distance d.sub.1 along an outer surface **312b\_2** of the carrier **312b**, that is less than a distance of spark gap **325** and/or less than a distance of the recessed channel **328b** proximate to the inner surface **312b\_1**. In some examples, the distance d.sub.1 can be greater and/or the same as a distance of spark gap **325**. In some examples, a carrier **312b** can form a recessed channel **328b** by removing a portion of the outer surface **312b\_2** as depicted in FIG. 3C.

[0131] FIG. 3D illustrates an example electrode pair **320c** having a recessed channel **328c** as part of a carrier **312c**. The recessed channel **328c** can have a substantially concave sidewall on a proximal **33** and/or distal **34** end along a second axis A2. In some examples, a recessed channel **328c** can have a distance d.sub.1 that is less than a distance of spark gap **325**. In some examples, the distance d.sub.1 can be greater than and/or the same as a distance of spark gap **325**. In some examples, a carrier **312c** can form a recessed channel **328c** by removing a portion of the outer surface **312c\_2** as depicted in FIG. 3D.

[0132] FIG. 3E illustrates an example electrode pair **320d** having a recessed channel **328d** as part of a carrier **312d**. In some examples, a recessed channel **328d** can have a distance d.sub.1 along an outer surface **312d\_2** that is greater than a distance of spark gap **325** and/or greater than a distance of the recessed channel **328d** proximate to an inner channel **312d\_1**. In some examples, the distance d.sub.1 can be substantially greater than and/or approximately the same as a distance of spark gap **325** along an outer surface **312d\_2**. In some examples, a carrier **312d** can form a recessed channel **328d** by removing a portion of the surface of the outer surface **312d\_2**. As depicted in FIG. 3E, a carrier **312d** can form a recessed channel **328d** having a substantially angled sidewall on a proximal **33** and/or distal **34** end of a second axis A2.

[0133] As described herein, a system can include any combination of electrode pairs (e.g., **120**, **220**, **320**, **320a-d**, **420**, **420a-d** and/or the like) with one or more combinations of recessed channels in a carrier to efficiently direct energy towards plaque of an artery. In some examples, a system can include one or more recessed channels. Recessed channels can include one or more electrode pairs. In some examples, a recessed channel can have one or more of the example geometries as described herein and/or the like.

[0134] FIG. 4A is an example cross-sectional view along a plane intersecting a first axis A1. FIG. 4A depicts an embedded electrode pair **420**. Electrode pair **420** can be electrically similar and/or the same as electrode pair **120** of FIG. 1. In some examples, an IVL catheter, such as IVL catheter **101**, **201A**, **201B**, and/or the like, can have one or more electrode pairs **420** electrically connected to an energy generator **250** to create an arc within an IVL catheter.

[0135] In some examples, carrier **412** can be the same and/or similar to carrier **112** of FIG. 1. Carrier **412** can have a solid core and/or a hollow channel along a first axis A1. A carrier **412** can be configured with a hollow channel to support, for example a guidewire (e.g., guidewire **118** of FIG. 1) therethrough. A carrier **412** can have an inner surface **412\_1** and an outer surface **412\_2**. The carrier **412** can have a volume between the inner surface **412\_1** and the outer surface **412\_2**. The volume can house electrodes **421** and/or **422**. The inner surface **412\_1** of a carrier **412** can form, for example, a lumen along a first axis A1. The outer surface **412\_2** can have a notch **428** as depicted in cross section of electrode pair **420**. Advantageously, electrodes **421** and/or **422** can be beneath (e.g., below, embedded within, and/or the like) the outer surface **412\_2** of a carrier **412**. Electrodes **421** and/or **422** can be exposed via a notch **428** along a proximal **33** and/or distal **34** side of a second axis A2. Electrodes **421** and/or **422** can be exposed to, for example, conductive fluid of an IVL catheter. Further, carrier **412** can include a cavity **427**. A cavity **427** can be, for example an additional area defining a spark gap **425** included as part of electrodes **421** and/or **422**. In some examples, a cavity **427** can be located on one, both, or none of the electrodes **421** and/or **422**. In some implementations a cavity **427** can be included as part of a carrier **412** (e.g., an inner surface **412\_1** and/or an outer surface **412\_2** and/or the like). In some examples, electrode **421** and/or electrode **422** can include at least one cavity **427**. In some examples, a first electrode of an

electrode pair **420** (e.g., electrode **421** and/or **422**) can include at least one cavity **427** while a second electrode of an electrode pair **420** (e.g., electrode **421** and/or **422**) does not include at least one cavity **427**. Advantageously, a cavity **427** along with the notch **428** of carrier **412** can be configured to optimize the directionality and/or control of sonic waves generated by an electrode pair **420**. For example, an arc between electrode **421** and/or **422** of electrode pair **420** can generate sonic waves within a notch **428** (e.g., beneath the outer surface **412\_2** and/or spaced inward from an outer surface **412\_2**) of the carrier **412**, thus directing the sonic waves outward towards a targeted area of a blood vessel. Further, a carrier **412** can have a solid core and/or the carrier **412** can include a hollow channel defined by an inner surface **412\_1** (e.g., along a first axis **A2**), creating a lumen therethrough (e.g., to support guidewire **118** of FIG. 1).

[0136] Electrode pair **420** further includes electrodes **421** and/or **422**. Electrodes **421** and/or **422** can be embedded within a carrier **412**. Additionally and/or alternatively, electrodes **421** and/or **422** can be positioned below (e.g., inward from an outer surface) an outer wall of the carrier **412**. During the manufacturing process of carrier **412**, an outer wall of carrier **412** can be removed to generate a notch **428** as illustrated in FIG. 4A, thus exposing electrodes **421** and/or **422** and/or creating spark gap **425**.

[0137] A notch **428** can have a first height  $h_{sub.1}$  from approximately 0.04 to 0.3 mm on a proximal **33** and/or distal **34** end along a second axis **A2**. A first height  $h_1$  can be, for example, measured from the outer surface **412\_2** to a bottom portion of a notch **428**. In some examples, a first height  $h_{sub.1}$  of a notch **428** can be more and/or less than approximately 0.04 to 0.3 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.4, 1 and/or the like). A notch **428** can have a second height  $h_{sub.2}$  measured from, for example, a top portion of an electrode pair **420** to an outer surface **412\_2** along a second axis **A2**. A second height  $h_{sub.2}$  can be approximately 0.01 to 0.06 mm along a second axis **A2**. In some examples, the height  $h_{sub.2}$  of a notch **428** can be more and/or less than 0.01 to 0.06 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.4, 1 and/or the like). A notch **428** can have a third height  $h_{sub.3}$  measured from, for example, a top portion of an electrode pair **420** to an inner surface **412\_1** along a second axis **A2**. A third height  $h_{sub.3}$  can be approximately 0.01 mm along a second axis **A2**. In some examples, a third height  $h_{sub.3}$  of a notch **428** can be more and/or less than approximately 0.01 to 0.03 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.4, 1 and/or the like). A notch **428** can have a fourth height  $h_{sub.4}$  measured from, for example, a top portion of an electrode pair **420** to an outer surface **412\_2**. A fourth height  $h_{sub.4}$  can be more and/or less than approximately 0.01 to 0.05 mm along a second axis **A2**. In some examples, a fourth height  $h_{sub.4}$  of a notch **428** can be more and/or less than approximately 0.01 to 0.05 mm (e.g., 0.001, 0.01, 0.1, 0.2, 0.4, 1 and/or the like). In some examples, a notch **428** can have a first distance  $d_{sub.1}$  of a notch **428** as measured along an outer surface **412\_2** of a carrier **412**. In some examples a first distance  $d_{sub.1}$  can be measured from a proximal **33** and/or distal **34** end along a second axis **A.sub.2**. A first distance  $d_{sub.1}$  can be, for example, approximately 0.05 to 0.1 mm. In some examples, a first distance  $d_{sub.1}$  of a notch **428** can be more and/or less than approximately 0.05 to 0.1 mm (e.g., 0.01, 0.1, 0.2, 0.3, 1, 2, and/or more). In some examples, a notch **428** can have a second distance  $d_{sub.2}$  of a notch **428** as measured from a proximal **33** and/or distal **34** side of a notch **428** to a proximal **33** and/or distal **34** end of an electrode **421** and/or **422**. A second distance  $d_{sub.2}$  can measure, for example, the amount of an electrode (e.g., electrode **421** and/or **422**) extending into a notch **428** along a first axis **A1**. In some examples a second distance  $d_{sub.2}$  can be measured from a proximal **33** and/or distal **34** end along a second axis **A2**. A second distance  $d_{sub.2}$  can be, for example, approximately 0.01 to 0.03 mm. In some examples, a second distance  $d_{sub.2}$  can be more and/or less than approximately 0.01 to 0.03 mm (e.g., 0.01, 0.1, 0.2, 0.3, 1, 2, and/or more). In some examples, a notch **428** and/or one or more aspects of an electrode pair **420** can have a varying height  $h_{sub.1}$ ,  $h_{sub.2}$ ,  $h_{sub.3}$ ,  $h_{sub.4}$ , and/or distance  $d_{sub.1}$ ,  $d_{sub.2}$ , depending on the number of conductive wires **423** and/or **424**, and/or type of electrodes **421** and/or **422** included and/or exposed to notch **428**. In some examples, a notch **428** has a reduced height  $h_{sub.1}$ ,  $h_{sub.2}$  and/or distance  $d_{sub.1}$  at

a distal end of a carrier **412** in comparison to a proximal end.

[0138] In some implementations, a first electrode **421** can be positioned at a distal end **34** and/or a second electrode **422** can be positioned at a proximal end **33** along a second axis A2. In some implementations, electrodes **421** and/or **422** can be positioned longitudinally, radially, axially, and/or at any other location along a first axis A1 and/or a second axis A2. In some implementations, a spark gap **425** can be created by positioning electrodes **421** and/or **422** longitudinally, radially, axially, and/or at any other location along a carrier **412**, and/or exposing one or more portions of the carrier **412** (e.g., removing at least a portion of an outer surface **412\_2** and/or the like).

[0139] Further, a composition of electrodes **421** and/or **422** can be one or more of a combination of gold, platinum-iridium alloy, stainless steel, a nickel-titanium alloy, and/or the like. Electrodes **421** and/or **422** can be electrically connected to conductive wires **423** and/or **424** as illustrated. In some examples, conductive wires **423** and/or **424** can be welded to electrodes **421** and/or **422**.

Conductive wires **423** and/or **424** can be configured in an N+1 configuration as described herein, to selectively transmit electrical energy to one or more electrode pairs **420**. In some configurations, electrode pair **420** can be wired in another configuration such as in parallel, series, individually wired (e.g., such as system **200B** of FIG. 2B), and/or the like.

[0140] In some implementations, an IVL catheter can include one or more of electrode pairs **120**, **320**, **420**, and/or the like. Additionally, and/or alternatively, an IVL catheter can include one or more sections having varying carrier configurations such as carrier **112**, **312**, and/or **412** and/or the like.

[0141] FIGS. 4A-4D illustrate examples of additional geometric shapes for a notch **428** of electrode pair **420**. In some examples, a notch **428** can have the same shape along a first axis A1 and/or a second axis A2. In some implementations a notch **428** can have a varying shape along a first axis A1 and/or a second axis A2. In some implementations, a carrier **412** can include more than one notch **428** and/or the like. For example, a notch **428** can be created having a first geometric shape on a proximal **33** end and a second geometric shape on a distal **34** end along a second axis A2. FIGS. 4A-4E are a few examples of additional geometric shapes for a notch **428**, inner surface **412\_1** and/or outer surface **412\_2** of a carrier **412** and are not meant to be limiting. Other shapes and/or a combination of one or more shapes not illustrated in FIGS. 4A-4E may be implemented. Advantageously, a notch **428**, **428a**, **428b**, **428c**, **428d**, and/or the like can be implemented by a system (e.g., **100**, **200A**, **200B**, and/or the like) to efficiently control the directionality and/or concentration of emitted energy as the result of one or more electrical arcs between two electrodes.

[0142] FIG. 4B illustrates an example electrode pair **420a** having a notch **428a** as part of a carrier **412a**. In some examples, a notch **428a** can have a distance  $d_{sub.1}$  along an outer surface **412a\_2** that is less than a distance of spark gap **425** and/or less than a distance of the notch **428a** proximate to an inner surface **412a\_1**. In some examples, the distance  $d_{sub.1}$  can be less than and/or the same as a distance of spark gap **425** along an outer surface **412a\_2**. In some examples, a carrier **412a** can form a notch **428a** by removing a portion of the outer surface **412a\_2**. As depicted in FIG. 4B, a carrier **412a** can form a notch **428a** having a substantially angled sidewall on a proximal **33** and/or distal **34** end of a second axis A2.

[0143] FIG. 4C illustrates an example electrode pair **420b** having a notch **428b** as part of a carrier **412b**. The notch **428b** can have a substantially convex sidewall on a proximal **33** and/or distal **34** end along a second axis A2. In some examples, a notch **428b** can have a distance  $d_{sub.1}$  along an outer surface **412b\_2** of the carrier **412b**, that is less than a distance of spark gap **425** and/or less than a distance of the notch **428b** proximate to the inner surface **412b\_1**. In some examples, the distance  $d_{sub.1}$  can be greater and/or the same as a distance of spark gap **425**. In some examples, a carrier **412b** can form a notch **428b** by removing a portion of the outer surface **412b\_2** as depicted in FIG. 4C.

[0144] FIG. 4D illustrates an example electrode pair **420c** having a notch **428c** as part of a carrier **412c**. The notch **428c** can have a substantially concave sidewall on a proximal **33** and/or distal **34** end along a second axis A2. In some examples, a notch **428c** can have a distance d.sub.1 that is less than a distance of spark gap **425**. In some examples, the distance d.sub.1 can be greater than and/or the same as a distance of spark gap **425**. In some examples, a carrier **412c** can form a notch **428c** by removing a portion of the outer surface **412c\_2** as depicted in FIG. 4D.

[0145] FIG. 4E illustrates an example electrode pair **420d** having a notch **428d** as part of a carrier **412d**. In some examples, a notch **428d** can have a distance d.sub.1 along an outer surface **412d\_2** that is greater than a distance of spark gap **425** and/or greater than a distance of the notch **428d** proximate to an inner channel **412d\_1**. In some examples, the distance d.sub.1 can be substantially greater than and/or approximately the same as a distance of spark gap **425** along an outer surface **412d\_2**. In some examples, a carrier **412d** can form a notch **428d** by removing a portion of the surface of the outer surface **412d\_2**. As depicted in FIG. 4E, a carrier **412d** can form a notch **428d** having a substantially angled sidewall on a proximal **33** and/or distal **34** end of a second axis A2.

[0146] As described above, a system (e.g., **100**, **200A**, **200B** and/or the like) can include any combination of electrode pairs (e.g., **120**, **220**, **320**, **320a-d**, **420**, **420a-d** and/or the like) with one or more combinations of recessed channels and/or notches in a carrier to efficiently direct energy towards plaque of an artery. As an illustrative example, a system can include one recessed channel and/or one or more notches, each having one or more of the geometries as described herein.

[0147] FIGS. 5A-13B illustrate one or more example implementations of IVL catheters that may be used to modify calcified lesions in blood vessels. Each of the example implementations of an IVL catheter can include one or more features as described herein, to provide physicians with the ability to efficiently navigate one or more blood vessels to target and/or modify various accumulations of calcified lesions such as symmetrical and/or non-symmetrical calcified plaque.

[0148] FIGS. 5A-5F, **6**, and/or **7** illustrate example implementations of an IVL catheter with conductive wires helically wound around a sheath and/or carrier. As a result of their helically wound conductive wires, IVL catheters of FIGS. 5A-5F, **6**, and/or **7** have a reduced overall cross-sectional area and/or increased rigidity compared to other IVL catheter types, advantageously allowing a physician to navigate the IVL catheter through one or more arteries to access a greater number of locations including plaque.

[0149] FIGS. 5A-5C illustrate example implementations of an IVL catheter **501** with conductive wires helically wound around a carrier. As depicted in FIG. 5A, IVL catheter **501** can include a balloon **511**. A balloon **511** can be the same and/or similar to balloon **111** of FIG. 1. A balloon **511** can be scaled **514** at a distal end **34** and/or scaled **513** at a proximal end **33**. An IVL catheter **501** can include a carrier **512**. A carrier **512** can be similar and/or the same as carrier **112** and/or **312** of FIGS. 1, and/or **3** respectively. Further, IVL catheter **501** can include electrode pairs **520**. Electrode pairs **520** can be the same and/or similar to electrode pair **320** of FIG. 3A. Balloon **511** can span a length of the IVL catheter **501** between 20 mm and 200 mm, between 20 mm and 150 mm, between 20 mm and 120 mm, between 20 mm and 100 mm, between 20 mm and 60 mm, between 40 mm and 150 mm, between 40 mm and 120 mm, between 60 mm and 120 mm, between 80 mm and 120 mm, between 100 mm and 150 mm, or any length therebetween. The length of the balloon **511** can be defined by the proximal and distal ends of the portion with the largest diameter. The diameter of the balloon **511** when inflated (e.g., the portion with the largest diameter), can be any length between 2 mm and 10 mm, such as 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, or 10 mm.

[0150] As illustrated in FIGS. 5B-5C an electrode pair **520** can have four insulated conductive wires including wire **524** and/or wire **523**. In some examples IVL catheter **501** can have more and/or less wires **523** and/or **524** depending on the desired number of electrode pairs **520** in IVL catheter **501**. Wire **523** and/or **524** can be wrapped in a helical shape around a carrier **512** and/or along a first axis A.sub.1. Advantageously, wrapping wire **523** and/or **524** a helical shape around



carrier **512** and/or along a first axis A.sub.1 can improve structural integrity while reducing the overall diameter of an IVL catheter **501**. Further, an IVL catheter **501** can have increased flexibility at a distal end **34** in comparison to a proximal end **33** as the number of wires **523** and/or **524** can be reduced with each electrode pair **520**. Thus, a flexible IVL catheter **501** can allow physicians to navigate one or more blood vessels and/or cross occluded segments to reach a desired calcified lesion.

[0151] Wire **523** and/or **524** can be in electrical communication with, for example an energy generator **250** as illustrated in FIG. 2A-2B. Further, wire **523** and/or **524** can be, for example, a 36 AWG wire (e.g., copper wire insulated with one or more insulating materials). In some examples the gauge of wire **523** and/or **524** can be more and/or less than 36 AWG as described herein. In some examples, wire **523** can be a first wire gauge while wire **524** can be a second wire gauge.

[0152] As further illustrated in FIG. 5C, electrode pair **520** can include a first electrode **521** and/or a second electrode **522**. Electrodes **521** and/or **522** can be for example, a part of wire **523** and/or **524** including a portion where the insulation has been removed to expose a conductor. In some examples, the conductor can be copper wire. In some examples, electrodes **521** and/or **522** can be electrodes welded to the conductor of wire **523** and/or **524**. Electrodes **521** and/or **522** can have a spark gap **525** therebetween. Spark gap **525** can be, for example, 1 mm. However, spark gap **525** can be wider and/or narrower depending on the configuration. For example, FIG. 6 depicts electrodes **521** and/or **522** wrapped around a carrier **512** such that a spark gap **525** exists axially and/or circumferentially along the carrier **512**. In some examples, electrode **521** and/or **522** can be positioned proximally **33** and/or distally **34** along wire **523** and/or **524** to increase and/or decrease spark gap **525** as necessary.

[0153] In some implementations, the number of wires **523** and/or **524** can be reduced as one travels longitudinally from a proximal end **33** of a carrier **512** to a distal end **34** of the carrier **512** based on the number of electrode pairs **520** associated with IVL catheter **501** (e.g., an N+1 configuration as mentioned above). In one implementation, an IVL catheter **501** can include a common wire **524** and/or three source wires **523** at a proximal end of the IVL catheter **501**. While traveling longitudinally toward a distal end **34** of the carrier **512**, the number of wires **523** and/or **524** can be reduced to three (e.g., one common wire **524** and/or two source wires **523**) as a first source wire **523** may be terminated at an electrode pair **520**. Consequently, a most distal **34** electrode pair **520** requires two wires to form an electrode pair **520**; a common wire **524** and/or a source wire **523**.

[0154] FIGS. 5D-5E illustrate example implementations of ring electrodes **521a**, **522a** as part of an electrode pair **520a**. An electrode pair **520a** may include a combination of ring electrodes **521a**, **522a** and/or another type of electrode (e.g., electrodes **321**, **322**, **421**, **422**, **521**, **522**, and/or the like). Advantageously, ring electrodes **521a**, **522a** used as part of an IVL catheter **101**, **201A**, **201B**, **501** (and/or another IVL catheter as described herein) can increase the lifespan and usefulness of an IVL catheter during a procedure in comparison to conventional IVL catheters. For example, a conventional IVL catheter as described above may limit the number of pulses a physician may emit (e.g., a cycle count), as electrical arcing occurring during each pulse may slowly degrade and/or erode the surface of an electrode within an electrode pair. In some cases, a physician may be limited to 300 pulses during a procedure with conventional IVL catheters. Pulse limitations may result in “pulse rationing,” where a physician elects to limit a number of pulses for a first calcified lesion, regardless of the effectiveness of the pulses on the first calcified lesion, in order to conserve pulses for subsequent calcified lesions. Physicians may pulse ration to reduce the number of procedures a patient may endure, reduce costs associated with replacing an IVL catheter during a procedure, and/or as covered by a patient's medical insurance.

[0155] Ring electrodes **521a**, **522a**, alone or in combination with one or more features described herein may achieve cycle counts far beyond 300 pulses, thereby increasing the longevity and reliability of an IVL catheter and improving outcomes for patients and physicians alike. For example, ring electrode **521a**, **522a** may have a larger surface area than other electrode types which

may disperse erosion and/or pitting events along a larger surface. Additionally ring electrodes **521a**, **522a** may uniformly distribute an electric field in comparison to other electrode types, thereby improving electroporation when for example, a balloon **111** of FIG. **1**, is coated with a type of medication designed to permeate into the cell membrane at a treatment site.

[0156] Ring electrodes **521a**, **522a** can be electrically coupled to an exposed conductor of wires **523**, **524**, to create an electrode pair **520a**. One or more ring electrodes **521a**, **522a** may operate along with another type of electrode and/or type of electrode pair described herein (e.g., **120**, **220**, **320**, **420** and/or the like) to generate a spark along a spark gap **525**.

[0157] Ring electrodes **521a**, **522a** may include any of, and/or a combination of gold, platinum, platinum-iridium alloy, stainless steel, a nickel-titanium alloy, a copper alloy, tungsten, and/or the like. In some examples, ring electrodes **521a**, **522a** may be approximately 45% nickel and/or approximately 50% copper.

[0158] FIG. **5E** illustrates a cross-section **500E** of wire **523** that includes a ring electrode **521a** encircling wire **523**. FIG. **5E** is described with reference to wire **523** and/or ring electrode **521a** of an electrode pair **520a**, however the description herein may interchangeably and/or equally apply to wires **524** and/or ring electrodes **522a** of an electrode pair **520a**. As illustrated in FIG. **5E**, wire **523** can include a conductor **523a** and an insulator **523b**. The conductor **523a** can be any suitable conductive material, such as copper, silver, gold, platinum, an alloy and/or the like. An insulator **523b** can include any suitable insulator for IVL catheters and/or the like.

[0159] Ring electrode **521a** may include an inner surface electrically coupled to an exposed portion **523c** of wire **523**. For example, ring electrode **521a** may fully and/or partially surround, enclose, encircle, and/or the like, wire **523**, to form a ring and/or a partial ring around wire **523** and/or around an exposed portion **523c** of wire **523**. Ring electrode **521a** may be soldered, crimped, welded, or adhesively bonded to an exposed portion **523c** of wire **523**. Ring electrode **521a** may have a minimum thickness  $T_{sub.1}$  as measured radially from a center axis  $A_{sub.3}$  and/or as measured along a radial axis  $A_{sub.4}$  of a wire **523**, **524**. A minimum thickness of a ring electrode **521a** may be approximately 0.001" to 0.002", however ring electrode **521a** may have any thickness (e.g., 0.0001", 0.001", 0.01", 0.1" and/or the like). Ring electrode **521a** may have a minimum length  $L_{sub.1}$  as measured longitudinally along a center axis  $A_{sub.3}$ . In some examples, a minimum length  $L_{sub.1}$  is 1 mm, however the minimum length may be more and/or less than 1 mm (e.g., 0.01 mm, 0.1 mm, 0.98 mm, 1.2 mm, 2.0 mm and/or the like). Additionally, an inner diameter ID and/or outer diameter OD of a ring electrode **521a** may be measured radially from a center axis  $A_{sub.3}$ . In some examples, the inner diameter ID and/or outer diameter OD of a ring electrode **521a** may be larger than, smaller than, and/or between the inner diameter and/or outer diameter of a wire **523** (e.g., conductor **523a** and insulator **523b**), and/or a portion of a conductor **523a** and/or insulator **523b**.

[0160] FIG. **5F** illustrates an example implementation of a variable-pitch helically wound coil **500F** of insulated wires. A coil **500F** may be wound around a carrier **112**, **512** and/or the like, as part of an IVL catheter **501**. Optionally and/or alternatively, conductive wires **523**, **524** may have a varying pitch as the conductive wires **523**, **524** are wound along a carrier **512**. For example, a pitch of helically wound wires **523**, **524** can be tightly wound **542** near an electrode pair **520** and/or loosely wound **541** at another location along the carrier **512**, such that a physician may determine the position of an electrode pair **520** by utilizing fluoroscopy, x-ray, and/or the like. In some examples, a coil **500F** at and/or near an electrode pair **520** may be tightly wound **542**, such that the wires **523**, **524** are touching and/or close to touching one another as depicted in FIG. **5F**. In some examples, a helically wound coil **500F** may be loosely wound **541** (e.g., spaced apart longitudinally) at another location along a carrier **512**. Consequently, tightly wound **542** wires may be identified (e.g., via fluoroscopy and/or the like) by a physician during a procedure, to indicate an approximate location of an electrode pair **520**, a spark gap **525**, and/or electrodes **521**, **522**, within a blood vessel. Additionally and/or alternatively, tightly wound **542** wires **523**, **524** may provide structural support

at and/or near electrode pairs **520**. In some cases, tightly wound **542** wires may increase the rigidity and ultimately the effectiveness of sonic waves electrode from an IVL catheter **501**. Additionally and/or optionally, a marker (such as marker **116** of FIG. **1**) may be positioned at and/or near an electrode pair **520**, to indicate the position of electrode pairs **520** to a physician during a procedure. [0161] FIGS. **6** and/or **7** illustrate example implementations of IVL catheters **601** and/or **701** with conductive wires helically wound around a carrier and/or one or more valves. Advantageously, an IVL catheter **601** and/or **701** with valves can be used by physicians to continuously flush conductive fluid through the IVL catheter **601** and/or **701**, to maintain a specified pressure within the IVL catheter and/or to remove heat generated by one or more electrical arcs generated inside the IVL catheter. Thus, IVL catheters **601** and/or **701** can allow a physician to execute a procedure without interruption due to deflating and/or inflating a catheter **601** and/or **701** due to excessive heat accumulation in an artery.

[0162] FIG. **6** illustrates an IVL catheter **601** including a balloon **611**. A balloon **611** can be the same and/or similar to balloon **111** of FIG. **1**. A balloon **611** can be sealed **614** at a distal end **34** and/or sealed **613** at a proximal end **33**. An IVL catheter **601** can include a carrier **612**. A carrier **612** can be similar and/or the same as carrier **112** and/or **312** of FIGS. **1**, and/or **3** respectively. Further, IVL catheter **601** can include electrode pairs **620**. Electrode pairs **620** can be the same and/or similar to electrode pair **320** of FIG. **3A**. Electrode pairs **620** can be positioned, for example, along and/or beneath the surface of a carrier **612** and/or between valves **617** as depicted in FIG. **6**. [0163] Additionally and/or alternatively, IVL catheter **601** can include valves **617**. Valves **617** can act as an inlet and/or an outlet for conductive fluid. In some implementations, valves **617** can be positioned longitudinally along a carrier **612** as depicted in FIG. **6**. An IVL catheter **601** can flush a balloon **611** with conductive fluid via valves **617**, to maintain a specified pressure within the balloon **611**. In some implementations, IVL catheter **601** can be configured to flush a balloon **611** with conductive fluid via valves **617**, to dissipate heat within an IVL catheter **601** caused by, for example, one or more electrical arcs generated across a spark gap. Additionally, an IVL catheter **601** configured with valves **617** may remove particulates generated during an electrical by flushing conductive fluid through the IVL catheter **601**.

[0164] FIG. **7** illustrates an IVL catheter **701** including a balloon **711**. A balloon **711** can be the same and/or similar to balloon **111** of FIG. **1**. A balloon **711** can be scaled **714** at a distal end **34** and/or scaled **713** at a proximal end **33**. An IVL catheter **701** can include a carrier **712**. A carrier **712** can be similar and/or the same as carrier **112** and/or **312** of FIGS. **1** and/or **3** respectively. Further, IVL catheter **701** can include electrode pairs **720**. Electrode pairs **720** can be the same and/or similar to electrode pair **320** of FIG. **3A**. Electrode pairs **720** can be positioned, for example, along and/or beneath the surface of a carrier **712**. Additionally, electrode pair **720** can be helically wound towards a proximal end **33** as depicted in FIG. **7**.

[0165] Additionally and/or alternatively, IVL catheter **701** can include valves **717**. Valves **717** can act as an inlet and/or an outlet for conductive fluid. In some implementations, valves **717** can be outside a carrier **712** as depicted in FIG. **7**. An IVL catheter **701** can flush a balloon **711** with conductive fluid via valves **717**, to maintain a specified pressure within the balloon **711**. In some implementations, IVL catheter **701** can be configured to flush a balloon **711** with conductive fluid via valves **717**, to dissipate heat within an IVL catheter **701** caused by, for example, one or more electrical arcs generated across a spark gap. Additionally, an IVL catheter **701** configured with valves **717** may remove particulates generated during an electrical by flushing conductive fluid through the IVL catheter **701**.

[0166] FIGS. **8A-8B** illustrate an example implementation of a Chronic Total Occlusion (CTO IVL) catheter **801** that may be used to treat a partially and/or fully occluded segment of a blood vessel by selectively transmitting sonic waves to one or more areas including calcified lesions. For example and as illustrated in FIG. **8A**, catheter **801** can treat the occluded segment using an extension **802** at a distal **34** end of the catheter **801**. An extension **802** can efficiently treat an

occluded segment by selectively emitting sonic waves at a distal end of catheter **801**. Sonic waves can break calcium lesions into smaller pieces, causing a blood vessel to open. Eventually, blood vessels may open enough to allow a catheter **801** to cross an occluded segment. Thus catheter **801** can significantly reduce procedure times and/or increase range of locations accessible by catheter **801** as one catheter can be used to modify and/or cross a partially and/or fully occluded segment. [0167] As illustrated in FIG. **8B**, extension **802** portion of catheter **801** can include a carrier **812**. A carrier **812** can be similar to and/or the same as carrier **112**. A carrier **812** may have a hollow and/or solid core. In some examples, a carrier **812** can terminate at a distal end **34** via a seal **814**. A seal **814** can be configured to keep saline within balloon **811**. A balloon **811** can vary in shape from a proximal end to a distal end **34**. For example, a balloon **811a** can be tapered from a seal **814** at a distal end, having a first diameter d.sub.1 to a proximal end having a second diameter d.sub.2. In some examples, a first diameter d.sub.1 can be approximately 0.5 mm. In some examples a first diameter d.sub.1 can be more and/or less than 0.5 mm (e.g., 0.01, 0.1, 1, 2, 3, etc.). In some examples, a second diameter d.sub.2 can be approximately 1 mm. In some examples a second diameter d.sub.2 can be more and/or less than 1 mm (e.g., 0.01, 0.1, 1, 2, 3, etc.). A balloon **811b** can have a continuous diameter from a distal end to a proximal end. In some examples, the diameter of balloon **811b** can be the same and/or similar to diameter d.sub.2 as described above. A balloon **811c** can be tapered from a distal end, having a second diameter d.sub.2 to a proximal end having a third diameter d.sub.3. In some examples, a second diameter d.sub.2 can be approximately 1 mm. In some examples a second diameter d.sub.2 can be more and/or less than 1 mm (e.g., 0.01, 0.1, 1, 2, 3, etc.).

[0168] In some examples, a third diameter d.sub.3 can be approximately 2 mm. In some examples a third diameter d.sub.3 can be more and/or less than 2 mm (e.g., 0.01, 0.1, 1, 2, 3, 4, 5, etc.). A balloon **811d** can have a continuous diameter from a distal end to a proximal end. In some examples, the diameter of balloon **811d** can be the same and/or similar to diameter d.sub.3 as described above. In some examples, balloon **811a**, **811b**, **811c**, and/or **811d** can be in fluid communication (e.g., one balloon **811**) and/or separate balloons **811a**, **811b**, **811c**, and/or **811d**.

[0169] Advantageously, during treatment, a seal **814** can contact a partially and/or fully occluded segment in order to modify calcified lesions. A carrier **812** can further support one or more electrode pairs **820** located near a distal end **34** of an extension **802**. Electrode pair **820** can be the same and/or similar to any of the electrode pairs described herein, such as electrode pairs **120**, **220**, **320**, **420**, **520**, **520a**, and/or the like. Electrode pair **820** can be configured to emit sonic waves axially towards a distal end **34** of a catheter **801**, radially, and/or in another direction to cause a seal **814** and/or balloon **811** to fracture plaque based on spark gap **825**. Additionally and/or optionally, there may be one or more electrode pairs **820** distributed proximally **33** along a carrier **812** as illustrated in FIG. **8A** and/or as illustrated in FIGS. **1**, **2**, and/or **5**.

[0170] In some examples, electrode pair **820** can be connected to energy generator **150** and/or **250** as described in FIGS. **1-2** respectively. Advantageously, a catheter **801** in electrical communication with an energy generator **150** and/or **250** can allow a physician to selectively generate an arc in electrode pair **820** at a distal end **34**, creating sonic waves that can target plaque at a specific location while avoiding emitting sonic waves at one or more additional location within a blood vessel.

[0171] FIGS. **9A-9C** illustrate an example implementation of a dual balloon IVL catheter **901**. As illustrated in FIG. **9A**, catheter **901** can include a first balloon **911\_1**. A first balloon **911\_1** can be scaled to a first carrier **915** via seal **914**. A first carrier **915** can be, for example a solid core carrier as described with reference to carrier **112** and/or **312** of FIGS. **1**, and/or **3** respectively. In some implementations, a first carrier **915** can be a conduit for one or more conductive wires (e.g., a hollow core), solid, and/or a lumen to support conductive fluid exchange. Conductive wires (e.g., wires) can be, for example inside a first carrier **915** and/or on the surface of a first carrier **915** as depicted in FIGS. **9B-9C**. A first carrier **915** can be used to support one or more electrode pairs

**920**. Electrode pairs **920** can each have a spark gap **925**. Electrode pairs **920** can be the same and/or similar to one or more configurations of electrode pairs **120**, **220**, **320**, **420**, and/or the like as described herein. Catheter **901** can further include a second balloon **911\_2**. A second balloon **911\_2** can be adjacent to a first balloon **911\_1**. A second balloon **911\_2** can include a second carrier **912** therethrough. A second carrier **912** can be the same as and/or similar to carrier **112** and/or **312** of FIGS. **1**, and/or **3** respectively as described herein. In some implementations, balloon **911\_1** and/or **911\_2** are two separate balloons. In some implementations, balloon **911\_1** and/or **911\_2** share a common wall between the two balloons (e.g., one balloon having two separate chambers). In some examples, a first balloon **911\_1** and/or a second balloon **911\_2** can be in fluid communication with one another. In some examples, a first balloon **911\_1** and/or a second balloon **911\_2** may not be in fluid communication with one another. Balloons **911\_1** and/or **911\_2** may be filled with saline and/or another liquid. In some examples, catheter **901** can include markers **916**. In some examples, a physician can use markers **916** under fluoroscopic guidance to ensure that a first balloon **911\_1** is positioned to face plaque. Advantageously, a dual balloon IVL catheter **901** implementation can be utilized, along with one or more features as described herein, to directionally control and/or amplify one or more sonic waves as generated by electrode pairs **920**.

[0172] FIG. **9B** depicts a cross section **900B** of catheter **901** while FIG. **9C** depicts a cross section of a blood vessel **900C** with catheter **901** inserted therethrough. As illustrated in FIGS. **9B** and/or **9C**, a first carrier **915** can include wires **923** and/or **924**. Wires **923** and/or **924** can be the same and/or similar to wires **123**, **124**, **223** and/or **224** of FIGS. **1**, **2A**, and/or **2B**. Wires **923** and/or **924** are depicted as inside a first carrier **915** and/or on the surface of the first carrier **915**, however, wires **923** and/or **924** can be located at another position. In some implementations, wires **923** and/or **924** are all located within a first carrier **915** while in some implementations one or more wires **923** and/or **924** are located on the surface of the first carrier **915**. Catheter **901** may be used by physicians to efficiently modify non-symmetrical plaque **971** in a blood vessel wall **970**. For example, a first balloon **911\_1** can include one or more electrode pairs **920** configured to generate sonic waves while a second balloon **911\_2** is configured to reflect sonic waves generated by electrode pair **920** back towards plaque **971**. A physician can position catheter **901** such that balloon **911\_1** is closest to non-symmetrical plaque **971**. Once a catheter **901** is in position, sonic waves generated by electrode pair **920** can directionally target non-symmetrical plaque **971**. Because a second balloon **911\_2** reflects the sonic waves generated by electrode pair **920**, plaque **971** receives an initial energy from the sonic wave and/or a reflected energy from balloon **911\_2**. Thus, a dual balloon IVL catheter **901** design may efficiently treat calcified lesions by directionally controlling sonic waves emitted from electrode pair **920**. Further a dual balloon IVL catheter **901** can reduce the risk of harming areas of a blood vessel wall **970** because a second balloon **911\_2** may act as a barrier, blocking emitted energy from an opposite side of the blood vessel wall **970**. [0173] FIGS. **10-11** illustrate example implementations of balloon-less IVL catheter **1001** and/or **1101** respectively. Catheter **1001** and/or **1101** can effectively and/or efficiently open a partially and/or fully occluded blood vessel, to restore flow while reducing complications, by concentrating energy at a distal end of the catheter **1001** and/or **1101**.

[0174] As depicted in FIG. **10**, catheter **1001** can include a thin membrane **1011**, a shaft **1015**, and/or a distal membrane **1016**. Catheter **1001** can further include a carrier **1012**, having electrode pairs **1020** and/or a cavity **1050**. Electrode pairs **1020** can be the same and/or similar to electrode pairs **120**, **220**, **320**, **420**, and/or the like as described herein. One or more electrode pairs **1020** can be located at a distal end **34** of catheter **1001**, such that sonic waves are concentrated at the distal end **34**. Cavity **1050** between a thin membrane **1011** and/or a carrier **1012** can be filled with, for example saline and/or another solution such as contrast. In some examples thin membrane **1011** can be flexible enough to navigate through one or more blood vessels, including crossing partially occluded lesions.

[0175] In some examples, a thin membrane **1011** can have a recessed portion. In some examples a

recessed portion of thin membrane **1011** can have a width  $w_{sub.1}$  of approximately 1 mm. In some examples a width  $w_{sub.1}$  can be more and/or less than 1 mm (e.g., 0.01, 0.1, 2, 5, 10 and/or the like). In some examples a recessed portion of thin membrane **1011** can have a height  $h_{sub.1}$  of approximately 0.5 mm. In some examples a height  $h_{sub.1}$  of thin membrane **1011** can be more and/or less than 0.5 mm (e.g., 0.001, 0.01, 0.1, 1, 1.5, 3 and/or the like).

[0176] In some implementations, a shaft **1015** and/or a distal membrane **1016** can be used to modify calcified lesions that may be difficult for another type of catheter to cross. For example, electrode pair **1020** can concentrate sonic waves at a distal end **34** of a catheter **1001**, where the sonic waves travel through a saline solution in cavity **1050** to a shaft **1015**, and/or then to a distal membrane **1016**. Consequently, a shaft **1015** and/or a distal membrane **1016** can transfer energy from the sonic waves as a mechanical force “F” as depicted in FIG. **10**, to modify a calcified lesion, such that a larger profile balloon may cross the calcified lesion. In some examples, thin membrane **1011** and/or distal membrane **1016** can be made of a less rigid material than shaft **1015** and/or carrier **1012**. In some examples, thin membrane **1011** and/or distal membrane **1016** can be made of a material that is as rigid and/or more rigid than shaft **1015** and/or carrier **1012**. In some examples shaft **1015** and/or carrier **1012** can be the same component, while in other examples, shaft **1015** is separate from carrier **1012**.

[0177] As depicted in FIG. **11**, catheter **1101** can include a thin membrane **1111**, a shaft **1115**, and/or a distal membrane **1116**. Catheter **1101** can further include a carrier **1112** having electrode pairs **1120** and/or a cavity **1150**. Electrode pairs **1120** can be the same and/or similar to electrode pairs **120**, **220**, **320**, **420**, and/or the like, as described herein. One or more electrode pairs **1120** can be located at a distal end **34** of a catheter **1101**, such that sonic waves are concentrated at the distal end **34**. Cavity **1150**, located between a thin membrane **1111** and/or a carrier **1112**, can be filled with, for example saline and/or another solution such as contrast. A thin membrane **1111**, and/or carrier **1112** can be similar and/or the same as thin membrane **1011** and/or carrier **1012** of FIG. **10**.

[0178] A shaft **1115** can extend towards a distal end **34** of a catheter **1101**. In contrast to shaft **1015** of FIG. **10**, shaft **1115** can have a constant diameter and/or a varying diameter providing a cavity **1150** that extends to a distal membrane **1116**. Advantageously, extending a cavity **1150** to a distal end **34** of catheter **1101** can provide, in some cases, optimized directional control of a mechanical force “F” as depicted in FIG. **11** for modifying a calcified lesion, such that a larger profile balloon may cross the calcified lesion. In some implementations, extending a cavity **1150** to a distal end **34** of catheter **1101** can provide improved flexibility in comparison to, for example catheter **1001**. For example, catheter **1001** may provide energy at a distal end **34**, primarily in an axial direction, while catheter **1101** may provide concentrated energy at a distal end **34** in an axial and/or a radial direction. In some examples, thin membrane **1111** and/or distal membrane **1116** can be made of a less rigid material than shaft **1115** and/or carrier **1112**. In some examples, thin membrane **1111** and/or distal membrane **1116** can be made of a material that is as rigid and/or more rigid than shaft **1115** and/or carrier **1112**. In some examples shaft **1115** and/or carrier **1112** can be the same component, while in other examples, shaft **1115** is separate from carrier **1112**.

[0179] In some examples, a thin membrane **1111** can have a recessed portion. In some examples a recessed portion of thin membrane **1111** can have a width  $w_{sub.1}$  of approximately 1 mm. In some examples a width  $w_{sub.1}$  can be more and/or less than 1 mm (e.g., 0.01, 0.1, 2, 5, 10 and/or the like). In some examples a recessed portion of thin membrane **1111** can have a height  $h_{sub.1}$  of approximately 0.5 mm. In some examples a height  $h_{sub.1}$  of thin membrane **1111** can be more and/or less than 0.5 mm (e.g., 0.001, 0.01, 0.1, 1, 1.5, 3 and/or the like).

[0180] FIGS. **12A-12C** illustrate an example implementation of an eccentric IVL catheter **1201**. Advantageously, an eccentric IVL catheter **1201** can be easily navigated into position within an artery, to effectively target symmetrical and/or non-symmetrical plaque without disrupting blood flow through the artery. FIG. **12A** is an example perspective view of eccentric IVL catheter **1201**, while FIG. **12B** is an example side view **1201B** of an eccentric IVL catheter **1201**. As illustrated in

FIGS. 12A-12B, catheter **1201** can include a balloon **1211** having a second carrier **1215** extending within the balloon **1211**. A second carrier **1215** can have a solid core and/or a hollow core. A second carrier **1215** can include one or more electrode pairs **1220**. Electrode pairs **1220** can be the same and/or similar to electrode pairs **120**, **220**, **320**, **420**, and/or the like, as described herein. A second first carrier **1215** can include wires **1223** and/or **1224**. Wires **1223** and/or **1224** can be the same and/or similar to wires **123**, **124**, **223** and/or **224** of FIGS. 1, 2A, and/or 2B and/or the like. Wires **1223** and/or **1224** are depicted as inside a second carrier **1215** and/or on the surface of the second carrier **1215**, however, wires **1223** and/or **1224** can be located at another position. In some implementations, wires **1223** and/or **1224** are all located within a second carrier **1215** while in some implementations one or more wires **1223** and/or **1224** are located on the surface of the second carrier **1215**. Catheter **1201** can further include a carrier **1212**. Carrier **1212** can have a hollow core and/or or a solid core. In some examples, carrier **1212** and/or second carrier **1215** can have a lumen therethrough as described with reference to carrier **112** of FIG. 1 (e.g., to support guidewire **118** of FIG. 1 and/or the like). In some examples, carrier **1212** and/or second carrier **1215** can include markers **1216** as described with reference to markers **116** of FIG. 1.

[0181] As depicted in cross-sectional view **1200C** of FIG. 12C, an IVL catheter **1201** can have a carrier **1212** positioned outside and/or adjacent to a balloon **1211**. In some examples, a carrier **1212** can be secured to an outer surface of a balloon **1211** via an adhesive. In some examples, a carrier **1212** can be attached at a proximal end **33** and/or a distal end **34** of a balloon **1211**. Further, a balloon **1211** can be molded into a shape as depicted in FIGS. 12C and/or another shape as necessary to modify one or more lesions. In some examples, a balloon **1211** can be shaped via a heat setting technique.

[0182] In some examples, catheter **1201** can be positioned such that balloon **1211** is adjacent to plaque (e.g., non-symmetrical plaque) while carrier **1212** is positioned on the opposite side of the plaque. Similar to one or more functions as described with reference to a dual balloon IVL catheter **901** of FIG. 9A, catheter **1201** can be positioned such that sonic waves emitted from electrode pair **1220** are transferred into non-symmetrical plaque, while energy emitted toward a carrier **1212** is reflected back to the non-symmetrical plaque.

[0183] FIGS. 13A-13B illustrate example implementations of a double occluding balloon IVL catheter **1301**. Catheter **1301** can have a relatively small profile, thus enabling a physician to navigate catheter **1301** into smaller blood vessels, to reach calcified lesions unavailable to one or more other catheter designs. As depicted in FIG. 13A, catheter **1301** can include a carrier **1312**, a distal balloon **1311\_1**, a proximal balloon **1311\_2**, electrode pairs **1320**, and/or markers **1316**. Further, balloon **1311\_1** can include a distal seal **1314\_1** and/or a proximal seal **1313\_1**, and/or balloon **1311\_2** can include a distal seal **1314\_2** and/or a proximal seal **1313\_2**. Markers **1316** can be the same and/or similar to markers **116** as described in FIG. 1. Electrode pairs **1320** can be the same and/or similar to electrode pairs **120**, **220**, **320**, **420**, and/or the like, as described herein. Further, catheter **1301** can include multiple sets of electrode pairs **1320** as described herein.

[0184] Balloon **1311\_1** and/or **1311\_2** can be the same and/or similar to, for example, balloon **111** as described with reference to FIG. 1, however, electrode pairs **1320** may not be located inside balloon **1311\_1** and/or **1311\_2**. Rather, electrode pairs **1320** can be positioned on the carrier **1312** between balloons **1311\_1** and/or **1311\_2**. In some examples, electrode pairs **1320** can be longitudinally spaced between balloons **1311\_1** and/or **1311\_2**. Advantageously, positioning electrode pairs **1320** outside balloons **1311\_1** and/or **1311\_2** can reduce the overall profile of catheter **1301**. Further, during treatment, balloons **1311\_1** and/or **1311\_2** can be filled with saline, resulting in a temporary occlusion of a blood vessel. Blood within the blood vessel can be trapped between balloon **1311\_1** and/or **1311\_2**. When electrode pairs **1320** generate sonic waves within the blood vessel, sonic energy is transferred from an area proximate to electrode pairs **1320** to the trapped blood, and/or to a calcified lesion. Thus the trapped blood acts as a conduit delivering energy to a calcified lesion similar to and/or the same as saline inside, for example, balloon **111** of

FIG. 1, as described herein.

[0185] FIG. 13B depicts a catheter **1301** in an example blood vessel **1300B**. An example blood vessel **1300B** can have walls **1370**. Example blood vessel **1300B** can include plaque **1371** within walls **1370** and/or blood **1372** between walls **1370**. Catheter **1301** can be positioned such that plaque **1371** is located between a distal balloon **1311\_1** and/or a proximal balloon **1311\_2**. As described with reference to FIG. 13A, balloons **1311\_1** and/or **1311\_2** can occlude the walls **1370** of blood vessel **1300B** near plaque **1371**, such that when electrode pairs **1320** generate sonic waves, blood **1372** can transfer energy, via sonic waves, to the plaque **1371**. Advantageously, catheter **1301** can have a relatively small profile, thus enabling a physician to navigate catheter **1301** into smaller blood vessels to reach calcified lesions unavailable to one or more other catheter designs.

[0186] FIGS. 14A-14B depict an indicator **117** for determining a change in state of the IVL catheter **1401** during a procedure. FIG. 14A depicts the walls **1470** and plaque **1471** before sonic pressure waves are emitted from an IVL catheter **1401**, while FIG. 14B depicts the walls **1470** and modified plaque **1472** after sonic pressure waves are emitted from an IVL catheter **1401**. As described above, an indicator **117** can be a check valve, a pressure sensor, a flow indicator, temperature sensor, and/or another sensor. An indicator **117** can be coupled to, as part of, along, and/or integrated into one or more locations of an IVL catheter **1401**. An indicator **117** may be coupled to an inflation lumen **1419** as depicted in FIGS. 14A-14B. An inflation lumen **1419** may fill a balloon of catheter **1401** with solution as described with reference to FIG. 1. The indicator signal **117a** can be connected (e.g., electrically, optically, pneumatically, hydraulically, and/or the like) between the indicator **117** and a controller (e.g., controller **251** and/or the like). A controller **251** may receive a signal **117a** from indicator **117**, and determine a change in state of an IVL catheter **1401**.

[0187] As depicted in FIG. 14A, a first volume  $V_{sub.1}$  of the IVL catheter **1401** may be small, as calcified plaque **1471** within the walls **1470** of a blood vessel may be rigid and thus confine, reduce, and/or define the maximum volume of catheter **1401** (e.g., the shape of a balloon of catheter **1401**). FIG. 14A further includes an example implementation of a check valve used as an indicator **117** although this is not meant to be limiting. Additional implementations of an indicator **117** may be substituted and/or utilized by an IVL catheter **1401** such as for example, a flow meter, a temperature sensor, a motion sensor and/or the like. As illustrated in the example of FIGS. 14A-14B, the indicator **117** includes a ball and a solenoid electrically coupled to the signal **117a**. During an IVL procedure, catheter **1401** is positioned near calcified plaque **1471** and pressurized with conductive fluid (e.g., to approximately 4 atmospheres) via an inflation lumen **1419**. When catheter **1401** and inflation lumen **1419** reach a stable pressure, one or more components of an indicator **117** may settle to a first state. As depicted in the example implementation of FIG. 14A, a stopper may be located at a first position  $P_{sub.1}$  within a check valve based on a pressure within the catheter **1401**.

[0188] FIG. 14B illustrates an example of a successful IVL procedure. During an effective procedure, sonic pressure waves are emitted from catheter **1401**, causing breaks, cracks, and/or modifications to calcified plaque **1472** within the walls **1470** of a blood vessel. When plaque **1472** is successfully modified, walls **1470** of a blood vessel and consequently catheter **1401** expand (e.g., a balloon of catheter **1401**) expands in volume. As a result, catheter **1401** increases from a first volume  $V_{sub.1}$  to a second volume  $V_{sub.2}$ , causing pressure within the catheter **1401** to decrease. Indicator **117** may be used to sense a pressure decrease within the catheter **1401**, and transmit a signal **117a** to a controller (e.g., controller **251**) for determining that a procedure has successfully modified calcified plaque **1471** at a location along a blood vessel. Specific to the example implementation of FIG. 14B, a stopper moves from a first position  $P_{sub.1}$  to a second position  $P_{sub.2}$  based on a change in pressure of the catheter **1401**.

[0189] Although a check valve is illustrated in FIGS. 14A-14B, an indicator **117** may include any type of sensor used to indicate a change in state of an IVL catheter **1401**. For example, an indicator



**117** can include a pressure sensor, flow sensor, temperature sensor, motion sensor, and/or the like. Additionally and/or optionally, a controller (e.g., controller **251**) may determine whether a balloon **111** has ruptured based on an input from an indicator **117**.

[0190] FIG. **15** illustrates an example workflow **1500** for synchronizing emitted energy from an IVL catheter in accordance with a determined cardiac rhythm, according to an example implementation such as cardiac synchronization system **200A** and/or **200B** as illustrated in FIGS. **2A-2B**. As an example, a controller **251** of a cardiac synchronization system **200A** and/or **200B** can be configured to execute example workflow **1500** of a cardiac synchronization routine. In an example implementation, example workflow **1500** may be executed after IVL catheter **201A** is inserted into a patient. Although example workflow **1500** is described with reference to cardiac synchronization system **200A** of FIG. **2A**, the example workflow **1500** can be implemented with a cardiac synchronization system **200B** of FIG. **2B** and/or the like. Additionally, example workflow **1500** may be implemented with any type of IVL catheter as described herein, such as for example, catheter **101**, **201A/B**, **501**, **601**, **701**, **801**, **901**, **1001**, **1101**, **1201**, **1301** and/or the like. Further an IVL catheter as disclosed herein and/or used to perform workflow **1500** can be configured with one or more electrode configurations such as for example, electrode pair **120**, **220**, **320**, **420**, **520**, **520a**, **620**, **720**, **820**, **920**, **1020**, **1120**, **1220**, **1320**, and/or the like.

[0191] In some procedures, an IVL catheter **201A** can be positioned in close proximity to the heart of a patient **270** and/or other electrically sensitive organs. Advantageously, timing electrical arcs in an IVL catheter **201A** according to a cardiac rhythm of a patient **270** can mitigate certain health risks. Example workflow **1500** begins at block **1502**.

[0192] At block **1502**, a controller **251** can receive an indication of a cardiac rhythm of a patient **270**. The cardiac rhythm can be determined by, for example, cardiac rhythm unit **260** of FIG. **2A-2B**. A cardiac rhythm unit **260** can transmit (e.g., wirelessly and/or wired) information associated with a patient **270** cardiac rhythm to, for example, the energy generator **250**. Further, a cardiac rhythm unit **260** can transmit a discrete signal based on one or more triggering events associated with a patient **270** cardiac rhythm to the energy generator **250**. As mentioned above, a cardiac rhythm unit **260** can be any device designed to monitor and/or determine one or more characteristics of a patient **270** cardiac rhythm, including but not limited to: a heart rate, P waves (electrical activity associated with the upper chambers), QRS complex (lower chambers of the heart), PR interval (the time between the beginning of the P wave and/or the start of the QRS complex), QT interval (time between the start of the QRS complex to the end of the T wave), T wave (ventricular repolarization), and/or the like. In some examples, the cardiac rhythm unit **260** can be an AccuSync® 72 ECG trigger monitor. In some examples, the cardiac rhythm unit **260** can detect an R-wave signal and/or in response, transmit a discrete based on one or more triggering events associated with the R-wave signal.

[0193] At block **1504**, a controller **251** can determine cardiac synchronization period(s) based on the received indication. A controller **251** can determine one or more periods to enable and/or disable electrical energy to an IVL catheter **201A**. A controller **251** can analyze one or more characteristics of a cardiac rhythm as received from the cardiac rhythm unit **260** (e.g., a heart rate, P waves, QRS complex, PR interval, QT interval, T wave, and/or the like). Further, a controller **251** can determine whether to transmit electrical energy to electrode pairs **220** located at a distal and/or proximal end of an IVL catheter **201A** while preventing the transmission of electrical energy to other electrode pairs **220**, based on the received cardiac rhythm. For example, a controller **251** can instruct multiplexer **255** to transmit electrical energy to electrode pair **220\_1** while further instructing multiplexer to prevent transmission of electrical energy to electrode pair **220\_2**. In some examples, a controller **251** can instruct the multiplexer **255** to select one or more channels to increase the concentration of sonic waves at a specific location within a blood vessel.

[0194] At block **1506**, a controller **251** can receive user input(s) requesting to generate sonic waves. User input(s) can be received from, for example a physician requesting to generate sonic waves in

an IVL catheter during an IVL procedure. Additionally and/or alternatively the controller **251** can receive user input(s) from another system.

[0195] At block **1508**, a controller **251** determines whether the user input(s) are received during one or more cardiac synchronization period(s). If the controller **251** determines that the user input(s) are received during a cardiac synchronization period, then the workflow **1500** can continue to block **1510**, where the controller **251** can cancel the request (e.g., not generate sonic waves). If the controller **251** determines that user input(s) are received outside one of a cardiac synchronization period(s), then the workflow **1500** can continue to block **1512**.

[0196] At block **1510**, a controller **251** can cancel a request to generate sonic waves. In some examples, if a controller **251** determines that energy generator **250**, arc generator **254**, and/or multiplexer **255** should be disabled based on the cardiac rhythm received from the cardiac rhythm unit **260**, the controller **251** can ignore requests from a user (e.g., a physician) to generate sonic waves in an IVL catheter **201A**. Additionally and/or alternatively, a controller **251** can determine, based on the cardiac rhythm of a patient, whether to selectively transmit electrical energy to one or more electrode pairs **220** during cardiac synchronization period(s) (e.g., transmitting electrical energy to electrode pair **220\_1** located at, for example, a distal and/or proximal end of an IVL catheter **201A** while preventing the transmission of electrical energy to electrode pair **220\_2**). In some examples, a controller **251** can instruct multiplexer **255** to transmit electrical energy to electrode pair **220\_1** while further instructing multiplexer to prevent transmission of electrical energy to electrode pair **220\_2**. In some examples, a controller **251** can instruct a multiplexer **255** to select one or more channels to increase the concentration of sonic waves at a specific location within a blood vessel. After a controller **251** cancels a request to generate sonic wave(s), the example workflow **1500** may end. In some examples, the example workflow **1500** can continue to block **1502** where a controller **251** can receive another indication of a cardiac rhythm.

[0197] At block **1512**, a controller **251** can emit sonic waves via electrode pairs **220**. As described herein, the sonic waves can be selectively emitted from one or more electrode pairs **220** via energy generator **250**, arc generator **254**, and/or multiplexer **255**. Further, a controller **251** can instruct arc generator **254** to generate sonic waves based on an electrical arc pattern having one or more characteristics as described herein (e.g., a monophasic pulse, a biphasic pulse, a frequency, pulse width, amplitude, phase, pulse shape, and/or the like). Once the controller **251** creates sonic waves per the user input, the workflow **1500** can continue to block **1502** where the controller **251** can receive another indication of a cardiac rhythm.

[0198] FIG. **16A** illustrates a portion of an example IVL catheter **1601** including a sheath **1618**, a carrier **1612**, and one or more insulated wires **1623**. IVL catheter **1601** can include a balloon with similar structural and/or operational features as any of the other example balloons shown and/or described herein. Sheath **1618** includes a lumen configured to receive a guidewire. A longitudinal axis **16LA1** of the IVL catheter **1602** passes through the center of the lumen of the sheath **1618**. IVL catheter **1601** can pass over the guidewire to navigate through blood vessel vasculature of a patient to be delivered to, and retracted, from a treatment site where IVL catheter **1601** can deliver sonic waves to treat calcified deposits. Carrier **1612** has an outer surface **1613** exposed to a solution in which the carrier **1612** is placed such as a saline solution within a balloon. Sheath **1618** and/or carrier **1612** can be formed of a flexible material, such as plastic or polymer. Accordingly, IVL catheter **1601** can bend as it travels through blood vessels of a patient without cracking, breaking, creasing, or otherwise permanently deforming sheath **1618** and/or carrier **1612**. Carrier **1612** may be formed of a different material than sheath **1618** and/or may be constructed at a different time than sheath **1618**. In some implementations, carrier **1612** may be placed over sheath **1618** (and insulated wires **1623**) as a liquid and may harden in place on the sheath **1618** and thus adhere to the sheath **1618** and/or insulated wires **1623**. In some implementations, sheath **1618** and carrier **1612** may be formed of a single, unitary material. In some implementations, IVL catheter **1601** may not include a carrier such that insulated wires **1623** are exposed to a solution surrounding the wires

insulated **1623** and/or sheath **1618**. In some implementations, insulated wires **1623** can be wrapped around the outer surface **1613** of the carrier **1612**. The carrier **1612** may be formed of an electrically insulative material.

[0199] In this example, IVL catheter **1601** has six insulated wires **1623** (e.g., wires **1623A-1623F**). Insulated wires **1623** are wrapped around sheath **1618** and also extend along the length of the sheath **1618** such that insulated wires are wound around sheath **1618** with a pitch. Insulated wires **1623** can be helically wound around sheath **1618**. The shape of the cross-sectional profile of the helix formed by the wrapped wires **1623** may depend on the cross-sectional shape of the sheath **1618**. For example, as shown here, insulated wires **1623** are helically wound in a circular helix because the cross-sectional shape of the sheath **1618** is circular. In some implementations, insulated wires **1623** can be helically wound around sheath **1618** in a polygonal helix such as an octagonal helix, nonagonal helix, decagonal helix, or the like, depending on the cross-sectional shape of the sheath **1618**. In this example, insulated wires **1623** form a sextuple helix around sheath **1618**. Advantageously, insulated wires **1623** can provide more structural support to IVL catheter **1601**, specifically to sheath **1618**, when wrapped around sheath **1618** than if the insulated wires **1623** were not wrapped but rather extended longitudinally along the sheath **1618** parallel with the sheath **1618**. The structural support provided by wrapped wires **1623** can inhibit IVL catheter **1601** (e.g., sheath **1618**) from cracking, creasing, etc. when bending in the blood vessels of a patient.

[0200] In this example, insulated wires **1623** are wound around sheath **1618** with a uniform pitch along at least the portion of the sheath **1618** that is shown. In some implementations, insulated wires **1623** are wound around sheath **1618** with a pitch that varies along the length of the sheath **1618** such as shown and/or described in FIG. 5F which can facilitate visualizing IVL catheter with imaging techniques such as fluoroscopy.

[0201] In this example, each of the insulated wires **1623** are wound around sheath **1618** with a same pitch as each of the other wires **1623** at least along the portion of the sheath **1618** that is shown. Thus, each of the insulated wires **1623** have the same pitch (whether varied or uniform) along the length of the sheath **1618**. In some implementations, at least one of the insulated wires **1623** can have a different pitch than at least one of the other insulated wires **1623**. In some implementations, each of the insulated wires **1623** can be wound with a unique pitch.

[0202] In this example, insulated wires **1623** are positioned adjacent one another. For example, insulated wire **1623B** is between insulated wires **1623A** and **1623C**, while insulated wire **1623D** is between insulated wires **1623C** and **1623E**, etc. Insulated wires **1623** each contact the wires to which they are adjacent. Adjacent wires can contact each other along their entire lengths or at least along a length of the sheath **1618** over which the wires extend. For example, insulated wire **1623A** extends alongside insulated wire **1623B** such that insulated wires **1623A** and **1623B** contact each other along an entire length of the sheath **1618** over which insulated wires **1623A** and **1623B** extend. In some implementations, one or more of the insulated wires **1623** may not contact one or more of the other insulated wires **1623**. For example, insulated wire **1623B** can be separated from insulated wire **1623A** and/or insulated wire **1623C** by a distance. Advantageously, positioning the insulated wires **1623** adjacent to, and in contact with, each other as shown here can facilitate controlling spark gap distances between electrode pairs of an emitter. For example, electrode **1620C2** may not be able to move closer to electrode **1620C1** because insulated wires **1623B-1623C** are between electrodes **1620C1** and **1620C2** and there are no gaps between insulated wires **1623A-1623D**. Similarly, insulated wires **1623E-1623F** can inhibit electrode **1620C2** from moving away from electrode **1620C1**. Thus, the insulated wires **1623** may preserve a constant distance between electrodes **1620C1** and **1620C2** by inhibiting electrodes **1620C1** and **1620C2** from moving closer to each other or away from each other. Maintaining proper distance between electrodes can facilitate creating sparks when sparks are desired or inhibiting sparks when sparks are not desired.

[0203] Insulated wires **1623** are parallel to each other in this portion of the IVL catheter **1601** that is shown such that none of the insulated wires **1623** cross each other at least in the portion shown.

In some implementations, one or more of the insulated wires **1623** may be non-parallel with one or more of the other insulated wires **1623**. For example, one or more of the insulated wires **1623** may cross (e.g., overlap) each other.

[0204] IVL catheter **1601** includes electrodes **1620C1**, **1620C2**, **1620D1**, and **1620D2**. Electrodes **1620C1** and **1620C2** form emitter **1620C** and may be referred to as an electrode pair. Electrodes **1620D1** and **1620D2** form emitter **1620D** and may be referred to as an electrode pair. As shown and/or described in greater detail at FIG. **16B**, an electrode can include a portion of an electrically conductive member of an insulated wire that is exposed (e.g., an exposed portion of an electrically conductive element). Thus, reference to an electrode may refer, in whole or in part, to at least an exposed portion of an electrically conductive member. In some cases, “electrode” and “exposed portion” may be used interchangeably. Electrodes **1620C1** and **1620D1** are positioned on insulated wire **1623A**. Electrode **1620C2** is positioned on insulated wire **1623D**. Electrode **1620D2** is positioned on insulated wire **1623E**.

[0205] Emitter **1620C** is separated from emitter **1620D** by distance Zeg. Specifically, electrode **1620C2** is separated from electrode **1620D1** by distance Zeg. Zeg is a straight line parallel with a longitudinal axis **16LA1** of the IVL catheter **1601**.

[0206] A spark can form at emitter **1620C** between electrode **1620C1** and electrode **1620C2** responsive to a voltage differential between electrodes **1620C1** and **1620C2** exceeding a threshold. The threshold can correspond with the distance between electrodes **1620C1** and **1620C2**. A spark can form at emitter **1620D** between electrode **1620D1** and electrode **1620D2** responsive to a voltage differential between electrodes **1620D1** and **1620D2** exceeding a threshold. The threshold can be same threshold as at emitter **1620C** at least because the distance between electrodes **1620D1** and **1620D2** is the same as the distance between electrodes **1620C1** and **1620C2**. A spark may not form between emitter **1620C** and emitter **1620D** (e.g., between electrodes **1620C2** and **1620D1**) at least because the distance between electrodes **1620C2** and **1620D1** (the Zeg distance) may be too great for a voltage differential between said electrodes to overcome a threshold. The voltage differential can have a pre-defined maximum because an energy generator connected to IVL catheter **1601** can have pre-defined energy outputs.

[0207] IVL catheter **1601** may be longer and include more emitters than what is shown in FIG. **16A**. For example, insulated wires **1623** may span a length of the IVL catheter **1601** between 20 mm and 250 mm, between 40 mm, and 250 mm, between 60 mm, and 250 mm, between 80 mm, and 250 mm, between 100 mm, and 250 mm, between 150 mm, and 250 mm, between 200 mm, and 250 mm, between 20 mm, and 100 mm, between 40 mm and 100 mm, between 60 mm and 100 mm, between 80 mm and 150 mm, between 100 mm, and 200 mm, between 150 mm and 200 mm, between 170 mm and 220 mm, between 180 mm and 210 mm, or an length therebetween.

[0208] FIG. **16B** is an enlarged view of a portion of the IVL catheter **1601**. Insulated wire **1623A** comprises insulative member **1624A** and electrically conductive member **1626A**. Insulative member **1624A** encases electrically conductive member **1626A** and electrically insulates electrically conductive member **1626A**. Electrically conductive member **1626A** extends along the length of the insulated wire **1623A** within insulative member **1624A** and is connected with an energy generator. Electrically conductive member **1626A** can conduct an electrical current and can hold a voltage with respect to other objects such as other insulated wires. Electrically conductive member **1626A** can be formed of a metal or metal allow such as copper. Insulative member **1624A** can be formed of a plastic or polymer. Insulated wire **1623C** includes insulative member **1624C** and electrically conductive member **1626C** with similar structural and operational features as described with respect to insulated wire **1623A**. Each of the other insulated wires **1623B** and **1623D-1623F** can also include insulative members and electrically conductive members with similar structural and operational features as described. Insulated wires **1623** can be any gauge wire such as between 30 AWG and 40 AWG, inclusive. In some implementations, all insulated wires **1623** may be the same gauge. In some implementations, one or more of the insulated wires **1623**

can have a different gauge than the others.

[0209] Carrier **1612** can include one or more carrier openings **1607**, such as carrier opening **1607A** and carrier opening **1607C**. Carrier opening **1607A** extends from the outer surface **1613** of the carrier **1612** to the insulated wire **1623A**. Insulative member **1624A** has an insulative member opening **1625A** that exposes a portion of the electrically conductive member **1626A** which can be referred to as an exposed portion **1627A**. Exposed portion **1627A** is an electrically conductive portion. The insulative member opening **1625A** (and by consequence the exposed portion **1627A**) is positioned within carrier opening **1607A**. For example, exposed portion **1627A** is aligned with (centered within) carrier opening **1607A**. Thus, carrier opening **1607A** exposes the exposed portion **1627A** of the electrically conductive member **1626A**. The exposed portion **1627C** of insulated wire **1623C** is exposed through insulative member opening **1625C** and carrier opening **1607C**.

[0210] In some implementations, carrier opening **1607A** can be formed at the same time as insulative member opening **1625A** which can ensure that the exposed portion is aligned with and/or positioned within carrier opening **1607A**. For example, a laser can form a carrier opening **1607A** and when finished can proceed to also form insulative member opening **1625A** immediately after.

[0211] In this example, carrier openings **1607A**, **1607C** are depicted as having a variable width. For example, carrier openings **1607A**, **1607C** are conically tapered from the outer surface **1613** to the insulated wires **1623A**, **1623C**, respectively. In some implementations, carrier openings **1607A**, **1607C** can have uniform widths from the outer surface **1613** to the respective insulated wires **1623**.

[0212] Carrier **1612** encases insulated wires **1623** such that insulated wires **1623** are positioned between sheath **1618** and outer surface **1613** of the carrier **1612**. However, as discussed, carrier openings **1607** are configured such that the carrier **1612** does not cover the exposed portions **1627A**, **1627C** of insulated wires **1623A**, **1623C**, respectively. Thus, carrier openings **1607** provide access to the exposed portions **1627A**, **1627C** such that a solution surrounding the carrier **1612**, such as a saline solution within a balloon, can conduct the exposed portions **1627A**, **1627C**.

[0213] Electrode **1620B1** is associated with (e.g., formed from) insulated wire **1623A**. Electrode **1620B2** is associated with (e.g., formed from) insulated wire **1623C**. Electrodes **1620B1** and **1620B2** are an electrode pair that form emitter **1620B**. Electrode **1620B1** can include (e.g., refer to) one or more of carrier opening **1607A**, insulative member opening **1625A**, and/or exposed portion **1627A**. Electrode **1620B2** can include (e.g., refer to) one or more of carrier opening **1607C**, insulative member opening **1625C**, and/or exposed portion **1627C**.

[0214] A spark (e.g., electrical current) can travel between electrode **1620B1** and electrode **1620B2**. For example, a spark can originate at exposed portion **1627A** and can travel through insulative member opening **1625A**, through carrier opening **1607A**, along and/or over the outer surface **1613** of the carrier **1612**, through carrier opening **1607C**, through insulative member opening **1625C**, and to exposed portion **1627C**. A spark travelling from electrode **1620B1** to electrode **1620B2** has been described, however, the spark can travel in either direction between electrodes **1620B1**, **1620B2**, depending on whether insulated wire **1623A** has a higher or lower voltage than insulated wire **1623C**. IVL catheter **1601** can be configured such that insulated wire **1623A** can alternate between having a higher or lower voltage than insulated wire **1623C**. A spark can travel between exposed portions **1627A** and **1627C** when a voltage differential between the exposed portions **1627A**, **1627C** exceeds a threshold.

[0215] FIG. **16C** illustrates a side view of various portions of IVL catheter **1601**. Electrodes **1620A1**, **1620A2** are shown on the far left portion of IVL catheter **1601** and are an electrode pair of a first emitter, electrodes **1620B1**, **1620B2** are shown on the middle, left portion and are an electrode pair of a second emitter, electrodes **1620C1**, **1620C2** are shown on the middle, right portion and are an electrode pair of third emitter, and electrodes **1620D1**, **1620D2** are shown on the far right portion and are an electrode pair of a fourth emitter. The four portions of IVL catheter **1601** may be circumferentially displaced from each other by an angle rotated about longitudinal axis **16LA1**. Thus, although electrodes **1620A1**, **1620A2**, **1620A3**, and **1620A4** are shown here as

though they were circumferentially aligned along the IVL catheter **1601**, they may not be aligned, but rather may be circumferentially offset from one another by an angle about longitudinal axis **16LA1**. Additional details regarding electrodes and/or emitters that are circumferentially offset from one another are shown and/or described with respect to FIG. **17C**.

[0216] As shown, emitters of electrode pairs are longitudinally displaced from one another along the length of the IVL catheter **1601** by distances Zeg. For example, electrode **1620A2** is separated from electrode **1620B1** by distance Zeg, and electrode **1620B2** is separated from electrode **1620C1** by distance Zeg, etc. In some implementations, each of the Zeg distances may be the same. In some implementations, one or more of the Zeg distances may differ from the others.

[0217] Zspc represents the length of insulated wires between electrodes on the same wire. For example, Zspc can represent the length of the insulated wire **1623B** between electrodes **1620A2**, **1620B1**, and can represent the length of insulated wire **1623C** between electrodes **1620B2** and **1620C1**, etc. In some implementations, each of the Zspc distances may be the same. In some implementations, one or more of the Zspc distances may differ from the others. The relationship of the Zeg distance between certain electrodes to the Zspc length between those electrodes may depend on the pitch at which the insulated wires **1623** are wound around sheath **1618**. For example, if the wires **1623** extended longitudinally along IVL catheter **1601** without being wound, the Zeg distance and the Zspc length may be the same, whereas in the example shown, the Zspc length is greater than the corresponding Zeg distance due to the wires **1623** being wound around sheath **1618**. Thus, Zeg may decrease relative to Zspc if the insulated wires **1623** are wound closer together with a smaller pitch.

[0218] The pair of electrodes **1620A1**, **1620A2** are separated from each other by a distance rsg which can be referred to as the spark gap distance. Electrode pairs **1620B1**, **1620B2**, and **1620C1**, **1620C2**, and **1620D1**, **1620D2**, are also separated by spark gap distances rsg. In some implementations, each of the rsg distances may be the same. In some implementations, one or more of the rsg distances may differ from the others.

[0219] Because the voltage differential required to create a spark increases as distance increases a larger spark gap distance rsg can result in spark with greater energy due to the higher voltage differential when the spark forms. Similarly, a smaller rsg can result in a spark with less energy. Sparks with greater energy can create sonic waves with greater energy which can more easily eradicate calcified deposits but also bear the risk of damaging healthy tissue (e.g., blood vessel walls). Thus, establishing a proper rsg distance can facilitate treating calcified lesions effectively while also minimizing health risks. The spark gap distance rsg can be between 0.2 mm and 1.5 mm, between 0.25 mm and 1.0 mm, between 0.25 mm and 0.75 m, between 0.35 mm and 0.6 mm, between 0.4 mm and 0.6 mm, between 0.5 and 1.0 mm, between 0.75 and 1.0 mm, or any value therebetween. In some implementations, the spark gap distance rsg can be about 0.4 mm, 0.5 mm, or about 0.6 mm.

[0220] The longitudinal distance between adjacent emitters (the Zeg distance) is greater than the spark distance rsg which allows sparks to form at desired locations while inhibiting sparks from forming at undesired locations. For example, to create a spark between electrodes **1620A1** and **1620A2**, an energy generator can drive voltage on insulated wires **1623A** and **1623B** to create a voltage differential between electrodes **1620A1** and **1620A2**. However, this will also create a voltage differential between electrodes **1620A2** and **1620B1**. But because electrodes **1620A1** and **1620A2** are closer together than electrodes **1620A2** and **1620B1** (e.g.,  $rsg < Zeg$ ), the voltage differential required to form a spark between electrodes **1620A1** and **1620A2** will be less than the voltage differential required to form a spark between electrodes **1620A2** and **1620B1**. Thus, maintaining the voltage differential within thresholds by controlling an energy generator output will allow a spark to form between electrodes **1620A1** and **1620A2** but not between electrodes **1620A2** and **1620B1**. Moreover, a spark will form between electrodes **1620A1** and **1620A2** thus precluding a spark from forming between electrodes **1620A2** and **1620B1**.

[0221] Although a large Zeg distance can inhibit undesired sparks from forming, a large Zeg distance also increases the distance between emitters (decreases emitter density on the IVL catheter **1601**) which can reduce treatment effectiveness. Thus, Zeg should be appropriately sized to inhibit undesired sparks without unduly sacrificing emitter density. Zeg can be between 1.0 mm and 10.0 mm, between 1.0 mm and 8.0 mm, between 1.0 mm and 6.0 mm, between 1.0 mm and 4.0 mm, between 1.0 mm and 3.0 mm, between 1.5 mm and 2.5 mm, between 2.0 mm and 7.0 mm, between 2.0 mm and 6.0 mm, between 3.0 mm and 6.0 mm, between 4.0 mm and 6.0 mm, between 5.0 mm and 6.0 mm, between 3.0 mm and 8.0 mm, between 4.0 mm and 8.0 mm, between 5.0 mm and 8.0 mm, between 6.0 mm and 8.0 mm, between 5.0 mm and 10.0 mm, or any value therebetween. In some cases, Zeg can be about 2.25 mm, or about 3.5 mm, or about 5.7 mm, or the like.

[0222] Zeg can be larger than rsg by about 2 to 15 times, 2 to 12 times, 2 to 10 times, 2 to 8 times, 2 to 6 times, 2 to 5 times, 2 to 4 times, 2 to 3 times, 5 to 15 times, 6 to 15 times, 7 to 15 times, 8 to 15 times, 9 to 15 times, 10 to 15 times, 12 to 15 times. For example, Zeg can be about 2 times larger than rsg, 3 times larger, 4 times larger, 5 times larger, 6 times larger, 7 times larger, 8 times larger, 9 times larger, 10 times larger, 11 times larger, 12 times larger, etc. As an example, if rsg is 0.5 mm, then Zeg can be about 11.4 times larger than rsg, or about 5.7 mm. As another example, if rsg is 0.5 mm, then Zeg can be about 4.5 times larger than rsg, or about 2.25 mm.

[0223] In some implementations, such as where insulated wires **1623** are wrapped around sheath **1618** as shown in FIGS. **16A-16C**, consecutive electrodes are separated by one or more turns of the wrapped wires **1623**. For example, electrode **1620A2** can be separated from electrode **1620B1** by 1 to 30 turns, 1 to 20 turns, 1 to 15 turns, 1 to 10 turns, 1 to 5 turns, 5 to 30 turns, 5 to 20 turns, 5 to 15 turns, 5 to 10 turns, 10 to 30 turns, 10 to 20 turns, 10 to 15 turns, 15 to 25 turns, or any number of turns therebetween. The distance between turns (e.g., the pitch of the wrapped wires **1623**) can be between 0.5 mm and 5.0 mm, between 0.5 mm and 4.0 mm, between 0.5 mm and 3.0 mm, between 0.5 mm and 2.0 mm, between 0.5 mm and 1.5 mm, between 0.5 mm and 1.0 mm, between 0.75 mm and 1.5 mm, between 0.75 mm and 1.25 mm, between 0.75 mm and 1.0 mm, between 1.0 mm and 1.5 mm, between 1.0 mm and 1.25 mm, or any distance therebetween. The wires **1623** provide more structural support to the sheath **1618** as pitch decreases and provide more flexibility to the sheath **1618** as pitch increases. Thus, an optimal pitch can be achieved as described herein that provides optimized structural support and flexibility for the IVL catheter **1601**.

[0224] A transverse cross-section through IVL catheter **1601** that is perpendicular to the longitudinal axis **16LA1** can pass through any of the electrodes without passing through the other electrode in the pair (e.g., can pass through electrode **1620A1** without passing through electrode **1620A1**). A longitudinal cross-section through IVL catheter **1601** that is parallel to longitudinal axis **16LA1** (and passes through longitudinal axis **16LA1**) can pass through any of the electrodes without passing through the other electrode in the pair (e.g., can pass through electrode **1620A1** without passing through electrode **1620A1**). Thus, electrodes in a pair can be circumferentially and/or longitudinally offset from each other.

[0225] FIG. **17A** is a schematic diagram illustrating example insulated wires **1723A-1723F** arranged in straight rows without being wrapped. FIG. **17A** may not be shown to scale. Insulated wires **1723** are configured to form sparks at emitters n=0, 1, 2, and 3. Emitter n=0 is formed from electrode 0,1 on wire **1723A** and electrode 0,2 on wire **1723B**. Emitter n=1 is formed from electrode 1,1 on wire **1723A** and electrode 1,2 on wire **1723C**. Emitter n=2 is formed from electrode 2,1 on wire **1723A** and electrode 2,2 on wire **1723D**. Emitter n=3 is formed from electrode 3,1 on wire **1723A** and electrode 3,2 on wire **1723E**. Electrodes shown and/or described herein can represent insulative member openings and/or exposed portions of electrically conductive members of insulated wires.

[0226] When insulated wires **1723** are arranged in straight rows without being wrapped, as shown here, electrode pairs in an emitter form a right triangle. Moreover, if insulated wires **1723** are wrapped in an IVL catheter, electrode pairs in an emitter may still form the same right triangle, or

at least a substantially similar right triangle, ignoring potentially small variations that may arise from wrapping. Example right triangles formed from emitters on wrapped wires are shown and/or described in FIG. 16C. In FIG. 17A, each right triangle of an emitter includes a hypotenuse shown by the spark gap distance  $r_{sg}$ , a longitudinal side (the side that is vertical with respect to the page) shown by  $(n+1)\Delta w$ , and a lateral side (the side that is horizontal with respect to the page). The hypotenuse (e.g.,  $r_{sg}$ ) of each triangle of the various emitters may be the same length. The lengths of the other sides of the triangles may vary from emitter to emitter. Because the spark gap distance  $r_{sg}$  is the same for each emitter, the energy differential required to form a spark at each emitter will also be the same or substantially similar.

[0227] The width (e.g., the diameter) of the wires **1723** is  $\Delta w$ . Moreover, the center to center spacing between adjacent wires is also  $\Delta w$  in this example because adjacent wires contact each other. The center to center spacing can be greater than  $\Delta w$  if adjacent wires do not contact each other. Arranging adjacent wires **1723** to contact each other as shown here can facilitate maintaining a constant center to center spacing between wires which can in turn facilitate maintaining constant spark gap distance  $r_{sg}$  in emitters because the spark gap distance  $r_{sg}$  is a function of the center to center spacing between adjacent wires **1723**. For example, the center to center spacing between any of the wires **1723** is already at a minimum because the wires **1723** are in contact with each other and thus will not decrease. Moreover, the center to center spacing between any of the wires **1723** will likely not increase because the wires **1723** will inhibit themselves from moving away from each other as they contact each other and hold each other in place.

[0228] The longitudinal distance  $(n+1)\Delta w$  between electrode pairs in an emitter is governed by the center to center spacing  $\Delta w$  between adjacent wires **1723** which in this example is also the same as the width of the wires **1723**. For example, in emitter  $n=0$ , electrode 0,2 is separated from electrode 0,1 by a longitudinal distance of  $(0+1)\Delta w$ ; and in emitter  $n=1$ , electrode 1,2 is separated from electrode 1,1 by a longitudinal distance of  $(1+1)\Delta w$ . Thus, in this example, the longitudinal distances between electrodes in the various emitter pairs is given in increments of  $\Delta w$ . The longitudinal distance  $(n+1)\Delta w$  is parallel with a longitudinal axis of an IVL catheter. The distance  $(n+1)\Delta w$  may represent the minimum longitudinal distance that can occur between electrodes such as in implementations where wires **1723** touch each other. In some cases, the longitudinal distance between electrodes in an emitter may be greater than  $(n+1)\Delta w$ , depending, for example, on the pitch with which the wires are wound around the sheath. For example, as shown in FIG. 16C, the longitudinal distances between electrodes in any given emitter may be greater than  $(n+1)\Delta w$ .

[0229]  $Z_{spc}$  represents the distance between consecutive emitters. For example,  $Z_{spc}$  is shown as the distance between electrode 0,2 and electrode 1,1. The  $Z_{spc}$  distance can be the same or different between various emitters. If the insulated wires **1723** are wound in an IVL catheter, the  $Z_{spc}$  distance may follow a helical path resulting in a straight longitudinal distance  $Z_{eg}$  between consecutive emitters as shown and/or discussed in FIG. 16C. The  $Z_{eg}$  distance is a function of  $Z_{spc}$  and pitch. If the wires **1723** are not wound,  $Z_{spc}$  may equal  $Z_{eg}$ .

[0230] The distance  $Z_{spc}$  can inhibit sparks from unintentionally forming between undesirable electrodes. For example, to form a spark at emitter  $n=0$ , an energy generator can drive voltage on wire **1723A** and wire **1723B** to create an energy differential between electrode 0,1 and electrode 0,2. However, this would also create an energy differential between electrode 1,2 and electrode 0,2 where it may not be desirable to form a spark. By regulating  $Z_{spc}$  (and  $Z_{eg}$ ) to be greater than  $r_{sg}$ , the energy differential required to form a spark between electrodes 0,2 and 1,1 may be greater than between electrodes 0,1 and 0,2 (assuming electrodes have the same surface areas). Thus, when  $Z_{spc}$  (and  $Z_{eg}$ ) is greater than  $r_{sg}$ , sparks may form between electrode pairs in an emitter but not between non-electrode pairs in adjacent emitters.

[0231] FIG. 17B is a schematic diagram illustrating example insulated wires **2023A-2023E** wrapped around sheath **2018** of IVL catheter **2001**. FIG. 17B may not be shown to scale. In this example, five insulated wires **2023A-2023E** are shown although any number of wires may be used.



Insulated wires **2023A-2023E** can have similar operational and/or structural features as any of the other insulated wires shown and/or described herein. Emitter  $n=0$  is formed from electrode 0,1 on wire **2023A** and electrode 0,2 on wire **2023B**. Emitter  $n=1$  is formed from electrode 1,1 on wire **2023A** and electrode 1,2 on wire **2023C**. Emitter  $n=2$  is formed from electrode 2,1 on wire **2023A** and electrode 2,2 on wire **2023D**. Emitter  $n=3$  is formed from electrode 3,1 on wire **2023A** and electrode 3,2 on wire **2023E**. Electrodes shown and/or described herein can represent insulative member openings and/or exposed portions of electrically conductive members of insulated wires. [0232] The electrodes  $n,1$  and  $n,2$  form right triangles that are shown as superimposed on IVL catheter **2001**. These right triangles include an rsg hypotenuse, a longitudinal side that is parallel with a longitudinal axis **20LA1** of the IVL catheter **2001** and a lateral side that is perpendicular to the longitudinal axis **20LA1**. The longitudinal sides have a length of  $Z_n$  and the lateral sides have a length of  $dY_n$ . The width of the wires **2023** and/or the center to center spacing between adjacent wires is shown by  $\Delta w$ .

[0233] The insulated wires **2023** are wrapped around the sheath **2018** such that they form an angle  $\theta_{sub.p}$  with the edge of the sheath as shown. The angle  $\theta_{sub.p}$  may be consistent along the length of the IVL catheter **2001**.

[0234] FIG. **17B** also shows other right triangles formed by the electrodes superimposed above IVL catheter **2001**, for clarity. These other right triangles include angles  $\theta_{sub.EM}$  which may be different for each of the triangles shown. These right triangles are arranged such that the rsg hypotenuse is parallel with the rsg hypotenuse of the triangles that are superimposed on the IVL catheter **2001** and such that the angle  $\theta_{sub.EM}$  extends from the rsg hypotenuse to a leg of the triangle that is parallel with the insulated wires **2023**. Accordingly, the angle from the edge of the sheath **2018** to the rsg hypotenuse is the sum of the  $\theta_{sub.EM}$  and  $\theta_{sub.p}$  angles when moving clockwise from the edge of the sheath **2018** to the rsg hypotenuse. Thus, the lengths of  $\Delta Z_{sub.z}$  and  $dY_{sub.n}$  can be calculated as follows:

$$[00001] \begin{bmatrix} Z_z \\ dY_n \end{bmatrix} = \begin{bmatrix} r_{SG} * \text{Math. cos}(-\theta_P + \theta_{EM}) * \text{Math.} \\ r_{SG} * \text{Math. sin}(-\theta_P + \theta_{EM}) * \text{Math.} \end{bmatrix}$$

[0235] The angles  $\theta_{sub.EM}$  can be calculated as follows:

$$[00002] \theta_{EM} = \sin^{-1} \left( \frac{(n+1)w}{r_{SG}} \right)$$

[0236] The lateral distance  $dY_n$  may be a function of the spark gap distance  $r_{sg}$  (which may be predetermined) and the longitudinal distance  $\Delta Z_n$  (which may be dictated by wire width and the number of wires between electrodes in a pair). Thus, as shown here, lateral distance may decrease as longitudinal distance  $\Delta Z_n$  increases (in order to maintain a constant  $r_{sg}$ ). In some implementations, the lateral distance  $dY_n$  may be zero and the longitudinal distance  $\Delta Z_n$  may be equal to  $r_{sg}$ . For example, another emitter can be formed from electrodes on wire **1723A** and wire **1723F** wherein the spark gap distance  $r_{sg}$  is a straight line between the electrodes parallel to longitudinal axis **20LA1** without forming a right triangle. In some cases, wire **2023A** may not form an emitter with another wire if the longitudinal distance  $\Delta Z_n$  between them would be greater than a predetermined spark gap distance  $r_{sg}$ . Thus, in some cases, one or more of the wires **1723** may not form an emitter with one or more of the other wires **1723**.

[0237] FIG. **17C** is a cross-section view of a portion of an example IVL catheter **1701** which includes a sheath **1718** having a lumen **1719** configured to receive a guidewire therethrough, insulated wires **1723** wrapped around the sheath **1718**, and a carrier **1712** encasing the wires **1723** and the sheath **1718**. FIG. **17C** may not be shown to scale. Longitudinal axis **17LA1** extends through the center of the lumen **1719** of the sheath **1718**. The carrier **1712** has an outer surface **1713**. IVL catheter **1701** has a plurality of electrodes (e.g., (0,1), (0,2), (1,1), (1,2), (2,1), (2,2), (3,1), (3,2)). In this example, electrodes are represented at the outer surface **1713** of the carrier **1712** where carrier openings may be positioned through which sparks may pass, however this is not intended to be limiting as “electrodes” may also refer to, and/or be represented by, exposed

portions and/or insulative member openings of wires **1723** which may be positioned at between carrier **1712** and the wires **1723**. Whether the discussing electrodes with respect to the outer surface **1713** of the carrier **1712** and/or between the carrier **1712** and the wires **1723**, the angles between electrodes would remain the same.

[0238] Electrode pair 0,1 and 0,2 form an emitter which may correspond to emitter  $n=0$  in FIG. **17A** (or FIG. **17B** in some cases). Electrode pair 1,1 and 1,2 form an emitter which may correspond to emitter  $n=1$  in FIG. **17A**. Electrode pair 2,1 and 2,2 form an emitter which may correspond to emitter  $n=2$  in FIG. **17A**. Electrode pair 3,1 and 3,2 form an emitter which may correspond to emitter  $n=3$  in FIG. **17A**. The angles  $\theta E0$ ,  $\theta E1$ ,  $\theta E2$ ,  $\theta E3$ , between respective electrodes in a pair may depend on the lateral distance (e.g.,  $dYn$ ) between respective electrodes in a pair. Thus, the relationship between the various angles may be as follows  $\theta E0 > \theta E1 > \theta E2 > \theta E3$ . In some implementations,  $\theta E0$  may be between about  $25^\circ$  and  $45^\circ$ ,  $\theta E1$  may be between about  $20^\circ$  and  $40^\circ$ ,  $\theta E2$  may be between about  $15^\circ$  and  $35^\circ$ , and  $\theta E3$  may be between about  $5^\circ$  and  $20^\circ$ .

[0239] The angles  $\theta G1$ ,  $\theta G2$ ,  $\theta G3$ , between the various emitters may depend on the distance (e.g.,  $Z_{spc}$ ) between adjacent emitters which may all be equal or substantially equal. Thus, in some cases, the various angles  $\theta G1$ ,  $\theta G2$ ,  $\theta G3$  may all be equal or substantially equal (assuming a constant pitch). One or more of  $\theta G1$ ,  $\theta G2$ ,  $\theta G3$  can be between  $50^\circ$  and  $85^\circ$ , between  $50^\circ$  and  $75^\circ$ , between  $50^\circ$  and  $60^\circ$ , between  $60^\circ$  and  $75^\circ$ , between  $55^\circ$  and  $70^\circ$ , between  $55^\circ$  and  $65^\circ$ , or between  $65^\circ$  and  $75^\circ$ .

[0240] The emitters are separated by angles  $\theta G1$ ,  $\theta G2$ ,  $\theta G3$ , which may be referred to as the emitters being circumferential offset. For example, the emitter formed by electrode pair 0,1 and 1,1 is circumferentially offset from the emitter formed by electrode pair 1,1, and 1,2 by angle  $\theta G1$ . A single wire (e.g., wire **1723A**) can have a plurality of electrodes that form a plurality of emitters, one or more of which are circumferentially offset from the others. Because the emitters are circumferentially offset (e.g., angular separation) from each other, the various emitters can emit sonic waves in a plurality of directions without having to rotate the IVL catheter **1701** thus allowing for more effective treatment. For example, calcium deposits may form non-uniformly and in more than one place on the surfaces of the vasculature of a patient. Circumferentially and/or longitudinally separating emitters can increase the likelihood of applying sonic waves from the emitters to the calcium deposits wherever they may have formed on the vasculature. In some aspects, consecutive emitters may be longitudinally separated by a distance without being radially separated by an angle or vice versa. Thus, as described, consecutive emitters may be located at different longitudinal positions on the IVL catheter regardless of the angle that separates them radially. Thus, in some cases, emitters, (e.g., emitters that are consecutively spaced without any other emitters between them) may not be circumferentially aligned and/or may not be longitudinally aligned, or in some cases they may be circumferentially aligned and/or longitudinally aligned.

[0241] A pair of electrodes of a single emitter can be circumferentially offset (as shown in FIG. **17C**) and/or longitudinally offset (as shown in FIGS. **17A-17B**). For example, electrodes 0,1 and 1,1 of emitter  $n=0$  are shown in FIG. **17C** as being circumferentially offset because they are separated by angle  $\theta E0$ . As such, a longitudinal cross-section of IVL catheter **1701** along longitudinal axis **17LA1** through the plane of the page that intersects one of electrodes 0,1 and 1,1 may not intersect the other electrode. Electrodes 0,1 and 1,1 can be longitudinally offset (as shown and/or described by the example electrodes in FIGS. **16C** and/or **17A-17B**) because they may be longitudinally separated by a distance such as the ( $n=1$ )  $w$  distance. As such, a transverse cross-section of IVL catheter **1701** parallel to the plane of the page that intersects one of electrodes 0,1 and 1,1 may not intersect the other electrode. Thus, in some cases, a pair of electrodes in an emitter may not be circumferentially aligned and/or may not be longitudinally aligned, or in some cases they may be circumferentially aligned and/or longitudinally aligned.

[0242] The carrier **1712** can be thicker than the wires **1723** such that the outer surface **1713** of the

carrier **1712** extends past the wires **1723** from the sheath **1718** as shown. The thickness of the carrier **1712** can be measured from the outer surface **1713** to a surface of the sheath **1718** that contacts the wires **1723**. The thickness of the wires **1723** can correspond to their diameter as determined by their AWG size. In some implementations, the carrier **1712** may be between 100% and 200% thicker than the wires **1723**, between 100% and 150% thicker, between 100% and 125% thicker, between 100% and 115% thicker, between 100% and 110% thicker, between 125% and 200% thicker, between 150% and 200% thicker, between 175% and 200% thicker, between 125% and 175% thicker, between 125% and 150% thicker, or between 200% and 250% thicker.

[0243] As shown in the cross section of FIG. **17C**, the insulated wires **1723** extend no further away from the sheath **1718** than the thickness of the wires **1723** themselves. This may be because the wires **1723** contiguously contact the sheath **1718**. For example, the wires **1723** may not overlap with one another or be stacked on top of each other etc. which would cause separation between the sheath **1718** and at least some of the wires **1723**. This may be the case along the entire IVL catheter **1701**. The diameter of the outer surface **1713** of the carrier **1712** can be between 0.02" and 0.06", between 0.03" and 0.05", between 0.03" and 0.045", between 0.03" and 0.04", between 0.035" and 0.05", between 0.04" and 0.05", or any value therebetween. As discussed, various implementations of IVL catheters can have anywhere from 3 insulated wires to 15 insulated wires, for example, or any other number of wires as shown and/or discussed herein. Thus, an IVL catheter with 10 insulated wires for example can have a diameter (of the carrier) between 0.03" and 0.05". In some cases, the diameter of various IVL catheters may not change regardless of the numbers of wires in each catheter. For example, an IVL catheter with 6 insulated wires can have the same carrier diameter as an IVL catheter with 12 insulated wires (and the diameter of each may be between 0.03" and 0.05").

[0244] The outer surface **1713** of the carrier **1712** may be circular. The outer surface **1713** of the carrier **1712** may be smooth without any protrusions being raised from the outer surface **1713**. Thus, the outer surface **1713** may be more flexible than if any objects were coupled to the outer surface **1713** or if any portions of the outer surface **1713** protruded from the circular cross-section.

[0245] The locations of electrodes on an IVL catheter can be determined to form carrier openings of the electrodes. For example, a laser drilling system can be programmed with locations at which to form carrier openings of electrodes. The locations of electrodes can be represented with cylindrical coordinates (r,  $\theta$ , z). For example, the location of electrodes (n, 1) and (n,2) in a pair can be shown by the following matrices, respectively:

$$[00003] \begin{matrix} R_{GWL} & R_{GWL} \\ Elec_{n,1} = [ & \text{OR} & ] Elec_{n,2} = [ & \text{OR} + & E_n & ] \\ & Elec_{n-1,2}(Z) + z_{eg} & & Elec_{n,1}(Z) + & Z_n & \end{matrix}$$

[0246] R.sub.GWL is the distance of the electrode from the longitudinal axis **17LA1** and can be equal to the radius of the outer surface **1713** of the carrier **1712**. R.sub.GWL may be constant for all electrodes at least because the carrier **1712** may have an outer surface **1713** with a uniform radius.  $\theta$ .sub.OR is the angular position of the first electrode in a pair measured from a reference point which may be the electrode from a previous pair (e.g., Elec.sub.n-1,2).  $\theta$ .sub.OR may be equal to  $\theta$ .sub.Gn in FIG. **17C**.  $\theta$ .sub.En is the angle between electrodes in a pair. For example, electrodes (0,1) and (0,2) shown in FIG. **17C** are separated by angle  $\theta$ .sub.E0.  $\theta$ .sub.En can vary from emitter to emitter.  $\theta$ .sub.En can be determined using the following equation, where  $dY_{sub.n} = r_{sub.SG} * |\sin(-(\theta_{sub.P} + \theta_{sub.EM}))|$  as described in FIG. **17B**:

$$[00004] E_n = 2 * \sin^{-1} \left( \frac{\text{Math. } dY_n \cdot \text{Math.}}{2 * R_{GWL}} \right)$$

[0247] The longitudinal coordinates of the electrodes are shown with Z coordinates. For example, the longitudinal location of electrode (n,1) is the longitudinal location of the electrode in the prior emitter (Elec(n-1,2)) plus the Zeg distance (which is a function of Zspc distance). The longitudinal location of electrode (n,2) is the longitudinal location of the first electrode in the pair (Elec(n,1))

plus the  $\Delta Z_{\text{sub}.n}$  distance. In some cases, the  $\Delta Z_{\text{sub}.n}$  distance can be approximated with  $(n+1)\Delta w$ , for example such that  $(n+1)\Delta w$  is always less than  $\Delta Z_{\text{sub}.n}$ . In some cases,  $\Delta Z_{\text{sub}.n} = r_{\text{sub}.SG} * |\cos(-(\theta_{\text{sub}.P} + \theta_{\text{sub}.EM}))|$  as described in FIG. 17B.

[0248] Substituting the equations above yields the following matrices of electrode coordinates that govern electrode positions in an IVL catheter:

$$R_{\text{GWL}}$$

$$\text{Elec}_{n,1} = \begin{bmatrix} OR \\ \text{Elec}_{n-1,2}(Z) + z_{\text{eg}} \end{bmatrix}$$

$$R_{\text{GWL}}$$

$$\text{Elec}_{n,2} = \begin{bmatrix} OR + 2 * \sin^{-1} \left( \frac{\text{Math. } dY_n \cdot \text{Math.}}{-2 * R_{\text{GWL}}} \right) \\ \text{Elec}_{n,1}(Z) + r_{\text{SG}} * \text{Math. } \cos(-P + EM) \cdot \text{Math.} \end{bmatrix}$$

[0249] These matrices can be programmed into a system to form carrier openings in an IVL catheter. For example, matrices of electrode coordinates can be programmed to a laser system that can use a laser to form carrier openings and/or insulative member openings (e.g., aligned with each other) at precise locations which can be associated with and/or serve as electrodes.

[0250] The longitudinal distance Zeg between consecutive emitters can vary depending on the implementation and may be calculated as follows:

$$[00006] Z_{\text{eg}} = \frac{(l_{\text{bln}} - (2 * d_{\text{gap}}) - \text{Math. } \sum_{i=1}^n z_n)}{n\text{EM} - 1}$$

[0251] As shown in the formula above, Zeg can depend on balloon length ( $l_{\text{sub}.bln}$ ), a gap on either end of the balloon ( $d_{\text{sub}.gap}$ ), the number of emitters (nEM), and the sum of the longitudinal distances of each emitter ( $\Delta Z_n$ ). The above formula may provide the maximum distance possible that Zeg could be given the constraints (e.g., number of emitters, working length of catheter). Implementing Zeg as the greatest distance possible may ensure that emitters are maximally spaced from each other and thus evenly distributed between ends of the catheter. The minimum distance of Zeg may be a function of the spark gap distance rsg. For example, Zeg may never be less than  $5 * r_{\text{sg}}$ ,  $4 * r_{\text{sg}}$ ,  $3 * r_{\text{sg}}$ ,  $2 * r_{\text{sg}}$ ,  $1.5 * r_{\text{sg}}$ , or the like. Such a constraint may inhibit sparks from unintentionally forming between undesired electrodes because a spark may not be capable of bridging a gap greater than rsg given the thresholds (voltage, time) at which an energy generator drives the wires.

[0252] FIG. 18A is a side view of a portion of an example IVL catheter **1801** which comprises a sheath **1818**, a carrier **1812** having an outer surface **1813**, and a plurality of insulated wires **1823**. The IVL catheter **1801** can include similar structural and/or operational features as any of the other example IVL catheters shown and/or described herein.

[0253] In this example, IVL catheter **1801** has 10 wires. In some implementations, IVL catheter **1801** can have 2 wires, 3 wires, 4 wires, 5 wires, 6 wires, 7 wires, 8 wires, nine wires, 10 wires, 11 wires, 12 wires, 13 wires, 14 wires, 15 wires, between 15 and 20 wires, etc. The insulated wires **1823** can electrically connect to an energy generator and can conduct energy originating from the energy generator. The insulated wires **1823** can change voltage responsive to a change in the energy they conduct. The insulated wires **1823** can each include an electrically conductive member that is enclosed within an electrically insulative member.

[0254] The portion of the IVL catheter **1801** shown in FIG. 18A may be a distal portion. For example, the insulated wires **1823** may terminate at this distal portion shown here and may connect to an energy generator a proximal portion on the other end of the IVL catheter **1801**. The carrier **1812** tapers at this portion of the IVL catheter **1801** such that the outer surface **1813** changes diameter. The sheath **1818** extends distally beyond the insulated wires **1823**.

[0255] In this example, the insulated wires **1823** are helically wound around the sheath **1818** along a length of the IVL catheter **1801**. The insulated wires **1823** can be wound with a uniform pitch or a

variable pitch. The sheath **1818** can be formed of a flexible material that can deform responsive to force. Advantageously, the helically-wound insulated wires **1823** can provide support to the sheath **1818** such as to inhibit the guidewire from breaking when bending and to inhibit the sheath of the IVL catheter **1801** from collapsing when bending. Accordingly, the structural support provided from the helically wound insulated wires **1823** can allow for a longer IVL catheter than may otherwise be possible without such helically wound insulated wires **1823**.

[0256] FIG. **18B** is a schematic diagram illustrating example insulated wires **1823A-1823J** arranged in straight rows without being helically wound. FIG. **18B** may not be shown to scale. Insulated wires **1823A-1823J** can correspond to insulated wires **1823** of IVL catheter **1801** shown and/or described in FIG. **18A** but in a state where they are not wrapped. Although shown in straight rows in FIG. **18B**, insulated wires **1823A-1823J** can be helically wound as shown and/or described in FIG. **18A**.

[0257] Insulated wires **1823A-1823J** are symbolically divided into columns with each column representing an emitter having an electrode pair. In this example, insulated wires **1823A-1823J** form 35 emitters each shown as a distinct column. The electrodes are shown as circles within each cell of the rows and columns and the electrodes represent one or more of an exposed portion of a wire, an insulative member opening of a wire, and/or a carrier opening aligned with an exposed portion. For example, emitter **1E** is formed by an electrode in insulated wire **1823A** and an electrode in insulated wire **1823B**. Electrodes in an emitter pair, are shown as being vertically aligned which may ignore, for simplicity, any horizontal displacement between such electrodes (e.g., the dYn component shown and/or described in FIG. **17B**). However, such a dYn component may exist although not explicitly represented in this schematic diagram.

[0258] Each of the insulated wires **1823A-1823J** can form a plurality of emitters. For example, as shown, insulated wire **1823A** can form five emitters (**1E-5E**) with wires **1823B-1823F**, respectively, and each of wires **1823B-1823F** can also form an additional five emitters each. The number of emitters that can be formed from a number of wires (n) may be given by the following formula:

$$[00007]\#ofemitters = \frac{n!}{(n-2)!2!}$$

[0259] Using the above formula, the following table shows example numbers of emitters that are possible given a certain number of wires. The table below is provided as example implementations of IVL catheter with various numbers of wires and emitters.

TABLE-US-00001 # of wires 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 # of emitters 1 3 6 10 15 21 28 36 45 55 66 78 91 105 120

[0260] As shown, 45 emitters are possible in implementations with 10 wires. The example implementation of FIG. **18B** has 10 wires and 35 emitters. For example, insulated wire **1823A** may not form an emitter with wires **1823G-1823J**, and insulated wire **1823B** may not form an emitter with wires **1823H-1823J**, etc. The number emitters that are possible in the implementation of FIG. **18B** (and other implementations) can be constrained by the distance between wires. For example, the minimum distance that could be achieved between hypothetical electrodes on wires **1823A** and **1823G** may be greater than the predetermined spark gap distance that is determined for this implementation. This may be due to the size of the wires. For example, if the insulated wires **1823** have a diameter of about 0.1 mm then the center to center spacing between wires **1823A** and **1823G** would be about 0.6 mm (assuming the wires are touching adjacent wires). If the spark gap distance is less than 0.6 mm (e.g., 0.5 mm) then a spark could not be formed between insulated wire **1823A** and any of wires **1823G-1823J**. Thus, in some cases, the number of emitters that are possible for a given number of wires may be constrained from the theoretical maximum given the spark gap distance and wire gauge size.

[0261] As shown in the formula and/or table above, the number of emitters that are possible may correspond exponentially with the number of wires. Advantageously, forming a plurality of emitters from each wire (rather than only a single emitter) can reduce the number of wires and/or can increase the number of emitters on the IVL catheter. Reducing the number of wires can reduce the

size of an IVL catheter allowing for more precise intravascular treatment. Increasing the number of emitters can allow an IVL catheter to produce more sonic energy (e.g., per length of the catheter). Moreover, a plurality of emitters from each wire can increase emitter density per length of catheter. Accordingly, the systems and devices described herein can implement a long IVL catheter (e.g., longer than 60 mm, longer than 80 mm, longer than 100 mm, longer than 150 mm, longer than 200 mm, etc.) without sacrificing emitter density on the catheter and/or without requiring significantly more wires.

[0262] In some implementations, an IVL catheter can have an insulated wire with a plurality of electrodes configured to form an emitter with another insulated wire also having a plurality of electrodes. In some implementations, an IVL catheter can have a plurality of insulated wires with each wire having a plurality of electrodes, such as at least three electrodes, such that each wire can form a plurality of emitters. In some implementations, each insulated wire in an IVL catheter can have the same number of electrodes as the number of wires minus one. For example, in an IVL catheter with six wires, each of those six wires can have five electrodes. In some implementations, each wire in an IVL catheter can have a plurality of electrodes that is less than the number of wires. In some implementations, each wire may have the same number of electrodes as each of the other wires.

[0263] As shown in the table above, various IVL catheter configurations are contemplated herein wherein an IVL catheter can form at least twice as many emitters as wires, at least three times as many emitters as wires, at least four times as many emitters as wires, etc. Various IVL catheter configurations are contemplated herein that have twice as many electrodes as wires, at least three times as many electrodes as wires, at least four times as many electrodes as wires, at least five times as many electrodes as wires, etc. The number of electrodes may be twice as much as the number of emitters.

[0264] In some implementations, an IVL catheter can have at least 5 wires configured to form between 6 and 10 emitters, inclusive. In some implementations, an IVL catheter can have at least 6 wires configured to form at least 10 emitters, such as between 10 and 15 emitters inclusive. In some implementations, an IVL catheter can have at least 7 wires configured to form at least 10 emitters, such as between 10 and 21 emitters inclusive. In some implementations, an IVL catheter can have at least 8 wires configured to form at least 15 emitters, such as between 15 and 28 emitters inclusive. In some implementations, an IVL catheter can have at least 9 wires configured to form at least 25 emitters, such as between 25 and 36 emitters inclusive. In some implementations, an IVL catheter can have at least 10 wires configured to form at least 30 emitters, such as between 30 and 45 emitters inclusive.

[0265] The insulated wires **1823A-1823J** are electrically connected with energy generator **1850**. Each of the insulated wires **1823A-1823J** can be connected with energy generator **1850** independently of each of the other insulated wires, such that energy generator **1850** can drive voltage on any of the wires **1823A-1823J** without driving voltage on any of the other wires. Insulated wires **1823A-1823J** can be directly electrically connected with energy generator **1850** without any other wires, conductors, points of contact, etc. between respective insulated wires **1823** and the energy generator **1850**. A direct electrical connection can include a mechanical connection such as physical contact between the insulated wires **1823** and the energy generator **1850**. For example, there may be no gaps between the energy generator **1850** and the wires **1823A-1823J**. Accordingly, energy generator **1850** can be directly and/or independently connected to a plurality of insulated wires that is each configured to form a plurality of emitters. Each of the insulated wires **1823A-1823J** may be contiguous throughout the length of each wire. For example, insulated wire **1823A** may not have any gaps or breaks along the length of the wire **1823A** between the energy generator **1850** and one or more of the electrodes on the insulated wire **1823A**.

[0266] Energy generator **1850** can be configured to drive a voltage on any of insulated wires **1823A-1823J**. Driving a voltage on a wire can include conducting electrical current through the

wire. Energy generator **1850** can drive the voltage on a wire high or low. For example, energy generator **1850** can drive the voltage on wires **1823A-1823J** according to any of the example pulse patterns shown and/or described herein such as in FIGS. **2C-2F**. Driving a voltage on a wire can induce a voltage differential between said wire and the other wires which can cause a spark to form. Energy generator **1850** can drive voltage on two of the wires **1823A-1823J** simultaneously. For example, energy generator **1850** can drive the voltage on one of the wires **1823A-1823J** high while driving the voltage on another one of the wires **1823A-1823J** low. Driving the voltage on two wires (e.g., high and low) can cause a single spark to form between the wires. The voltage differential between two wires that are driven high and low respectively may be greater than the voltage differential between other wires. For example, energy generator **1850** can drive a voltage on insulated wire **1823A** (either high or low) and can simultaneously drive a voltage on insulated wire **1823F** (with an opposite polarity of insulated wire **1823A** and which may or may not be equal in magnitude to the voltage on insulated wire **1823A**). Accordingly, a voltage differential can form between insulated wires **1823A** and **1823F** which may be greater than a voltage differential between any other two wires. If said voltage differential between insulated wires **1823A** and **1823F** exceeds a threshold sufficient to form a spark, a spark can form between electrodes on insulated wires **1823A** and **1823F**.

[0267] The voltage at which the energy generator **1850** drives the wires **1823A-1823J** may correspond to a spark gap distance which may be the same for all emitters. For example, the energy generator **1850** can be programmed with limits to constrain the voltage at which it drives the wires within certain thresholds to avoid causing sparks between unintentional electrodes (e.g., a non-emitter pair of electrodes). Thus, for example, driving insulated wire **1823A** and insulated wire **1823C** can induce a voltage differential the two wires, however, said voltage differential may only be sufficient to induce a spark at emitter **2E** but may not be sufficient to induce a spark between the electrode on wire **1823C** in emitter **2E** and the electrode on wire **1823A** in emitter **3E** (which is a non-emitter pair), at least because the distance between those electrodes is greater than the spark gap distance between the electrodes in emitter **2E**.

[0268] Energy generator **1850** can drive voltage on any of the wires **1823A-1823J** to selectively cause a spark to form at any of emitters **1E-35E** without causing a spark to form at any of the other emitters. Thus, energy generator **1850** can cause sparks to form one at a time. Energy generator **1850** can drive voltage on wires **1823** in rapid succession to cause sparks to form in rapid succession. For example, energy generator **1850** can cause sparks to form sequentially within microseconds, milliseconds, or centiseconds of each other.

[0269] When energy generator **1850** drives one of the wires **1823** with a high voltage and another with a low voltage to form a spark, an electrical current can travel distally away from the generator **1850** down a live wire and can return proximally toward the energy generator **1850** via a return wire. For example, if the energy generator **1850** drives wires **1823A** and **1823B** high and low respectively, electrical current can travel from energy generator **1850** to emitter **1E** via wire **1823A** which acts as the live wire. The electrical current can continue to travel from wire **1823A** to wire **1823B** in the form of a spark that bridges the gap between electrodes in emitter **1E**. Electrical current can travel from emitter **1E** to energy generator **1850** via wire **1823B** which acts as the return wire. Accordingly, any of wires **1823A-1823J** can act as either a live wire conducting current from the energy generator **1850** or can act as a return wire conducting energy to the energy generator **1850**. Moreover, insulated wires **1823** can alternate between acting as live wire or return wire depending on which of the wires the energy generator **1850** drives with voltage. In some implementations, return wire and ground wire may be used interchangeably.

[0270] Although FIG. **18B** is not shown to scale, the horizontal distribution of the electrodes may be representative. For example, on insulated wire **1823C**, the electrode in emitter **11E** may be closer to the electrode in emitter **12E** than to the electrode in emitter **6E**. Accordingly, the electrodes on insulated wire **1823C** are non-uniformly distributed along wire **1823C**. This may be

the case for one or more of the insulated wires **1823**. On wire **1823A**, the electrodes may be uniformly distributed from each other along the wire **1823A** such that the distance between each of the electrodes on wire **1823A** is the same. In some implementations, the wires **1823A-1823J** may all be the same length.

[0271] Wires **1823A-1823J** may be defined by a distal end identified by the emitter that is most distal to the energy generator **1850** (e.g., emitter **1E**) and a proximal end identified by the emitter that is the most proximal to the energy generator **1850** (e.g., emitter **35E**). For one or more of the wires **1823A-1823J**, the distance between the most proximal emitter of that wire and the proximal end of the wires is between 25% to 50%, or at least 50% of the distance between the proximal and distal ends of the wires **1823**. This can be seen in at least wires **1823A-1823C** where emitters **5E**, **10E**, and **15E**, respectively, are more than half the distance from the proximal end on the right to the distal end on the left. For one or more of the wires **1823A-1823J**, the distance between the most distal emitter of that wire and the distal end of the wires is between 25% to 50%, or at least 50% of the distance between the proximal and distal ends of the wires **1823**. This can be seen in at least wires **1823I-1823J** where emitters **20E** and **25E**, respectively, are more than half the distance from the distal end on the left to the proximal end on the right. In some implementations, at least half the length of one or more of the wires **1823** may not have any electrodes. For example, at least half the length of insulated wire **1823A** has no electrodes between emitter **5E** and the proximal end shown on the right toward the energy generator **1850**.

[0272] The distance from the proximal end demarcated by emitter **35E** and the distal end demarcated by emitter **1E** may be between 40 mm and 250 mm, between 40 mm and 220 mm, between 40 mm and 150 mm, between 40 mm and 100 mm, between 40 mm and 80 mm, between 60 mm and 220 mm, between 80 mm and 220 mm, between 100 mm and 220 mm, between 100 mm and 200 mm, between 100 mm and 180 mm, between 100 mm and 150 mm, between 150 and 200 mm, or any length therebetween. These example distances may also apply if the wires **1823A-1823J** are wrapped around a sheath in an IVL catheter. Thus, an IVL catheter can have 35 emitters spanning 200 mm, for example. Or in other words, an emitter spaced about every 5.7 mm along a longitudinal distance of the IVL catheter.

[0273] In FIG. **18B**, the bottom three rows beneath the rows of wires **1823** show angular and longitudinal distances between the electrodes and/or emitters of the insulated wires **1823** which are provide as non-limiting examples.  $\theta_{sub.En}$  shows the angle between electrodes in a pair.  $\theta_{sub.Gn}$  shows the angle between consecutive emitters. In this example,  $\theta_{sub.En} + \theta_{sub.Gn}$  equals  $120^\circ$  for each emitter. In some implementations, the sum of  $\theta_{sub.En}$  and  $\theta_{sub.Gn}$  can vary between one or more emitters. In some implementations,  $\theta_{sub.Gn}$  can be the same for each emitter. Zeg shows the longitudinal distance between consecutive emitters. In this example, the longitudinal distance between each emitter is 5.7 mm. These bottom three rows showing angular and longitudinal separation can be provided as instructions when forming the electrodes and/or emitters and can be interpreted from top to bottom and from left to right. For example, at emitter **1E**, the electrode can be formed on wire **1823A**, then the IVL catheter can be rotated  $60^\circ$  (the  $\theta_{sub.E1}$  angle). At this stage of the process in some aspects, the IVL catheter can be longitudinally translated by a distance of Zn as shown and/or described in FIGS. **17A-17B**. The other electrode in emitter **1E** can then be formed on wire **1823B**. After both electrodes of emitter **1E** are formed, the IVL catheter can be rotated  $60^\circ$  (the  $\theta_{sub.G1}$  angle) and translated longitudinally 5.7 mm to emitter **2E** where the electrode on wire **1823A** can be formed. This process can continue until all electrodes are formed for all emitters **1E-35E**.

[0274] FIG. **19** is a flowchart of a process of making an IVL catheter, or portions thereof. At block **1901**, a sheath can be provided that has a lumen that can received a guidewire therethrough. At block **1903** one or more insulated wires can be wrapped around the sheath. The insulated wires can be helically wrapped with a uniform pitch or with a pitch that varies. At block **1905**, the one or more insulated wires can optionally be encased within a carrier that encases the wires and the



sheath.

[0275] At block **1907**, a first electrode of an nth emitter can be formed. Forming an electrode can include forming an insulative member opening within an insulative member of an insulated wire to expose a portion of an electrically conductive member of the insulated wire. In implementations with a carrier, forming an electrode can include forming a carrier opening. The carrier opening can be aligned with the insulative member opening and/or exposed portion of the insulated wire. A laser can form the electrode (e.g., the carrier opening, insulative member opening, and/or exposed portion). For example, the electrode can be formed with a laser etching process that removes portions of the carrier and/or insulative member with optical energy from a laser. In some implementations, the carrier opening can be formed at the same time (e.g., immediately before and/or during a same procedure) as the insulative member opening and/or exposed portion. For example, a laser can form a carrier opening and then can proceed to form the insulative member opening immediately thereafter such as without modifying the energy or position of the laser. Forming the carrier opening and the insulative member openings with the same laser beam can ensure that the carrier opening is aligned with the insulative member opening which can ensure that the exposed portion is exposed through the carrier opening and moreover that each of the exposed portions of the various electrodes have the same amount of surface area that is exposed through the various carrier openings which can ensure consistent energy differentials required to form spark gaps at the various emitters.

[0276] At block **1909**, the sheath together with the one or more insulated wires wrapped around thereon can be rotated and/or translated. In some implementations, such as when using a laser to form electrodes, the sheath may remain stationary while a laser travels relative to the sheath and/or wires. Rotating can include any of the example  $\theta_{sub.E}$  angles shown and/or discussed herein. Translating can include any of the example  $(n+1)_w$  distances shown and/or discussed herein.

[0277] At block **1911**, a second electrode of the nth can be formed which may be similar to how the first electrode was formed.

[0278] At block **1913**, the sheath together with the one or more insulated wires wrapped around thereon can be rotated and/or translated, whether actually moved or an electrode forming device or system is moved relative to it. Rotating can include any of the example  $\theta_{sub.EG}$  angles shown and/or discussed herein. Translating can include any of the example  $Z_{eg}$  distances shown and/or discussed herein.

[0279] The process can continue to iterate through any of blocks **1907-1913** until all of the electrodes and/or emitters have been formed. In some implementations, blocks **1907-1913** can be performed before the wires have been wrapped around the sheath at block **1903** and/or before the carrier encases the insulated wires at block **1905**. As such, carrier openings can be formed after exposed portions have been formed in some aspects.

#### I. Additional Considerations

[0280] All of the U.S. patents, U.S. patent application publications, U.S. patent applications, foreign patents, foreign patent applications and non-patent publications referred to in this specification and/or listed in the Application Data Sheet, are incorporated herein by reference, in their entirety. Such documents may be incorporated by reference for the purpose of describing and disclosing, for example, materials and methodologies described in the publications, which might be used in connection with the present disclosure. The publications discussed above and throughout the text are provided solely for their disclosure prior to the filing date of the present application. Nothing herein is to be construed as an admission that the inventors are not entitled to antedate any referenced publication by virtue of prior invention.

[0281] Although certain implementations and examples have been described herein, it will be understood by those skilled in the art that many aspects of the systems and devices shown and described in the present disclosure may be differently combined and/or modified to form still further implementations or acceptable examples. All such modifications and variations are intended

to be included herein within the scope of this disclosure. A wide variety of designs and approaches are possible. No feature, structure, or step disclosed herein is essential or indispensable. The various features and processes described herein may be used independently of one another, or may be combined in various ways. For example, elements may be added to, removed from, or rearranged compared to the disclosed example implementations. All possible combinations and sub-combinations are intended to fall within the scope of this disclosure.

[0282] Any methods and processes described herein are not limited to any particular sequence, and the blocks or states relating thereto can be performed in other sequences that are appropriate. For example, described blocks or states may be performed in an order other than that specifically disclosed, or multiple blocks or states may be combined in a single block or state, or certain method or process blocks may be omitted, or certain blocks or states may be performed in a reverse order from what is shown and/or described. The example blocks or states may be performed in serial, in parallel, or in some other manner. Blocks or states may be added to or removed from the disclosed example implementations.

[0283] The methods disclosed herein may include certain actions taken by a practitioner; however, they can also include any third-party instruction of those actions, either expressly or by implication.

[0284] The methods and tasks described herein may be performed and fully automated by a computer system. The computer system may, in some cases, include multiple distinct computers or computing devices (e.g., physical servers, workstations, storage arrays, cloud computing resources, etc.) that communicate and interoperate over a network to perform the described functions. Each such computing device typically includes a processor (or multiple processors) that executes program instructions or modules stored in a memory or other non-transitory computer-readable storage medium or device (e.g., solid state storage devices, disk drives, etc.). The various functions disclosed herein may be embodied in such program instructions, and/or may be implemented in application-specific circuitry (e.g., ASICs or FPGAs) of the computer system. Where the computer system includes multiple computing devices, these devices may, but need not, be co-located. The results of the disclosed methods and tasks may be persistently stored by transforming physical storage devices, such as solid state memory chips and/or magnetic disks, into a different state. The computer system may be a cloud-based computing system whose processing resources are shared by multiple distinct entities or other users. The systems and modules may also be transmitted as generated data signals (for example, as part of a carrier wave or other analog or digital propagated signal) on a variety of computer-readable transmission mediums, including wireless-based and wired/cable-based mediums, and may take a variety of forms (for example, as part of a single or multiplexed analog signal, or as multiple discrete digital packets or frames).

[0285] Many other variations than those described herein will be apparent from this disclosure. For example, depending on the implementation, certain acts, events, or functions of any of the algorithms described herein can be performed in a different sequence, can be added, merged, or left out altogether (for example, not all described acts or events are necessary for the practice of the algorithms). Moreover, in certain implementations, acts or events can be performed concurrently, for example, through multi-threaded processing, interrupt processing, or multiple processors or processor cores or on other parallel architectures, rather than sequentially. In addition, different tasks or processes can be performed by different machines and/or computing systems that can function together.

[0286] Various illustrative logical blocks, modules, routines, and algorithm steps that may be described in connection with the disclosure herein can be implemented as electronic hardware (e.g., ASICs or FPGA devices), computer software that runs on computer hardware, or combinations of both. Various illustrative components, blocks, and steps may be described herein generally in terms of their functionality. Whether such functionality is implemented as specialized hardware versus software running on general-purpose hardware depends upon the particular application and design constraints imposed on the overall system. The described functionality can be implemented in

varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the disclosure.

[0287] Moreover, various illustrative logical blocks and modules that may be described in connection with the implementations disclosed herein can be implemented or performed by a machine, such as a general purpose processor, a digital signal processor (“DSP”), an application specific integrated circuit (“ASIC”), a field programmable gate array (“FPGA”) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor can be a microprocessor, controller, microcontroller, or state machine, combinations of the same, or the like.

[0288] A processor can include electrical circuitry configured to process computer-executable instructions. A processor can include an FPGA or other programmable devices that performs logic operations without processing computer-executable instructions. A processor can also be implemented as a combination of computing devices, for example, a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration. Although described herein primarily with respect to digital technology, a processor may also include primarily analog components. For example, some, or all, of the signal processing algorithms described herein may be implemented in analog circuitry or mixed analog and digital circuitry. A computing environment can include any type of computer system, including, but not limited to, a computer system based on a microprocessor, a mainframe computer, a digital signal processor, a portable computing device, a device controller, or a computational engine within an appliance, to name a few.

[0289] The elements of any method, process, routine, or algorithm described in connection with the disclosure herein can be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module can reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, hard disk, a removable disk, a CD-ROM, or any other form of a non-transitory computer-readable storage medium. An exemplary storage medium can be coupled to the processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium can be integral to the processor. The storage medium can be volatile or nonvolatile. The processor and the storage medium can reside in an ASIC. The ASIC can reside in a user terminal. In the alternative, the processor and the storage medium can reside as discrete components in a user terminal.

[0290] Conditional language used herein, such as, among others, “can,” “could,” “might,” “may,” “e.g.,” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain features, elements, and/or steps are optional. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required or that one or more embodiments necessarily include logic for deciding, with or without other input or prompting, whether these features, elements, and/or steps are included or are to be always performed. The terms “comprising,” “including,” “having,” and the like are synonymous and are used inclusively, in an open-ended fashion, and do not exclude additional elements, features, acts, operations, and so forth. Also, the term “or” is used in its inclusive sense (and not in its exclusive sense) so that when used, for example, to connect a list of elements, the term “or” means one, some, or all of the elements in the list. Further, the term “each,” as used herein, in addition to having its ordinary meaning, can mean any subset of a set of elements to which the term “each” is applied.

[0291] Conjunctive language such as the phrase “at least one of X, Y, and Z,” unless specifically stated otherwise, is otherwise understood with the context as used in general to convey that an item, term, etc. may be either X, Y, or Z. Thus, such conjunctive language is not generally intended to imply that certain embodiments require the presence of at least one of X, at least one of Y, and at

least one of Z.

[0292] Language of degree used herein, such as the terms “approximately,” “about,” “generally,” and “substantially” as used herein represent a value, amount, or characteristic close to the stated value, amount, or characteristic that still performs a desired function or achieves a desired result. For example, the terms “approximately,” “about,” “generally,” and “substantially” may refer to an amount that is within less than 10% of, within less than 5% of, within less than 1% of, within less than 0.1% of, and within less than 0.01% of the stated amount. As another example, in certain embodiments, the terms “generally parallel” and “substantially parallel” refer to a value, amount, or characteristic that departs from exactly parallel by less than or equal to 10 degrees, 5 degrees, 3 degrees, or 1 degree. As another example, in certain embodiments, the terms “generally perpendicular” and “substantially perpendicular” refer to a value, amount, or characteristic that departs from exactly perpendicular by less than or equal to 10 degrees, 5 degrees, 3 degrees, or 1 degree.

[0293] As used herein, “real-time” or “substantial real-time” may refer to events (e.g., receiving, processing, transmitting, displaying etc.) that occur at a same time as each other, during a same time as each other, or overlap in time with each other. “Real-time” may refer to events that occur at distinct or non-overlapping times the difference between which is imperceptible and/or inconsequential to humans such as delays arising from electrical conduction or transmission. A human may perceive real-time events as occurring simultaneously, regardless of whether the real-time events occur at an exact same time. As a non-limiting example, “real-time” may refer to events that occur within a time frame of each other that is on the order of milliseconds, seconds, tens of seconds, or minutes. For example, “real-time” may refer to events that occur within a time frame of less than 1 minute, less than 30 seconds, less than 10 seconds, less than 1 second, less than 0.05 seconds, less than 0.01 seconds, less than 0.005 seconds, less than 0.001 seconds, etc.

[0294] Unless otherwise explicitly stated, articles such as “a” or “an” should generally be interpreted to include one or more described items. Accordingly, phrases such as “a device configured to” are intended to include one or more recited devices. Such one or more recited devices can also be collectively configured to carry out the stated recitations. For example, “a processor configured to carry out recitations A, B and C” can include a first processor configured to carry out recitation A working in conjunction with a second processor configured to carry out recitations B and C.

[0295] As used herein, “system,” “instrument,” “apparatus,” and “device” generally encompass both the hardware (for example, mechanical and electronic) and, in some implementations, associated software (for example, specialized computer programs for operational control) components.

[0296] It should be emphasized that many variations and modifications may be made to the herein-described implementations, the elements of which are to be understood as being among other acceptable examples. All such modifications and variations are intended to be included herein within the scope of this disclosure. Any section headings used herein are merely provided to enhance readability and are not intended to limit the scope of the implementations disclosed in a particular section to the features or elements disclosed in that section. The foregoing description details certain implementations. It will be appreciated, however, that no matter how detailed the foregoing appears in text, the systems and methods can be practiced in many ways. As is also stated herein, it should be noted that the use of particular terminology when describing certain features or aspects of the systems and methods should not be taken to imply that the terminology is being re-defined herein to be restricted to including any specific characteristics of the features or aspects of the systems and methods with which that terminology is associated.

[0297] Those of skill in the art would understand that information, messages, and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced

throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[0298] While the above detailed description has shown, described, and pointed out novel features, it can be understood that various omissions, substitutions, and changes in the form and details of the devices or algorithms illustrated can be made without departing from the spirit of the disclosure. As can be recognized, certain portions of the description herein can be embodied within a form that does not provide all of the features and benefits set forth herein, as some features can be used or practiced separately from others. The scope of certain embodiments disclosed herein is indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

## II. Example Clauses

[0299] Examples of the implementations of the present disclosure can be described in view of the following example clauses. The features recited in the below example implementations can be combined with additional features disclosed herein. Furthermore, additional inventive combinations of features are disclosed herein, which are not specifically recited in the below example implementations, and which do not include the same features as the specific implementations below. For sake of brevity, the below example implementations do not identify every inventive aspect of this disclosure. The below example implementations are not intended to identify key features or essential features of any subject matter described herein. Any of the example clauses below, or any features of the example clauses, can be combined with any one or more other example clauses, or features of the example clauses or other features of the present disclosure.

[0300] Clause 1. An intravascular lithotripsy system configured to modify calcified plaque within a blood vessel of a subject, the system comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire coupled to the sheath and comprising an electrically conductive member, an insulative member encasing the electrically conductive member, a first insulative member opening forming a first exposed portion of the first insulated wire, and a second insulative member opening forming a second exposed portion of the first insulated wire; a second insulated wire coupled to the sheath and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, a first insulative member opening forming a first exposed portion of the second insulated wire, and a second insulative member opening forming a second exposed portion of the second insulated wire; a third insulated wire coupled to the sheath and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the third insulated wire, a first insulative member opening forming a first exposed portion of the third insulated wire, and a second insulative member opening forming a second exposed portion of the third insulated wire, wherein the first insulated wire is helically wound around the sheath, wherein the second insulated wire is helically wound around the sheath adjacent to the first insulated wire, wherein the third insulated wire is helically wound around the sheath, adjacent to the second insulated wire; and an energy generator configured to: induce a first spark between the first exposed portion of the first insulated wire and the first exposed portion of the second insulated wire; induce a second spark between the second exposed portion of the first insulated wire and the first exposed portion of the third insulated wire; and induce a third spark between the second exposed portion of the second insulated wire and the second exposed portion of the third insulated wire, wherein the first insulated wire is directly electrically connected with the energy generator independently from the second and third insulated wires and configured to conduct current between the energy generator and the second exposed portion of the first insulated wire past the first exposed portion of the first insulated wire when forming the second spark without forming the first spark, wherein the second insulated wire is directly electrically connected with the energy generator independently from the first and third insulated wires and configured to conduct current between the energy generator and

the second exposed portion of the second insulated wire past the first exposed portion of the second insulated wire when forming the third spark without forming the first spark, wherein the third insulated wire is directly electrically connected with the energy generator independently from the second and second insulated wires and configured to conduct current between the energy generator and the second exposed portion of the third insulated wire past the first exposed portion of the third insulated wire when forming the third spark without forming the second spark.

[0301] Clause 2. The intravascular lithotripsy system of Clause 1, wherein the energy generator is configured to conduct current to the first, second, or third insulated wires without a dedicated return wire.

[0302] Clause 3. The intravascular lithotripsy system of any of Clauses 1-2, wherein the energy generator is configured to drive voltage on the first, second, and third insulated wires independently to cause the first, second, and third insulated wires to transition between operating at least as a live wire conducting current from the energy generator or as a return wire conducting current to the energy generator.

[0303] Clause 4. The intravascular lithotripsy system of any of Clauses 1-3, wherein the energy generator is configured to drive voltage on the first and second insulated wires without driving voltage on the third insulated wire to induce the first spark without inducing the second spark and the third spark.

[0304] Clause 5. The intravascular lithotripsy system of any of Clauses 1-4, wherein a first distance between the first exposed portion of the first insulated wire and the first exposed portion of the second insulated wire is less than a second distance between the second exposed portion of the first insulated wire and the first exposed portion of the second insulated wire, wherein the energy generator is configured to induce a voltage differential between the first and second insulated wires within a threshold sufficient to induce the first spark over the first distance and insufficient to induce a fourth spark over the second distance.

[0305] Clause 6. The intravascular lithotripsy system of any of Clauses 1-5, wherein a first distance between the first exposed portion of the first insulated wire and the first exposed portion of the second insulated wire is the same as a second distance between the second exposed portion of the second insulated wire and the second exposed portion of the third insulated wire thereby allowing the first and third sparks to form responsive to a same voltage differential caused by the energy generator.

[0306] Clause 7. The intravascular lithotripsy system of any of Clauses 1-6, wherein the first exposed portion of the first insulated wire is circumferentially offset from the second exposed portion of the first insulated wire around an outer surface of the sheath.

[0307] Clause 8. The intravascular lithotripsy system of any of Clauses 1-7, wherein the first, second, and third insulated wires are a same length.

[0308] Clause 9. The intravascular lithotripsy system of any of Clauses 1-8, wherein the second insulated wire extends alongside and contacts the first and third insulated wires.

[0309] Clause 10. The intravascular lithotripsy system of any of Clauses 1-9, wherein a distance between the second exposed portion of the first insulated wire and a proximal end of the first insulated wire is at least half a distance between the first exposed portion of the first insulated wire and the proximal end of the first insulated wire.

[0310] Clause 11. The intravascular lithotripsy system of any of Clauses 1-10, wherein the first insulated wire comprises a proximal insulative member opening forming a proximal exposed portion of the first insulated wire, wherein a distance between the first and proximal exposed portions of the first insulated wire is less than a distance between the proximal exposed portion and a proximal end of the first insulated wire.

[0311] Clause 12. The intravascular lithotripsy system of any of Clauses 1-11, further comprising: a fourth insulated wire coupled to the sheath and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the fourth insulated wire, and at

least three insulative member openings forming at least three exposed portions of the fourth insulated wire; and wherein the first insulated wire comprises a third insulative member opening forming a third exposed portion of the first insulated wire; wherein the energy generator is directly electrically connected with the fourth insulated wire and configured to: induce a fourth spark between the third exposed portion of the first insulated wire and the at least three exposed portions of the fourth insulated wire.

[0312] Clause 13. The intravascular lithotripsy system of Clause 12, wherein the first, second, third, and fourth exposed portions of the first insulated wire are uniformly spaced.

[0313] Clause 14. The intravascular lithotripsy system of any of Clauses 12-13, wherein the second insulated wire comprises a third insulative member opening forming a third exposed portion of the second insulated wire, wherein the energy generator is configured to: induce a sixth spark between the third exposed portion of the second insulated wire and the at least three exposed portions of the fourth insulated wire.

[0314] Clause 15. The intravascular lithotripsy system of Clause 14, wherein the first, second, third, and fourth exposed portions of the second insulated wire are non-uniformly spaced.

[0315] Clause 16. The intravascular lithotripsy system of any of Clauses 1-15, further comprising a balloon around at least a portion of the sheath and configured to be expanded with a conductive fluid configured to conduct a sonic wave originating from the spark, wherein the exposed portions of the first and second insulated wires are exposed to the conductive fluid at least when the balloon is expanded, wherein no portion of the balloon contacts the exposed portions of the first and second insulated wires.

[0316] Clause 17. The intravascular lithotripsy system of Clause 16, wherein the balloon is coated with medication.

[0317] Clause 18. The intravascular lithotripsy system of any of Clauses 1-17, wherein: the first insulated wire is wound around the sheath with a first pitch; and the second insulated wire is wound around the sheath with a second pitch that is substantially equal to the first pitch.

[0318] Clause 19. The intravascular lithotripsy system of any of Clauses 1-18, wherein the first insulated wire is wound around the sheath with a uniform pitch along the sheath.

[0319] Clause 20. The intravascular lithotripsy system of any of Clauses 1-19, wherein the first insulated wire is wound around the sheath with a variable pitch along the sheath.

[0320] Clause 21. The intravascular lithotripsy system of any of Clauses 1-20, wherein the first and second insulated wires are removably electrically connected to the energy generator.

[0321] Clause 22. The intravascular lithotripsy system of any of Clauses 1-21, further comprising a carrier encasing the first and second insulated wires and the sheath, the carrier comprising: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire.

[0322] Clause 23. The intravascular lithotripsy system of Clause 22, wherein the first and second carrier openings are configured such that the exposed portions of the electrically conductive member are not covered by the carrier.

[0323] Clause 24. The intravascular lithotripsy system of any of Clauses 1-23, wherein each of the first, second, and third, insulated wires is capable of forming a spark with each of the other insulated wires.

[0324] Clause 25. An intravascular lithotripsy system configured to modify calcified plaque within a blood vessel of a subject, the system comprising: a sheath comprising a lumen configured to receive a guidewire; at least three insulated wires, each of the at least three insulated wires comprising at least two exposed portions spaced from one another along a length of the insulated wire, wherein the at least three insulated wires are helically wound around an outer surface of the sheath and independently electrically connected with an energy generator, the exposed portions of the at least three insulated wires defining a plurality of emitters spaced from one another along a

length of the sheath and independently operable by the energy generator; and the energy generator configured to induce a spark via each of the plurality of emitters.

[0325] Clause 26. The intravascular lithotripsy system of Clause 25, wherein the plurality of emitters comprises: a first emitter defined by a first exposed portion of a first one of the at least three insulated wires and a first exposed portion of a second one of the at least three insulated wires; a second emitter defined by a second exposed portion of the first one of the at least three insulated wires and a first exposed portion of a third one of the at least three insulated wires; and a third emitter defined by a second exposed portion of the second one of the at least three insulated wires and a second exposed portion of the third one of the at least three insulated wires.

[0326] Clause 27. The intravascular lithotripsy system of Clause 25, wherein each of the at least three insulated wires is configured to form at least one of the plurality of emitters with each of the other at least three insulated wires.

[0327] Clause 28. The intravascular lithotripsy system of Clause 25, wherein the plurality of emitters are formed from the at least three insulated wires without any other insulated wires.

[0328] Clause 29. The intravascular lithotripsy system of Clause 25, wherein the at least three insulated wires comprises at least four insulated wires, wherein the plurality of emitters comprises more emitters than the at least four insulated wires.

[0329] Clause 30. The intravascular lithotripsy system of Clause 25, wherein the at least three insulated wires does not include a dedicated return wire.

[0330] Clause 31. An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject, the intravascular lithotripsy catheter comprising: [0331] a sheath comprising a lumen configured to receive a guidewire, wherein a longitudinal axis of the intravascular lithotripsy catheter extends through the lumen; a first insulated wire wound around and contacting an outer surface of the sheath, the first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire wound around and contacting the outer surface of the sheath, the second insulated wire arranged adjacent the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; wherein the exposed portion of the second insulated wire is circumferentially offset from the exposed portion of the first insulated wire by an angle originating at the longitudinal axis; wherein the exposed portion of the second insulated wire is longitudinally offset from the exposed portion of the first insulated wire by a longitudinal distance extending along the intravascular lithotripsy catheter parallel to the longitudinal axis; and a carrier encasing the first and second insulated wires and the sheath, the carrier comprising: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire; wherein the intravascular lithotripsy catheter is configured to be electrically connected to an energy generator that is operable to cause a spark to travel longitudinally along the intravascular lithotripsy catheter and circumferentially around the intravascular lithotripsy catheter between the exposed portions of the first and second insulated wires.

[0332] Clause 32. The intravascular lithotripsy catheter of Clause 31, wherein the carrier comprises an inner surface configured to contact the first and second insulated wires and an outer surface opposite the inner surface, wherein the intravascular lithotripsy catheter is configured such that the spark travels from the exposed portion of the first insulated wire, through the first carrier opening, above the outer surface of the carrier, through the second carrier opening, and to the exposed portion of the second insulated wire.

[0333] Clause 33. The intravascular lithotripsy catheter of any of Clauses 31-32, wherein the



carrier has a fixed volume.

[0334] Clause 34. The intravascular lithotripsy catheter of any of Clauses 31-33, wherein the carrier comprises a different material than at least one of the electrically conductive members of the insulated wires or the sheath.

[0335] Clause 35. The intravascular lithotripsy catheter of any of Clauses 31-34, wherein the first and second carrier openings are configured such that the exposed portions of the electrically conductive member are not covered by the carrier.

[0336] Clause 36. The intravascular lithotripsy catheter of any of Clauses 31-35, further comprising a balloon configured to hold conductive fluid around at least a portion of the sheath, wherein the carrier inhibits the balloon from contacting the exposed portions of the electrically conductive members of the first and second insulated wires, wherein the exposed portions of the electrically conductive members of the first and second insulated wires are exposed to the conductive fluid.

[0337] Clause 37. The intravascular lithotripsy catheter of Clause 36, wherein the carrier is configured to separate the balloon from the exposed portions of the electrically conductive members of the first and second insulated wires.

[0338] Clause 38. The intravascular lithotripsy catheter of Clause 36, wherein the balloon is coated with medication.

[0339] Clause 39. The intravascular lithotripsy catheter of any of Clauses 31-38, wherein: the first insulated wire is wound around the outer surface of the sheath with a first pitch; and the second insulated wire is wound around the outer surface of the sheath with a second pitch that is substantially equal to the first pitch.

[0340] Clause 40. The intravascular lithotripsy catheter of any of Clauses 31-39, wherein the first insulated wire is wound around the outer surface of the sheath with a uniform pitch along the sheath.

[0341] Clause 41. The intravascular lithotripsy catheter of any of Clauses 31-40, wherein the first insulated wire is wound around the outer surface of the sheath with a variable pitch along the sheath.

[0342] Clause 42. The intravascular lithotripsy catheter of any of Clauses 31-41, further comprising an energy generator configured to: induce an energy differential between (i) the exposed portion of the electrically conductive member of the first insulated wire and (ii) the exposed portion of the electrically conductive member of the second insulated wire to induce the spark between the exposed portions of the electrically conductive members of the first and second insulated wires.

[0343] Clause 43. The intravascular lithotripsy catheter of Clause 42, wherein the first and second insulated wires are removably electrically connected to the energy generator.

[0344] Clause 44. An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject, the intravascular lithotripsy catheter comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire arranged adjacent the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; and a longitudinal axis extending through the sheath; wherein the first and second insulated wires are wrapped around the sheath such that: the exposed portion of the second insulated wire is arranged at a different longitudinal location than the exposed portion of the first insulated wire relative to said longitudinal axis relative to said longitudinal axis; the exposed portion of the second insulated wire is arranged at a different angular location than the exposed portion of the first insulated wire relative to a plane defined normal to said longitudinal axis.

[0345] Clause 45. The intravascular lithotripsy catheter of Clause 44, wherein the first and second

insulated wires are configured to be electrically connected to an energy generator that is operable to cause a spark to travel: longitudinally along the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire; and circumferentially around the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire.

[0346] Clause 46. The intravascular lithotripsy catheter of any of Clauses 44-45, wherein: the first insulated wire is wound around the sheath with a first pitch; and the second insulated wire is wound around the sheath with a second pitch that is substantially equal to the first pitch.

[0347] Clause 47. An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject, the intravascular lithotripsy catheter comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; and a longitudinal axis extending through the sheath; wherein the first and second insulated wires are wrapped around the sheath such that: a transverse cross-section through the intravascular lithotripsy catheter that is perpendicular to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire; and a longitudinal cross-section through the intravascular lithotripsy catheter that is parallel to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire.

[0348] Clause 48. The intravascular lithotripsy catheter of Clause 47, wherein the first and second insulated wires are configured to be electrically connected to an energy generator that is operable to cause a spark to travel: longitudinally along the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire; and circumferentially around the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire.

[0349] Clause 49. The intravascular lithotripsy catheter of any of Clauses 47-48, wherein: the first insulated wire is wound around the sheath with a first pitch; and the second insulated wire is wound around the sheath with a second pitch that is substantially equal to the first pitch.

[0350] Clause 50. An intravascular lithotripsy system configured to modify calcified plaque within a blood vessel of a subject, the system comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire helically wound around and contacting an outer surface of the sheath, the first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the first insulated wire; a second insulated wire helically wound around and contacting the outer surface of the sheath, the second insulated wire arranged adjacent to, and in contact with, the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the second insulated wire, wherein the second insulated wire is helically wound parallel to the first insulated wire; and an energy generator electrically connected with the first and second insulated wires and configured to: induce a voltage differential between (i) the exposed portion of the first insulated wire and (ii) the exposed portion of the second insulated wire; and cause said voltage differential to exceed a threshold to induce a spark between the exposed portions of the first and second insulated wires.

[0351] Clause 51. The system of Clause 50, wherein: said energy differential is a first energy differential; said insulative member opening of the first insulated wire is a first insulative member opening of the first insulated wire and said exposed portion of the first insulated wire is a first

exposed portion of the first insulated wire; said first insulated wire further comprises a second insulative member opening forming a second exposed portion of the first insulated wire; the system further comprises a third insulated wire helically wound around and contacting the outer surface of the sheath, the third insulated wire arranged adjacent one of the first or second insulated wires and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the third insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the third insulated wire; and the energy generator is electrically connected with the third insulated wire and further configured to: induce a second voltage differential between (i) the second exposed portion of the first insulated wire and (ii) the exposed portion of the third insulated wire; and cause said second energy differential to exceed the energy threshold to induce a spark between the second exposed portion of the first insulated wire and the exposed portion of the third insulated wire.

[0352] Clause 52. The system of Clause 51, wherein the first voltage differential is the same amount of energy as the second voltage differential.

[0353] Clause 53. The system of any of Clauses 51-52, wherein each of the first, second, and third insulated wires are independently electrically connected to the energy generator.

[0354] Clause 54. The system of any of Clauses 51-53, wherein the sheath comprises a length; and the first and second exposed portions of the first insulated wire and the exposed portions of the second and third insulated wires are arranged such that: the spark induced between the first exposed portion of the first insulated wire and the exposed portion of the second insulated wire is induced at a first location along the length of the sheath; the spark induced between the second exposed portion of the first insulated wire and the exposed portion of the third insulated wire is induced at a second location along the length of the sheath; and the second location is spaced from the first location.

[0355] Clause 55. The system of any of Clauses 51-54, wherein the system is configured to cause said first energy differential between (i) the first exposed portion of the first insulated wire and (ii) the exposed portion of the second insulated wire without causing said second energy differential between (i) the second exposed portion of the first insulated wire and (ii) the exposed portion of the third insulated wire.

[0356] Clause 56. The system of any of Clauses 51-55, wherein: said insulative member opening of the second insulated wire is a first insulative member opening of the second insulated wire and said exposed portion of the second insulated wire is a first exposed portion of the second insulated wire; said second insulated wire further comprises a second insulative member opening forming a second exposed portion of the second insulated wire; said insulative member opening of the third insulated wire is a first insulative member opening of the third insulated wire and said exposed portion of the third insulated wire is a first exposed portion of the third insulated wire; said third insulated wire further comprises a second insulative member opening forming a second exposed portion of the third insulated wire; the energy generator is further configured to: induce the third voltage differential between (i) the second exposed portion of the second insulated wire and (ii) the second exposed portion of the third insulated wire; and cause said third energy differential to exceed the energy threshold to induce a spark between the second exposed portion of the second insulated wire and the second exposed portion of the third insulated wire.

[0357] Clause 57. The system of any of Clauses 50-56, further comprising a balloon around at least a portion of the sheath and configured to be expanded with a conductive fluid configured to conduct a sonic wave originating from the spark, wherein the exposed portions of the first and second insulated wires are exposed to the conductive fluid at least when the balloon is expanded, wherein no portion of the balloon contacts the exposed portions of the first and second insulated wires.

[0358] Clause 58. The system of any of Clauses 50-57, wherein: the first insulated wire is wound around the outer surface of the sheath with a first pitch; and the second insulated wire is wound

around the outer surface of the sheath with a second pitch that is substantially equal to the first pitch.

[0359] Clause 59. The system of any of Clauses 50-58, wherein the first insulated wire is wound around the outer surface of the sheath with a uniform pitch along the sheath.

[0360] Clause 60. The system of any of Clauses 50-59, wherein the first insulated wire is wound around the outer surface of the sheath with a variable pitch along the sheath.

[0361] Clause 61. The system of any of Clauses 50-60, wherein the first and second insulated wires are removably electrically connected to the energy generator.

[0362] Clause 62. The system of any of Clauses 50-61, further comprising a carrier encasing the first and second insulated wires and the sheath, the carrier comprising: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire.

[0363] Clause 63. The system of Clause 62, wherein the first and second carrier openings are configured such that the exposed portions of the electrically conductive member are not covered by the carrier.

[0364] Clause 64. An intravascular lithotripsy system configured to modify calcified plaque within a blood vessel of a subject, the system comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire wound around and contacting an outer surface of the sheath, the first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the first insulated wire; a second insulated wire wound around and contacting the outer surface of the sheath, the second insulated wire arranged adjacent the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the second insulated wire; and an energy generator electrically connected with the first and second insulated wires and configured to induce a spark between the exposed portions of the first and second insulated wires.

[0365] Clause 65. The system of Clause 64, further comprising a balloon around at least a portion of the sheath and configured to be expanded with a conductive fluid configured to conduct a sonic wave originating from the spark.

[0366] Clause 66. The system of Clause 65, wherein the balloon is configured to be transitioned between an expanded state and a non-expanded state, and wherein the exposed portions of the first and second insulated wires are exposed to the conductive fluid at least when the balloon is in the expanded state.

[0367] Clause 67. The system of any of Clauses 65-66, wherein the balloon is configured to be transitioned between an expanded state and a non-expanded state, and wherein the exposed portions of the first and second insulated wires are exposed to the conductive fluid when the balloon is in the expanded state and when the balloon is in the non-expanded state.

[0368] Clause 68. The system of any of Clauses 65-67, wherein the system is configured such that no portion of the balloon contacts the exposed portions of the first and second insulated wires.

[0369] Clause 69. The system of any of Clauses 65-68, wherein the balloon is configured to be transitioned between an expanded state and a non-expanded state, and wherein the system is configured such that: no portion of the balloon contacts the exposed portions of the first and second insulated wires when the balloon is in the expanded state; and no portion of the balloon contacts the exposed portions of the first and second insulated wires when the balloon is in the non-expanded state.

[0370] Clause 70. The system of any of Clauses 64-69, wherein: the first insulated wire is wound around the outer surface of the sheath with a first pitch; and the second insulated wire is wound around the outer surface of the sheath with a second pitch that is substantially equal to the first

pitch.

[0371] Clause 71. The system of any of Claims 64-70, wherein the first insulated wire is wound around the outer surface of the sheath with a uniform pitch along the sheath.

[0372] Clause 72. The system of any of Claims 64-71, wherein the first insulated wire is wound around the outer surface of the sheath with a variable pitch along the sheath.

[0373] Clause 73. The system of any of Claims 64-72, wherein the first and second insulated wires are independently electrically connected to the energy generator.

[0374] Clause 74. The system of any of Claims 64-73, wherein the first and second insulated wires are removably electrically connected to the energy generator.

[0375] Clause 75. The system of any of Claims 64-74, further comprising a carrier encasing the first and second insulated wires and the sheath, the carrier comprising: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire.

[0376] Clause 76. The system of Claim 75, wherein the first and second carrier openings are configured such that the exposed portions of the electrically conductive member are not covered by the carrier.

[0377] Clause 77. The system of any of Claims 64-76, wherein: the sheath comprises a sheath length; the first insulated wire comprises a first length; the second insulated wire comprises a second length; each of the first and second lengths are greater than the sheath length.

[0378] Clause 78. A method of manufacturing an intravascular lithotripsy catheter, comprising: providing a sheath comprising a lumen configured to receive a guidewire; helically winding a first insulated wire around the sheath, the first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member; helically winding a second insulated wire around the sheath, the second insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire; and forming an insulative member opening in the first insulated wire to form an exposed portion of the first insulated wire; forming an insulative member opening in the second insulated wire to form an exposed portion of the second insulated wire to allow a spark to form between the exposed portions of the first and second insulated wires.

[0379] Clause 79. The method of Claim 78, further comprising forming the insulative member openings in the first and second insulated wires with a laser.

[0380] Clause 80. The method of any of Claims 78-79, further comprising helically winding the second insulated wire adjacent to the first insulated wire.

[0381] Clause 81. The method of any of Claims 78-80, further comprising: helically winding the first insulated wire around the sheath with a first pitch; and helically winding the second insulated wire around the sheath with a second pitch, wherein the first pitch and the second pitch are the same.

[0382] Clause 82. The method of any of Claims 78-81, further comprising helically winding the first insulated wire around the sheath with a uniform pitch.

[0383] Clause 83. The method of any of Claims 78-82, further comprising helically winding the first insulated wire around the sheath with a variable pitch.

[0384] Clause 84. The method of any of Claims 78-83, further comprising helically winding the first insulated wire around the sheath before forming the insulative member opening in the first insulated wire.

[0385] Clause 85. The method of any of Claims 78-84, further comprising forming the insulative member opening in the first insulated wire before helically winding the first insulated wire around the sheath.

[0386] Clause 86. The method of any of Claims 78-85, further comprising providing a carrier encasing the first and second insulated wires and the sheath.

[0387] Clause 87. The method of Clause 86, further comprising: forming a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and forming a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire.

[0388] Clause 88. The method of Clause 87, further comprising: forming the first carrier opening when forming the exposed portion of the electrically conductive member of the first insulated wire; and forming the second carrier opening when forming the exposed portion of the electrically conductive member of the second insulated wire.

[0389] Clause 89. The method of any of Clauses 87-88, further comprising forming the first and second carrier openings with a laser.

## Claims

1. An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject, the intravascular lithotripsy catheter comprising: a sheath comprising a lumen configured to receive a guidewire, wherein a longitudinal axis of the intravascular lithotripsy catheter extends through the lumen; a first insulated wire wound around and contacting an outer surface of the sheath, the first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire wound around and contacting the outer surface of the sheath, the second insulated wire arranged adjacent the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; wherein the exposed portion of the second insulated wire is circumferentially offset from the exposed portion of the first insulated wire by an angle originating at the longitudinal axis; wherein the exposed portion of the second insulated wire is longitudinally offset from the exposed portion of the first insulated wire by a longitudinal distance extending along the intravascular lithotripsy catheter parallel to the longitudinal axis; and a carrier encasing the first and second insulated wires and the sheath, the carrier comprising: a first carrier opening aligned with the exposed portion of the electrically conductive member of the first insulated wire; and a second carrier opening spaced from the first carrier opening and aligned with the exposed portion of the electrically conductive member of the second insulated wire; wherein the intravascular lithotripsy catheter is configured to be electrically connected to an energy generator that is operable to cause a spark to travel longitudinally along the intravascular lithotripsy catheter and circumferentially around the intravascular lithotripsy catheter between the exposed portions of the first and second insulated wires.

2. The intravascular lithotripsy catheter of claim 1, wherein the carrier comprises an inner surface configured to contact the first and second insulated wires and an outer surface opposite the inner surface, wherein the intravascular lithotripsy catheter is configured such that the spark travels from the exposed portion of the first insulated wire, through the first carrier opening, above the outer surface of the carrier, through the second carrier opening, and to the exposed portion of the second insulated wire.

3. The intravascular lithotripsy catheter of claim 1, wherein the carrier has a fixed volume.

4. The intravascular lithotripsy catheter of claim 1, wherein the carrier comprises a different material than at least one of the electrically conductive members of the insulated wires or the sheath.

5. The intravascular lithotripsy catheter of claim 1, wherein the first and second carrier openings are configured such that the exposed portions of the electrically conductive member are not covered by the carrier.

- 6.** The intravascular lithotripsy catheter of claim 1 further comprising a balloon configured to hold conductive fluid around at least a portion of the sheath, wherein the carrier inhibits the balloon from contacting the exposed portions of the electrically conductive members of the first and second insulated wires, wherein the exposed portions of the electrically conductive members of the first and second insulated wires are exposed to the conductive fluid.
- 7.** The intravascular lithotripsy catheter of claim 6, wherein the carrier is configured to separate the balloon from the exposed portions of the electrically conductive members of the first and second insulated wires.
- 8.** The intravascular lithotripsy catheter of claim 6, wherein the balloon is coated with medication.
- 9.** The intravascular lithotripsy catheter of claim 1, wherein: the first insulated wire is wound around the outer surface of the sheath with a first pitch; and the second insulated wire is wound around the outer surface of the sheath with a second pitch that is substantially equal to the first pitch.
- 10.** The intravascular lithotripsy catheter of claim 1, wherein the first insulated wire is wound around the outer surface of the sheath with a uniform pitch along the sheath.
- 11.** The intravascular lithotripsy catheter of claim 1, wherein the first insulated wire is wound around the outer surface of the sheath with a variable pitch along the sheath.
- 12.** The intravascular lithotripsy catheter of claim 1, further comprising an energy generator configured to: induce an energy differential between (i) the exposed portion of the electrically conductive member of the first insulated wire and (ii) the exposed portion of the electrically conductive member of the second insulated wire to induce the spark between the exposed portions of the electrically conductive members of the first and second insulated wires.
- 13.** The intravascular lithotripsy catheter of claim 12, wherein the first and second insulated wires are removably electrically connected to the energy generator.
- 14.** An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a subject, the intravascular lithotripsy catheter comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire arranged adjacent the first insulated wire and comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; and a longitudinal axis extending through the sheath; wherein the first and second insulated wires are wrapped around the sheath such that: the exposed portion of the second insulated wire is arranged at a different longitudinal location than the exposed portion of the first insulated wire relative to said longitudinal axis relative to said longitudinal axis; the exposed portion of the second insulated wire is arranged at a different angular location than the exposed portion of the first insulated wire relative to a plane defined normal to said longitudinal axis.
- 15.** The intravascular lithotripsy catheter of claim 14, wherein the first and second insulated wires are configured to be electrically connected to an energy generator that is operable to cause a spark to travel: longitudinally along the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire; and circumferentially around the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire.
- 16.** The intravascular lithotripsy catheter of claim 14, wherein: the first insulated wire is wound around the sheath with a first pitch; and the second insulated wire is wound around the sheath with a second pitch that is substantially equal to the first pitch.
- 17.** The intravascular lithotripsy catheter of claim 14, wherein the first insulated wire is wound around the sheath with a uniform pitch along the sheath.
- 18.** An intravascular lithotripsy catheter for modifying calcified plaque within a blood vessel of a

subject, the intravascular lithotripsy catheter comprising: a sheath comprising a lumen configured to receive a guidewire; a first insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member, and an insulative member opening forming an exposed portion of the electrically conductive member; a second insulated wire comprising an electrically conductive member, an insulative member encasing the electrically conductive member of the second insulated wire, and an insulative member opening forming an exposed portion of the electrically conductive member of the second insulated wire; and a longitudinal axis extending through the sheath; wherein the first and second insulated wires are wrapped around the sheath such that: a transverse cross-section through the intravascular lithotripsy catheter that is perpendicular to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire; and a longitudinal cross-section through the intravascular lithotripsy catheter that is parallel to said longitudinal axis passes through the exposed portion of the first insulated wire without passing through the exposed portion of the second insulated wire.

**19.** The intravascular lithotripsy catheter of claim 18, wherein the first and second insulated wires are configured to be electrically connected to an energy generator that is operable to cause a spark to travel: longitudinally along the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire; and circumferentially around the intravascular lithotripsy catheter from the exposed portion of the first insulated wire to the exposed portion of the second insulated wire.

**20.** The intravascular lithotripsy catheter of claim 18, wherein: the first insulated wire is wound around the sheath with a first pitch; and the second insulated wire is wound around the sheath with a second pitch that is substantially equal to the first pitch.

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