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(54) **INSERTABLE TUBE SURGICAL ROBOT**

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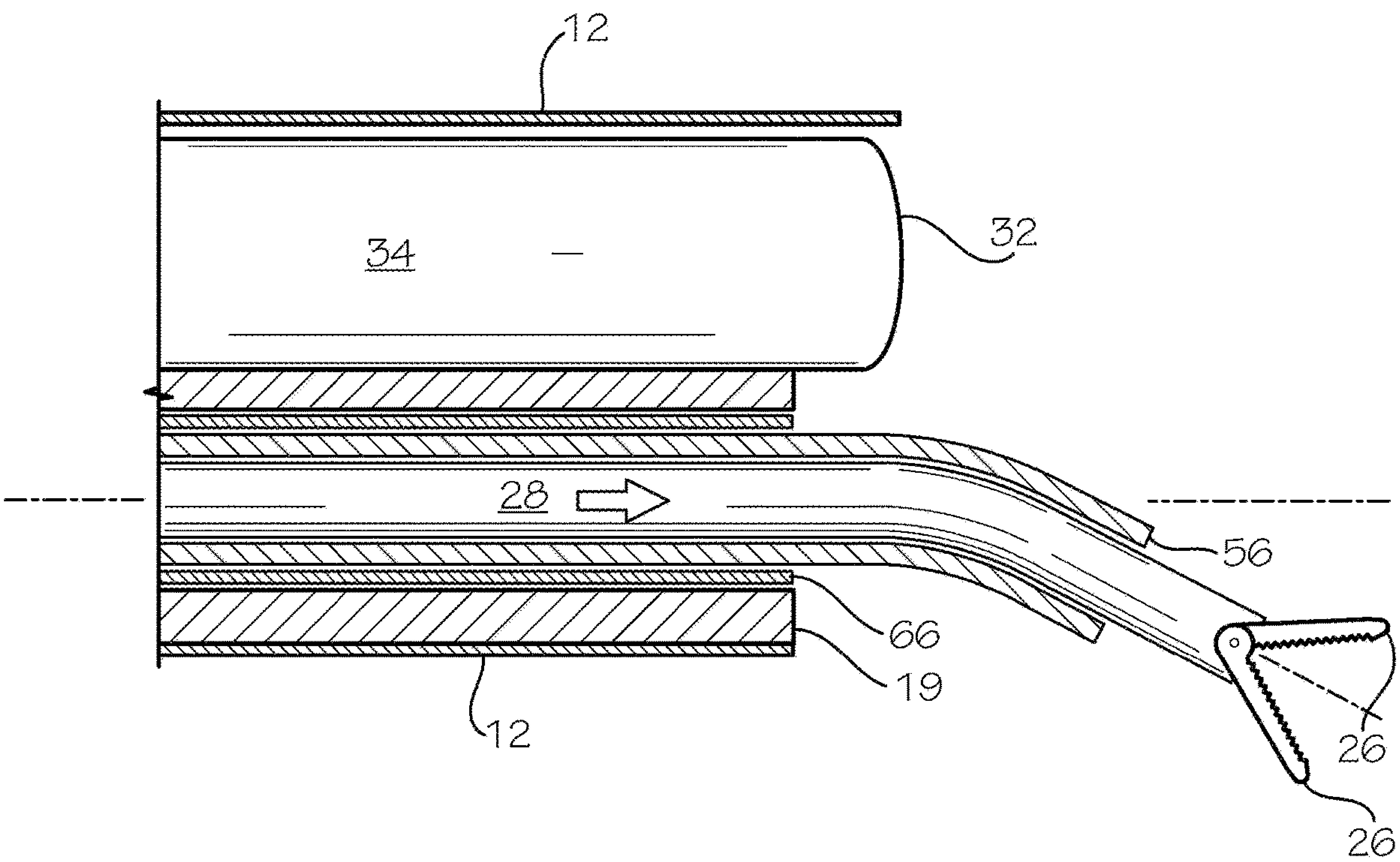
(57) **ABSTRACT**

An insertable robot for minimally invasive surgery includes a tube array having a guide tube housed within a straightening tube. The guide tube includes a curved working end. The guide tube may be axially translated and rotated relative to the straightening tube such that the curved working end is constrained inside the straightening tube, causing the curved working end to achieve a smaller dimension. The tube array is inserted into a working channel on an endoscope, resectoscope or trocar. Once the tube array is inserted, the curved working end of the guide tube is translated forward beyond the distal end of the working channel, allowing the curved working end to return to its pre-formed shape. A surgical tool is inserted through the guide tube for an operation. The straightening tube allows the guide tube curved working end to be temporarily straightened during insertion and removal of the tube array.



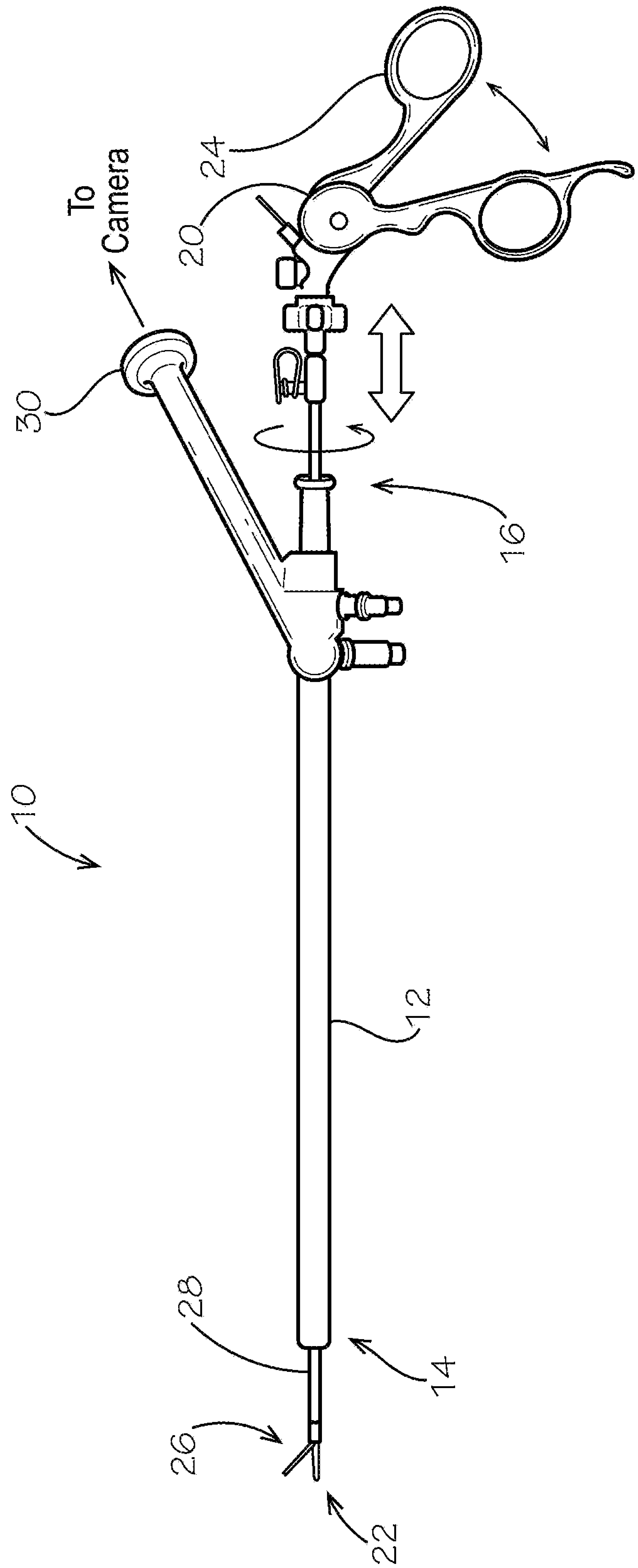
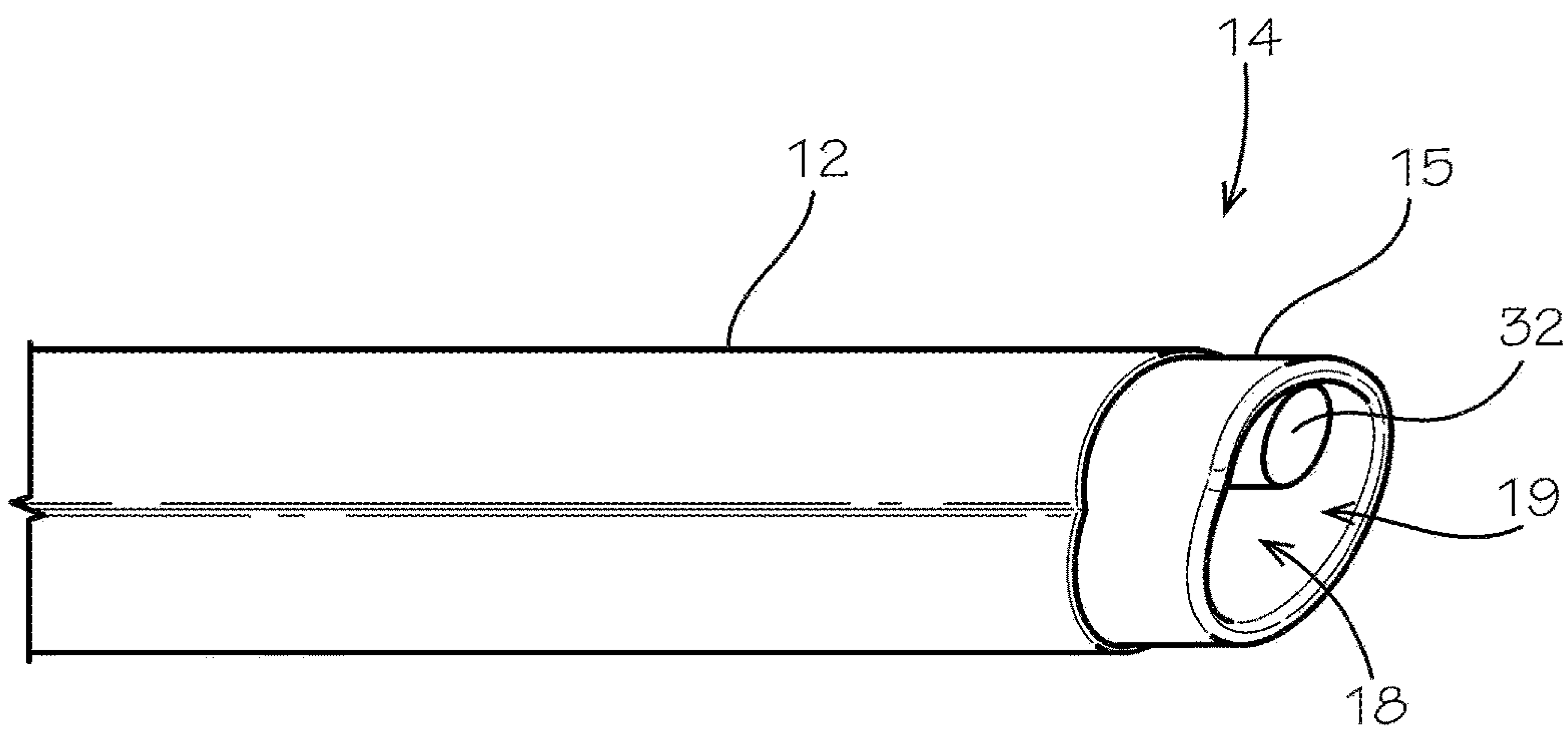
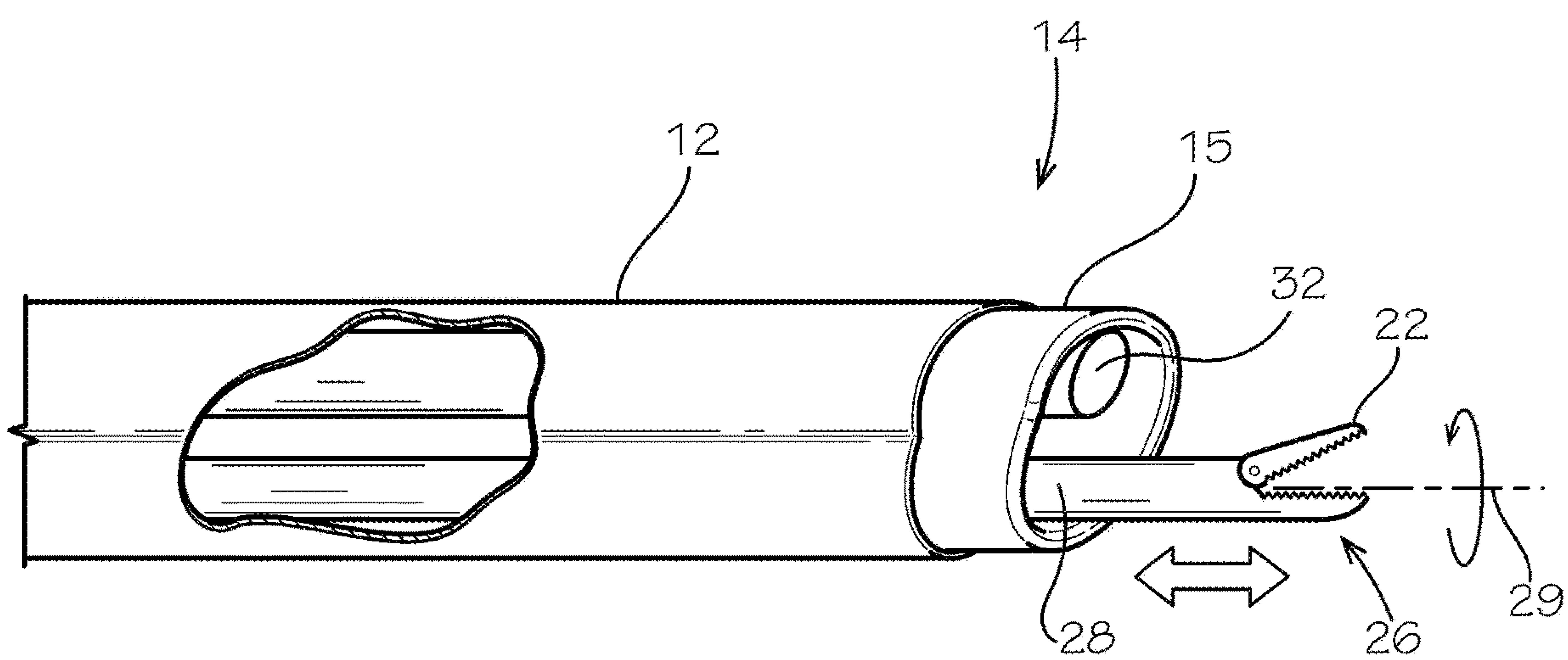


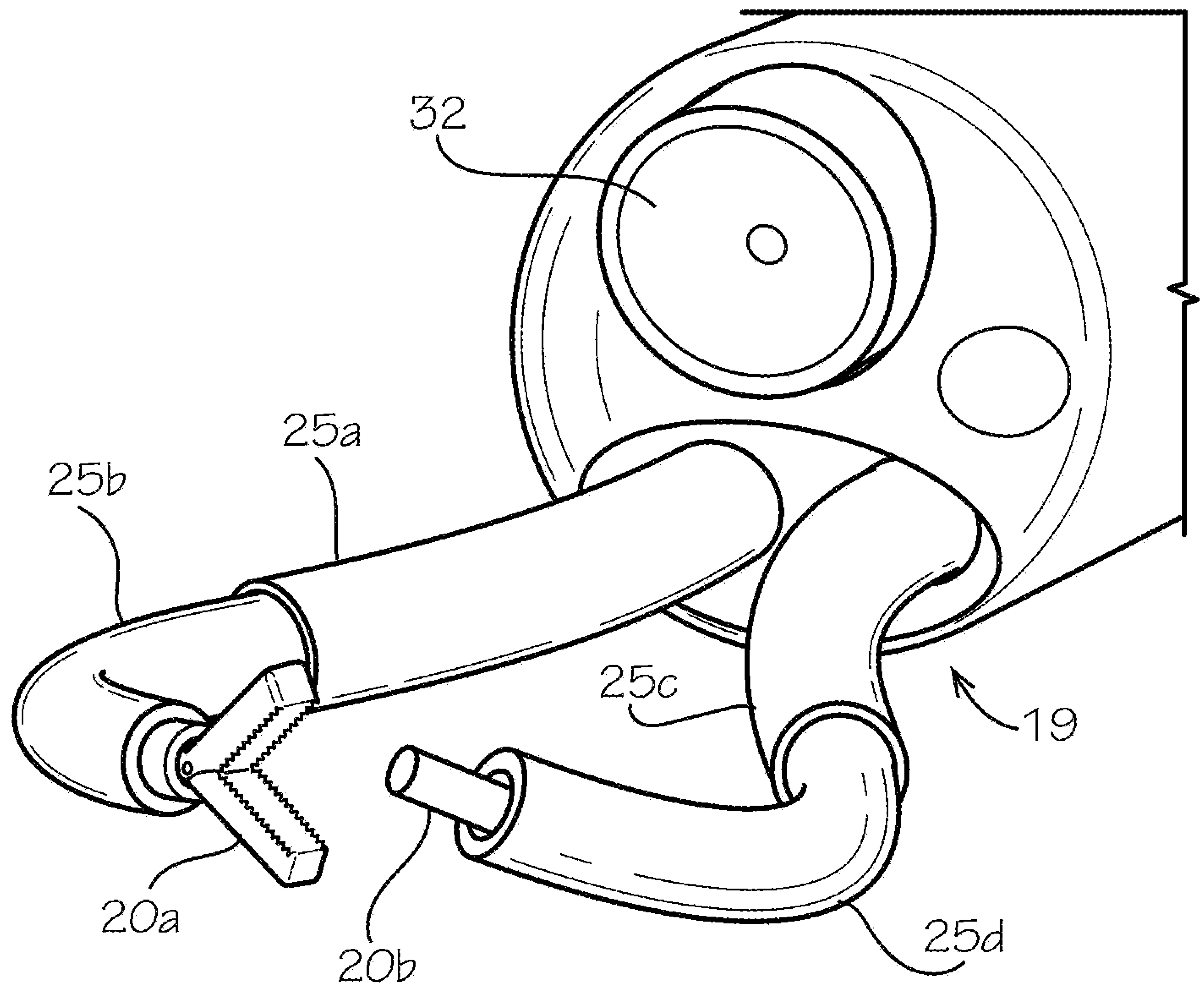
FIG. 1



PRIOR ART
FIG. 2A



PRIOR ART
FIG. 2B



PRIOR ART

FIG. 3

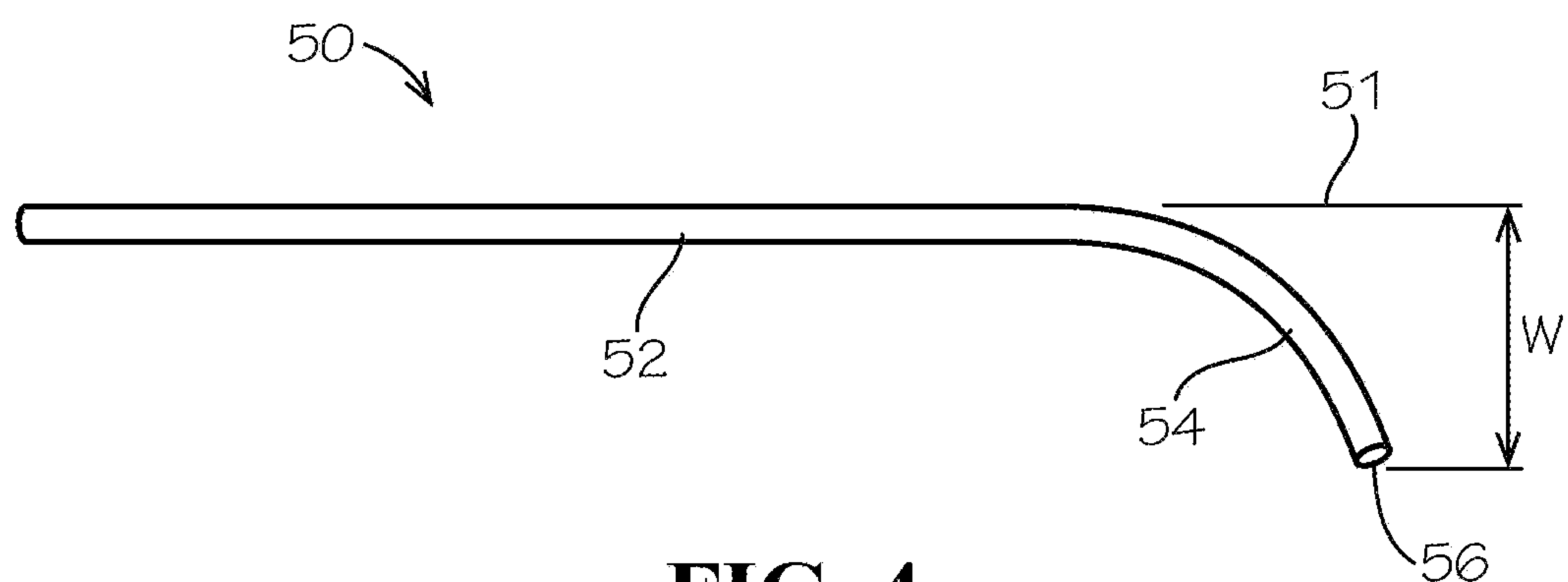


FIG. 4

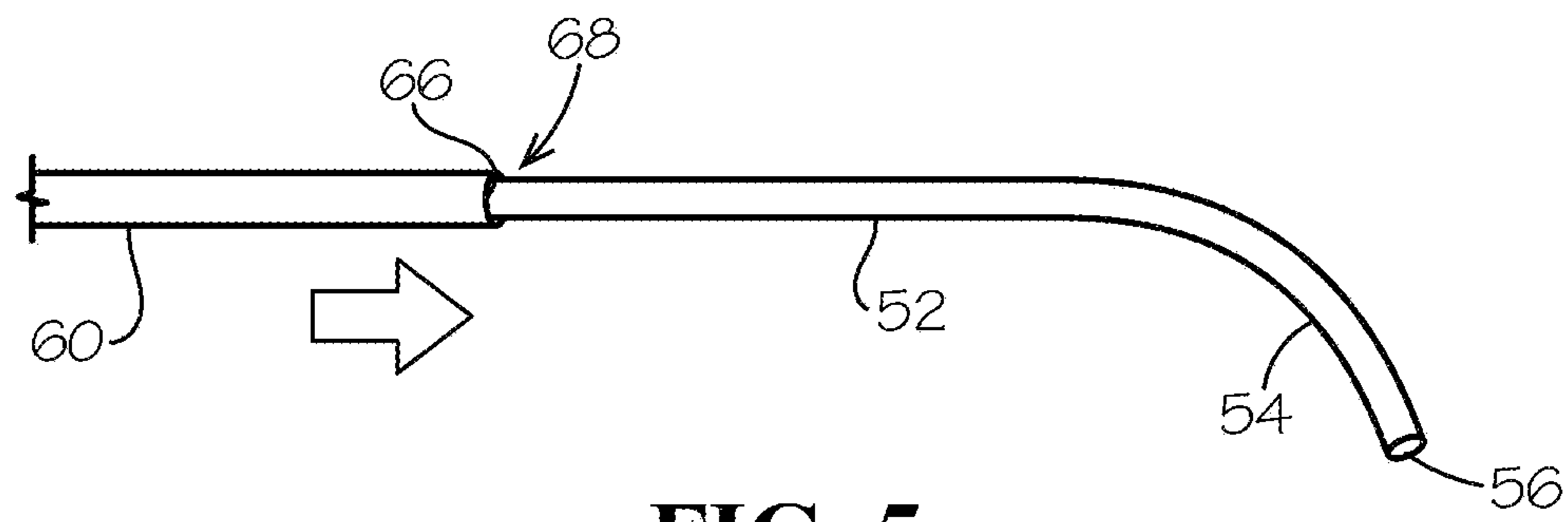


FIG. 5

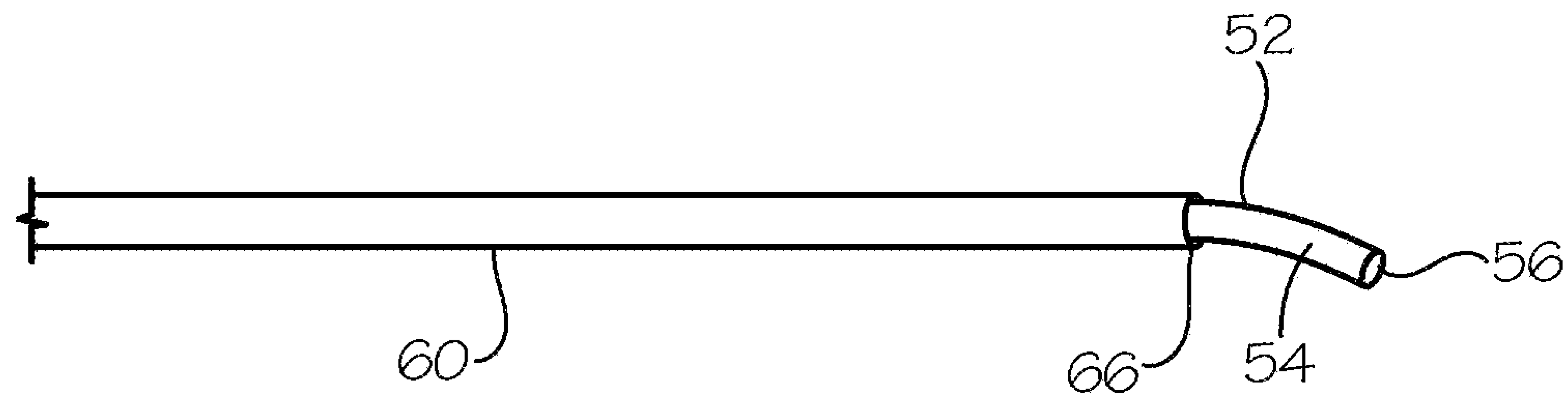


FIG. 6

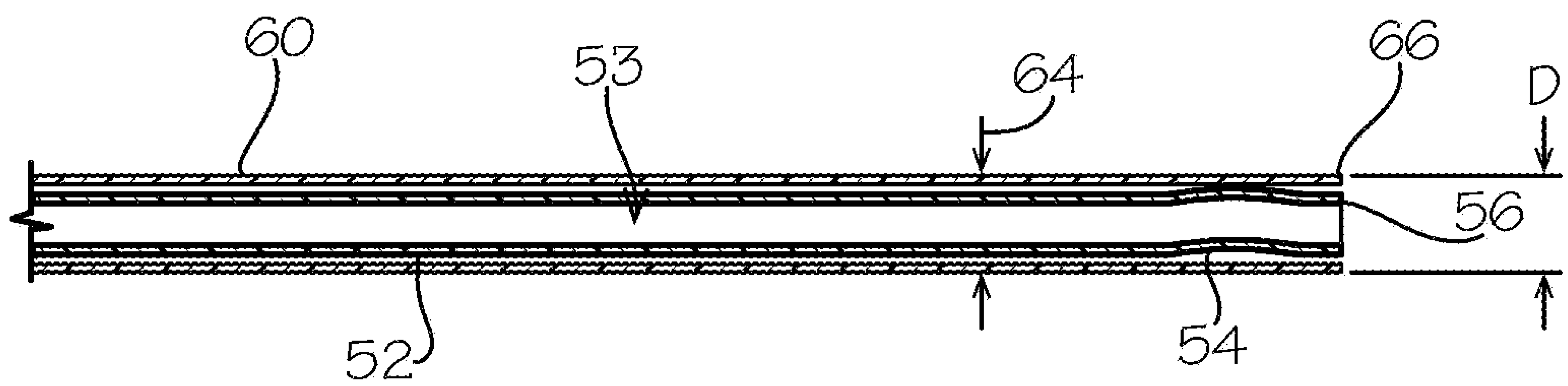


FIG. 7

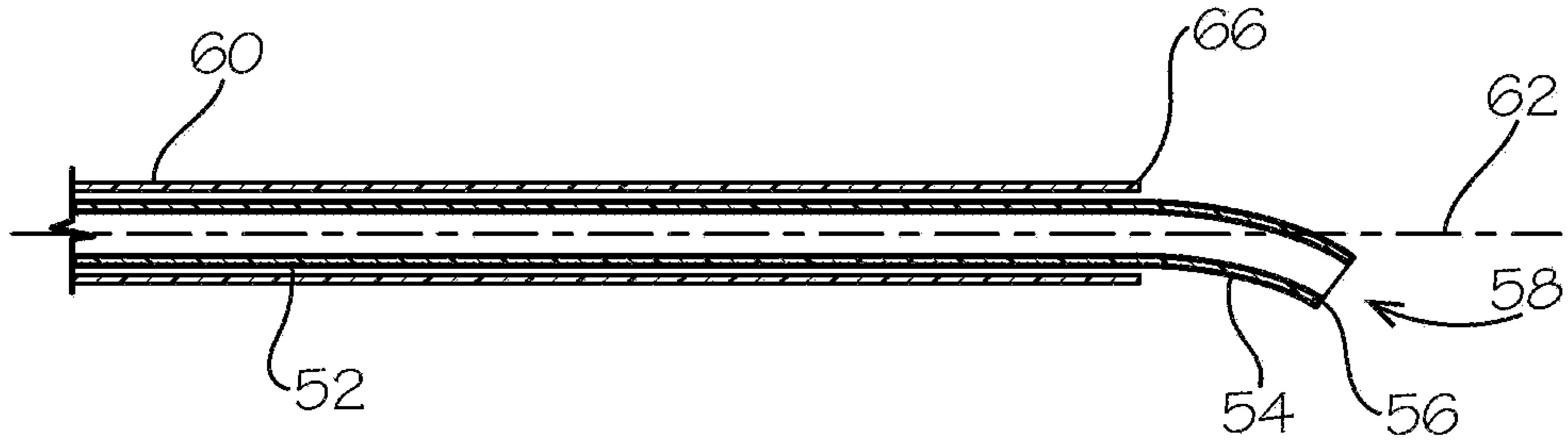


FIG. 8

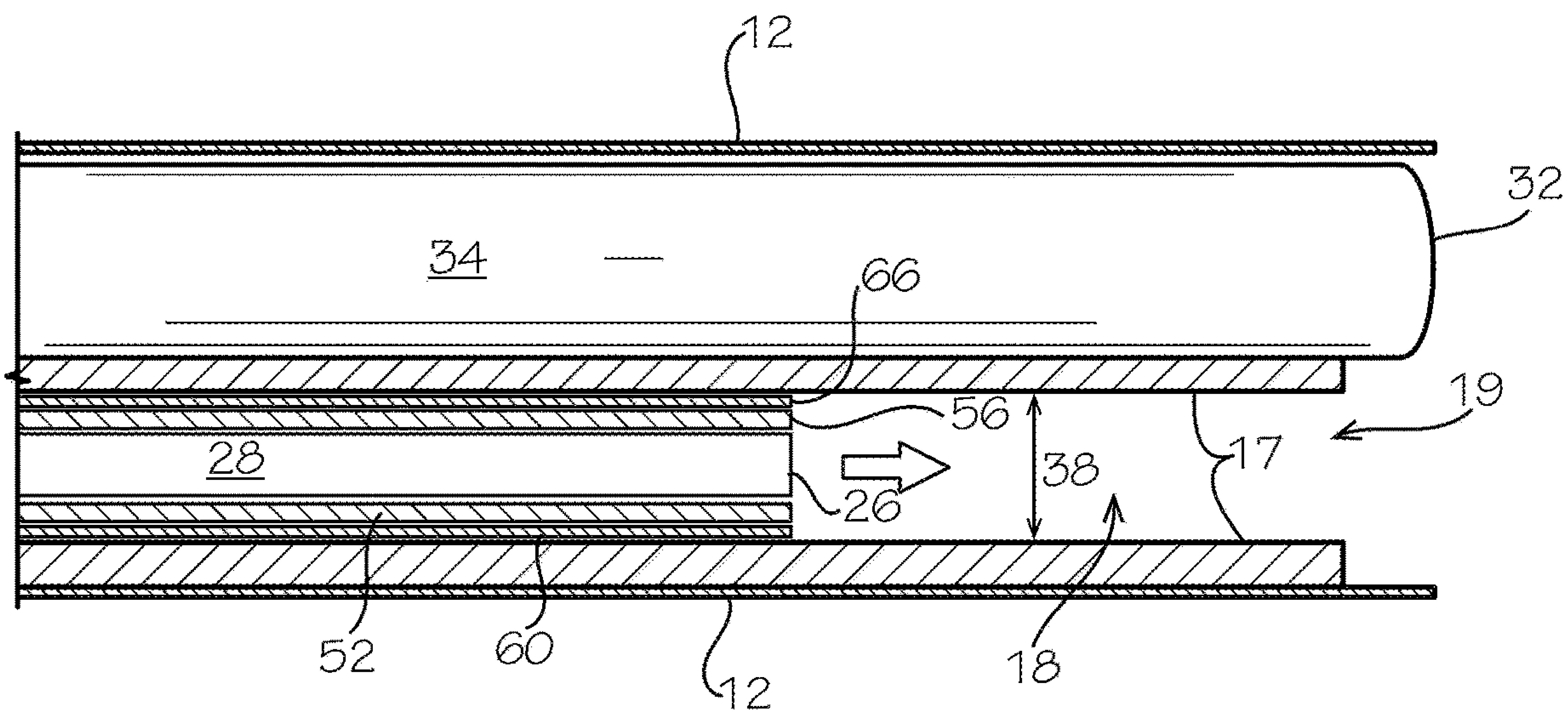

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FIG. 9

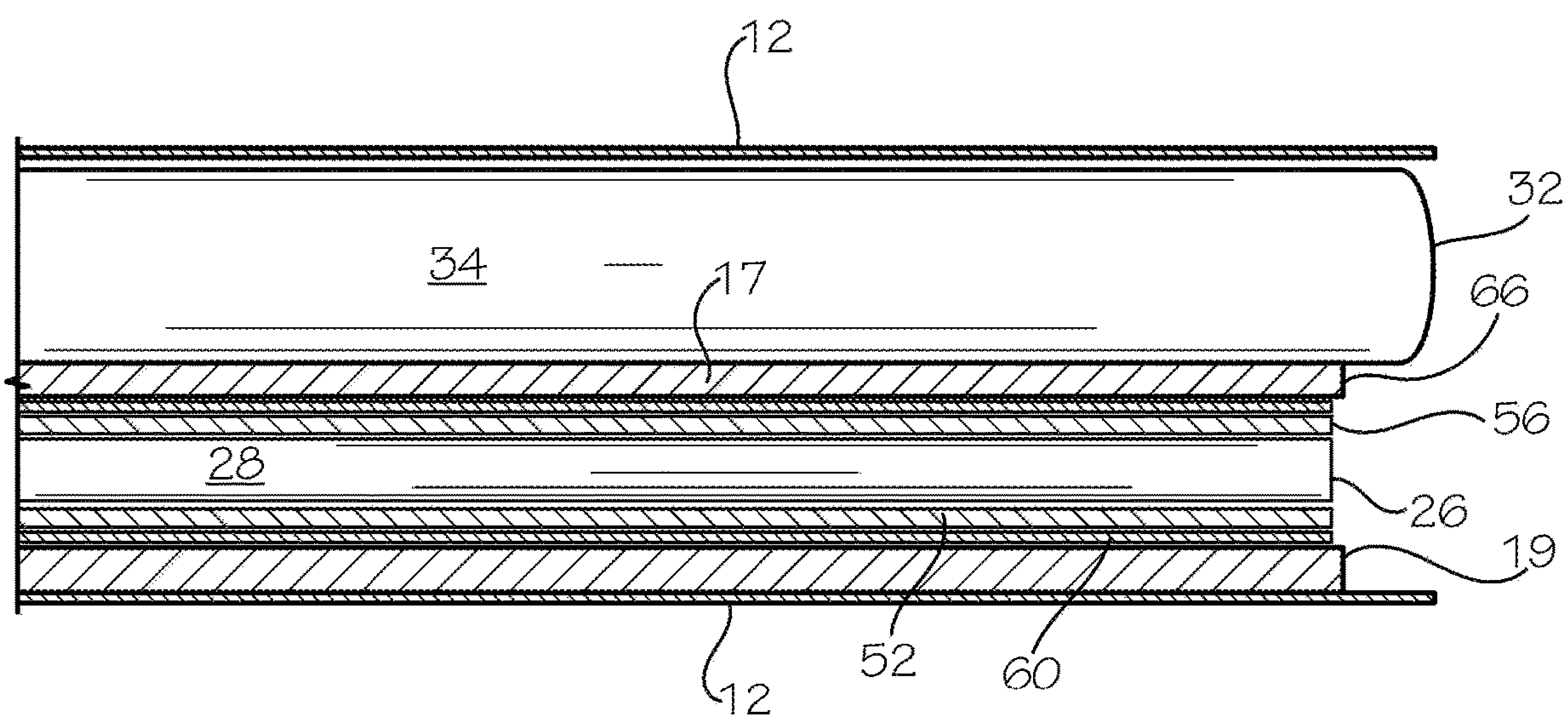
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FIG. 10

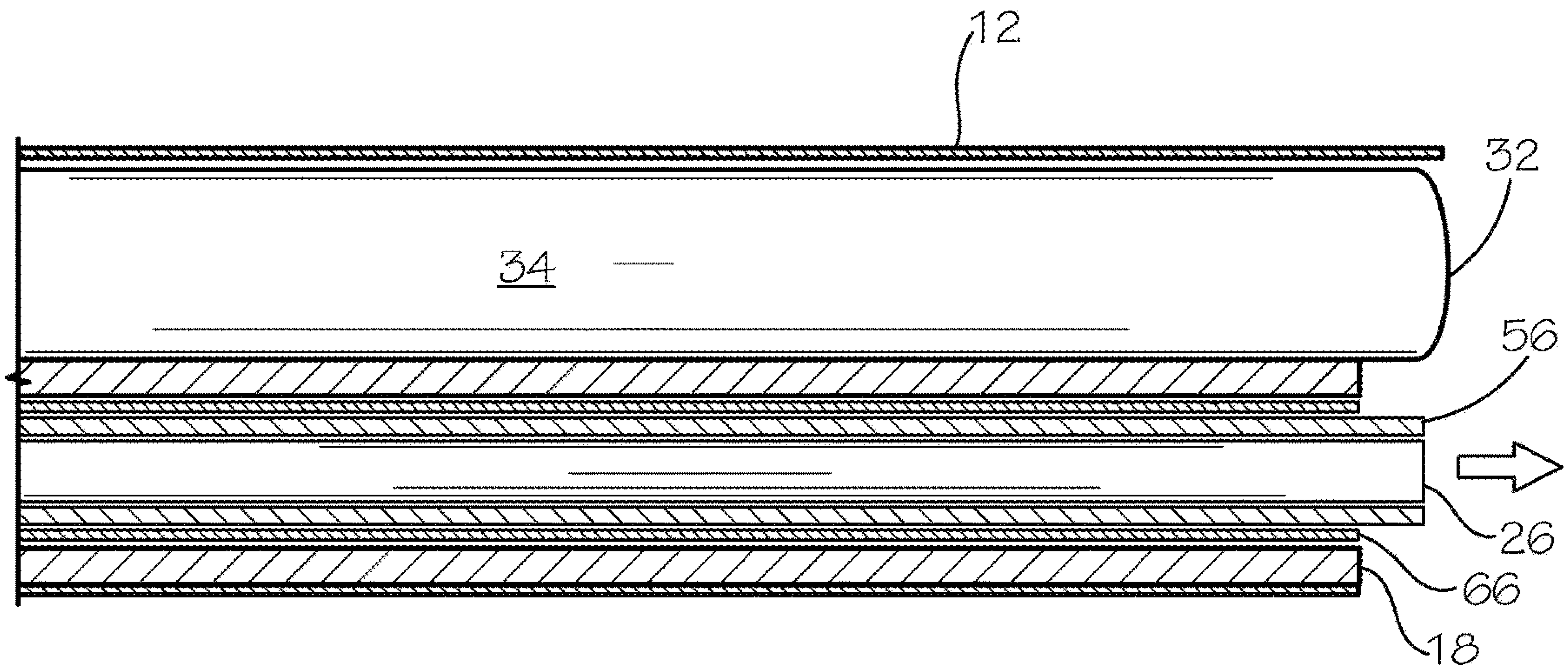

FIG. 11

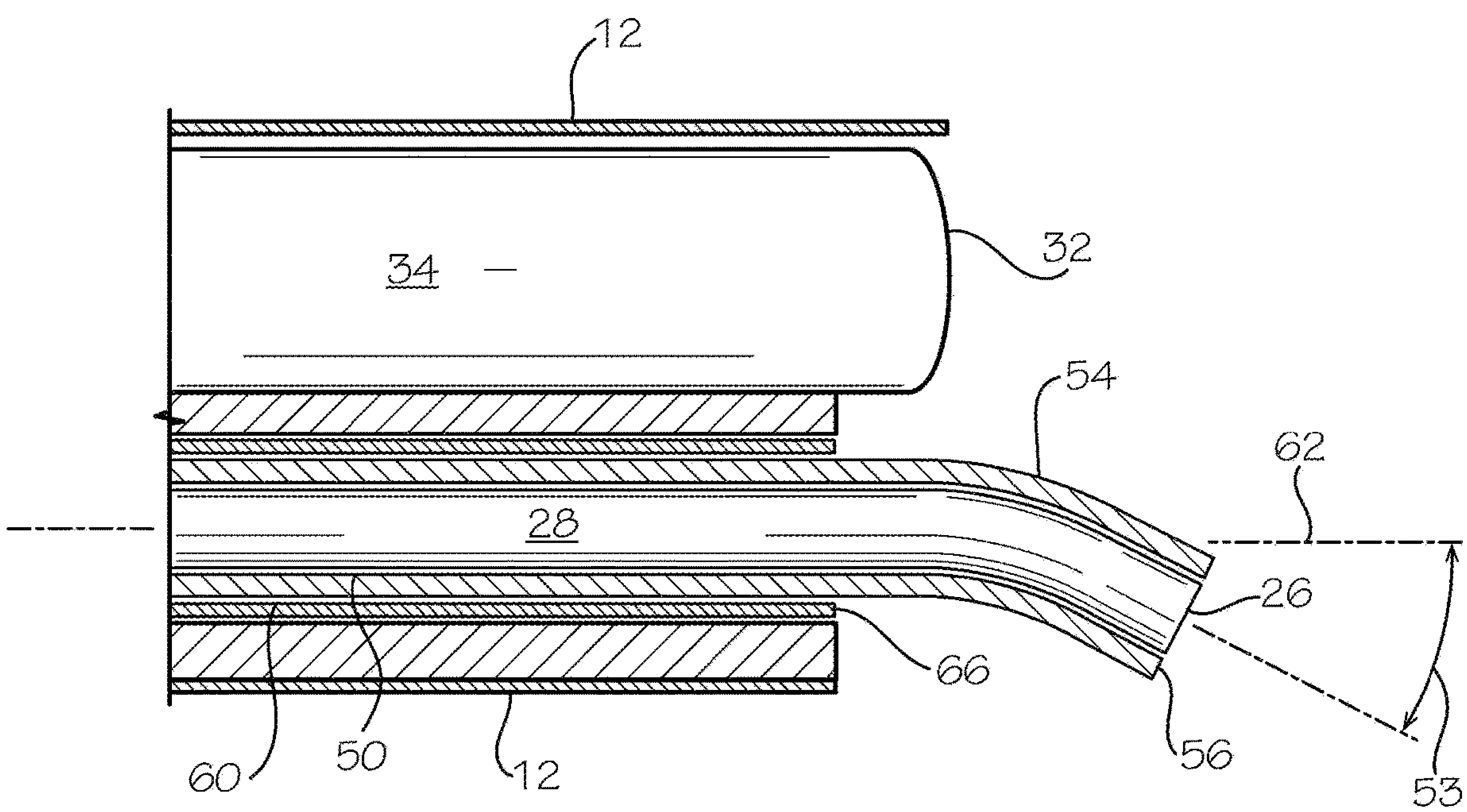

FIG. 12

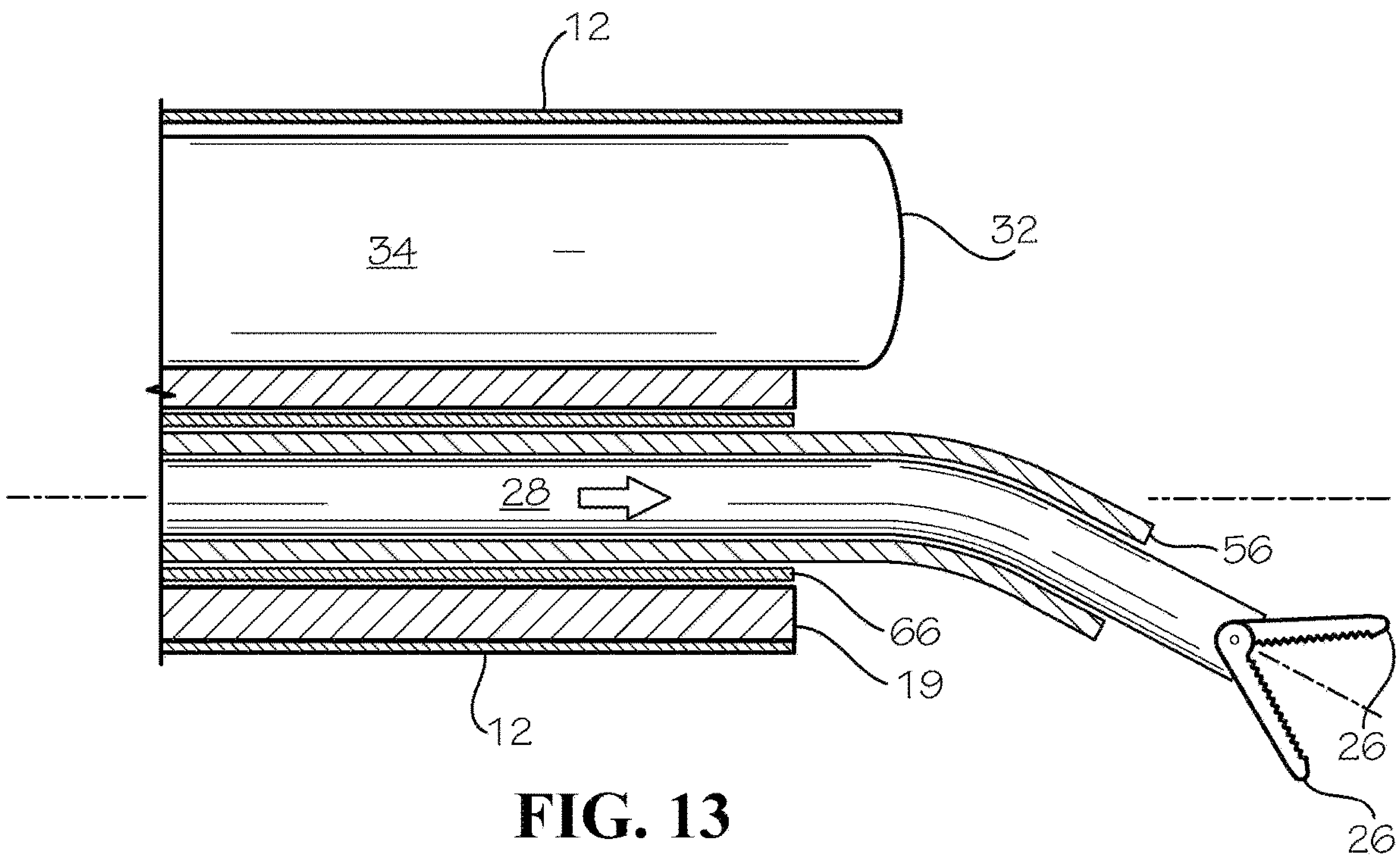

FIG. 13

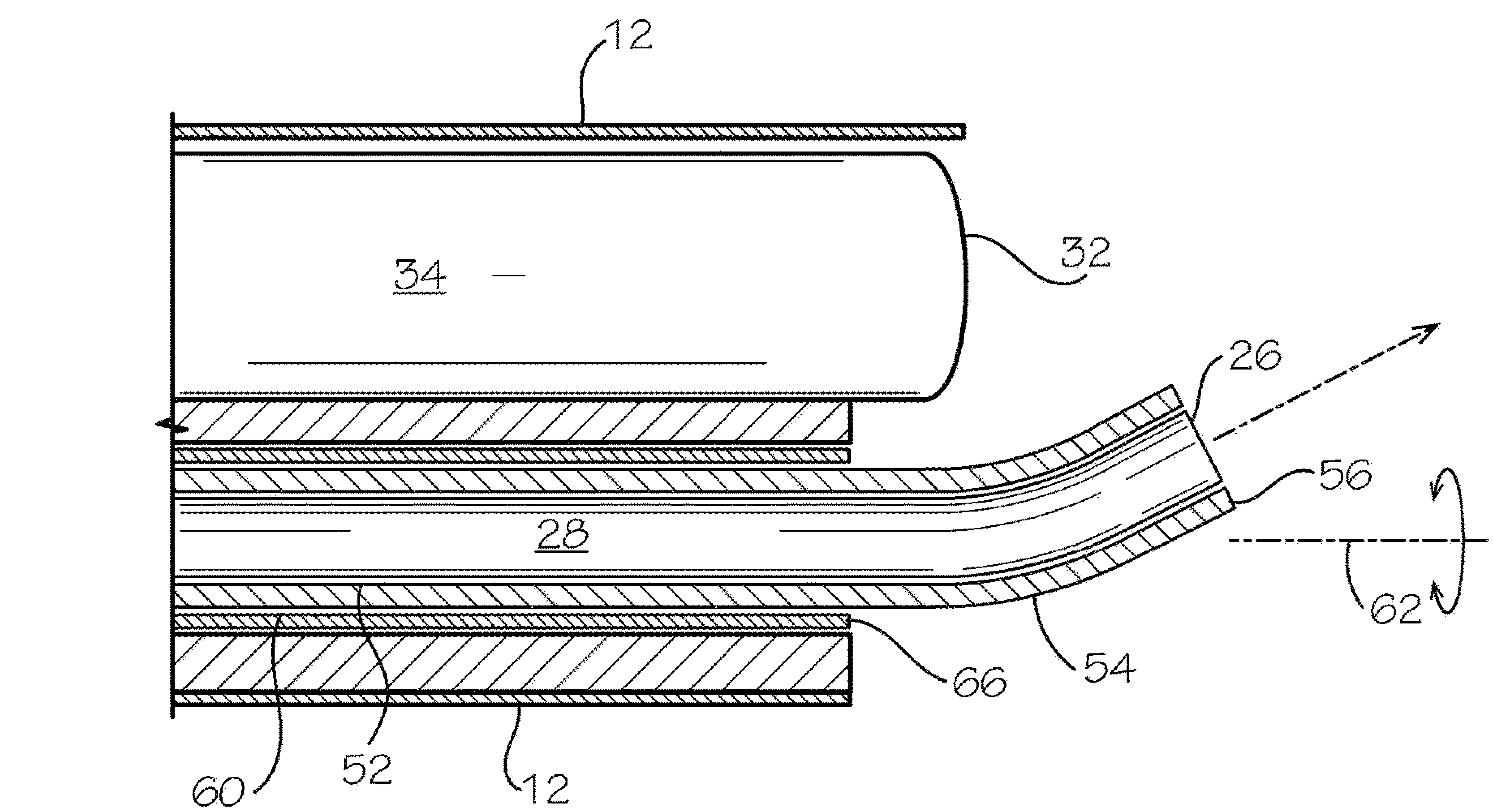

FIG. 14

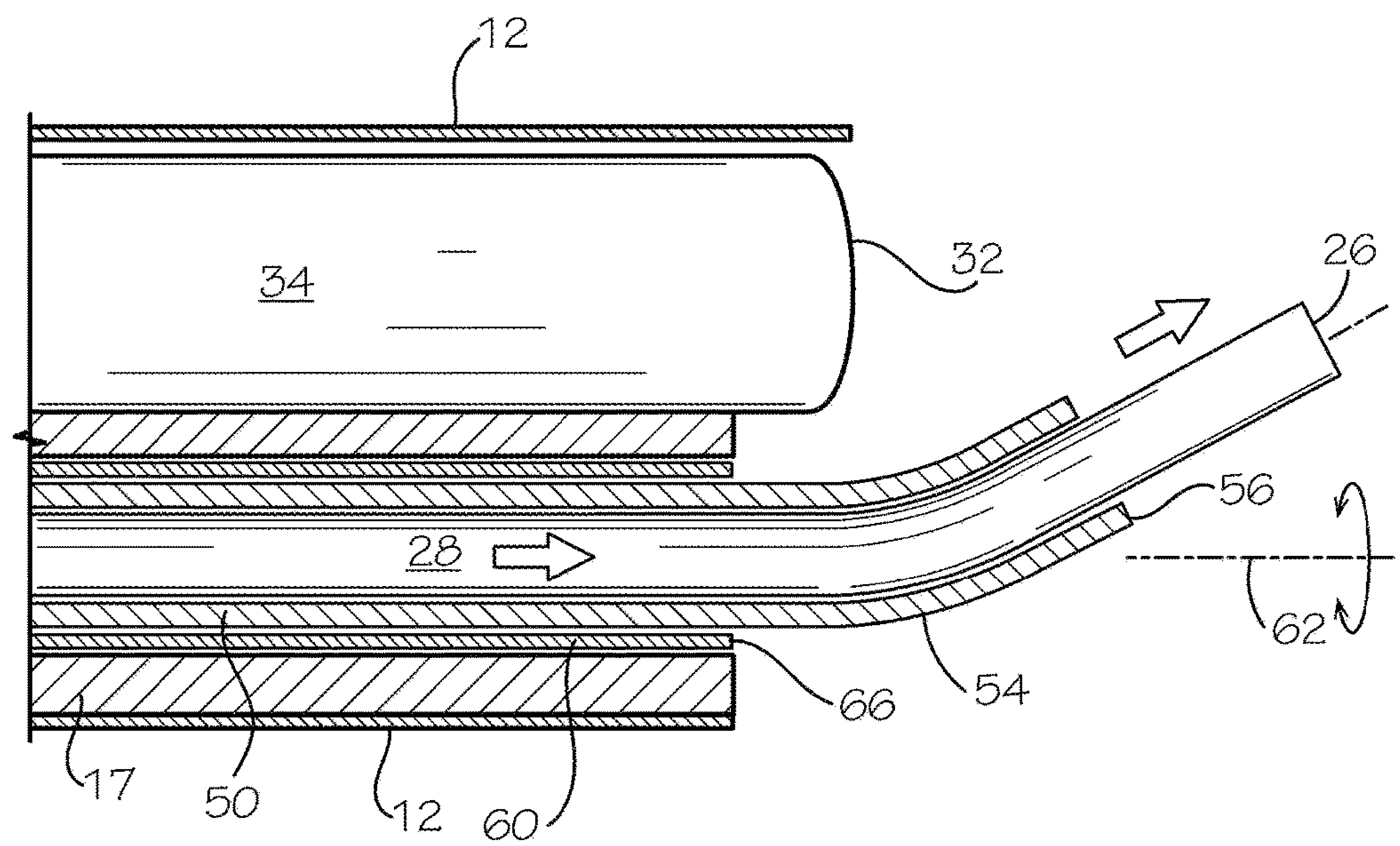
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FIG. 15

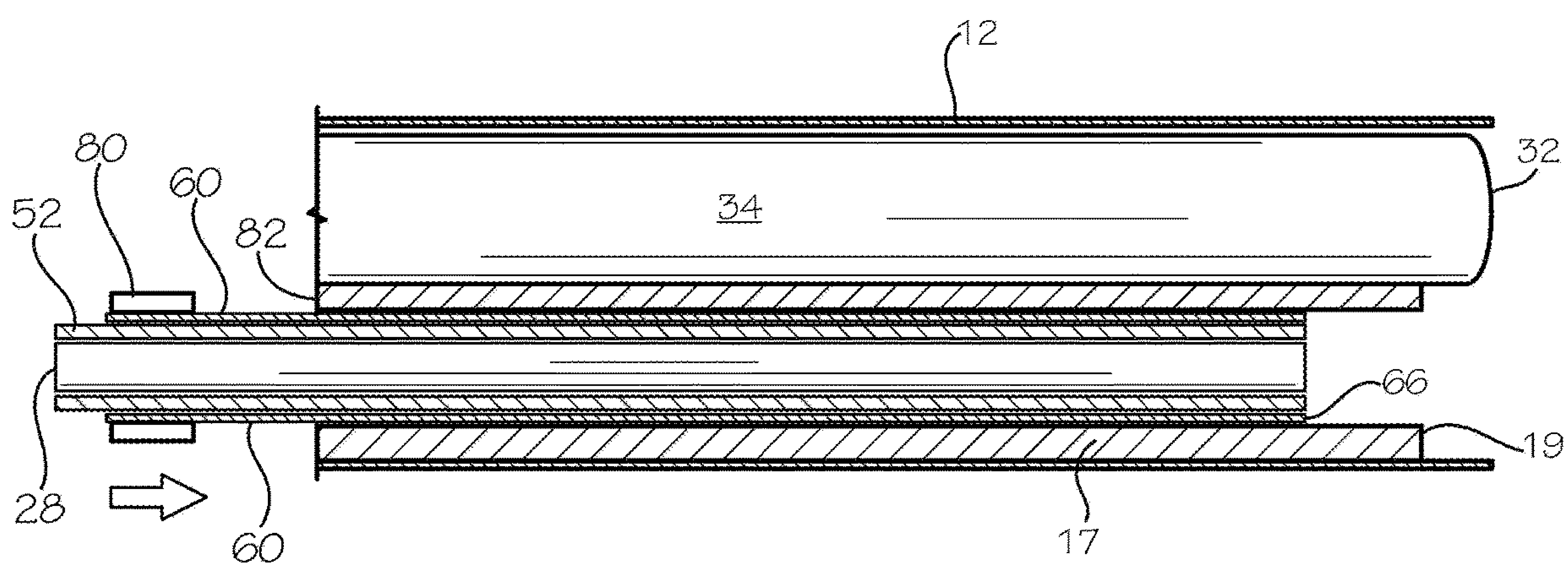
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FIG. 16

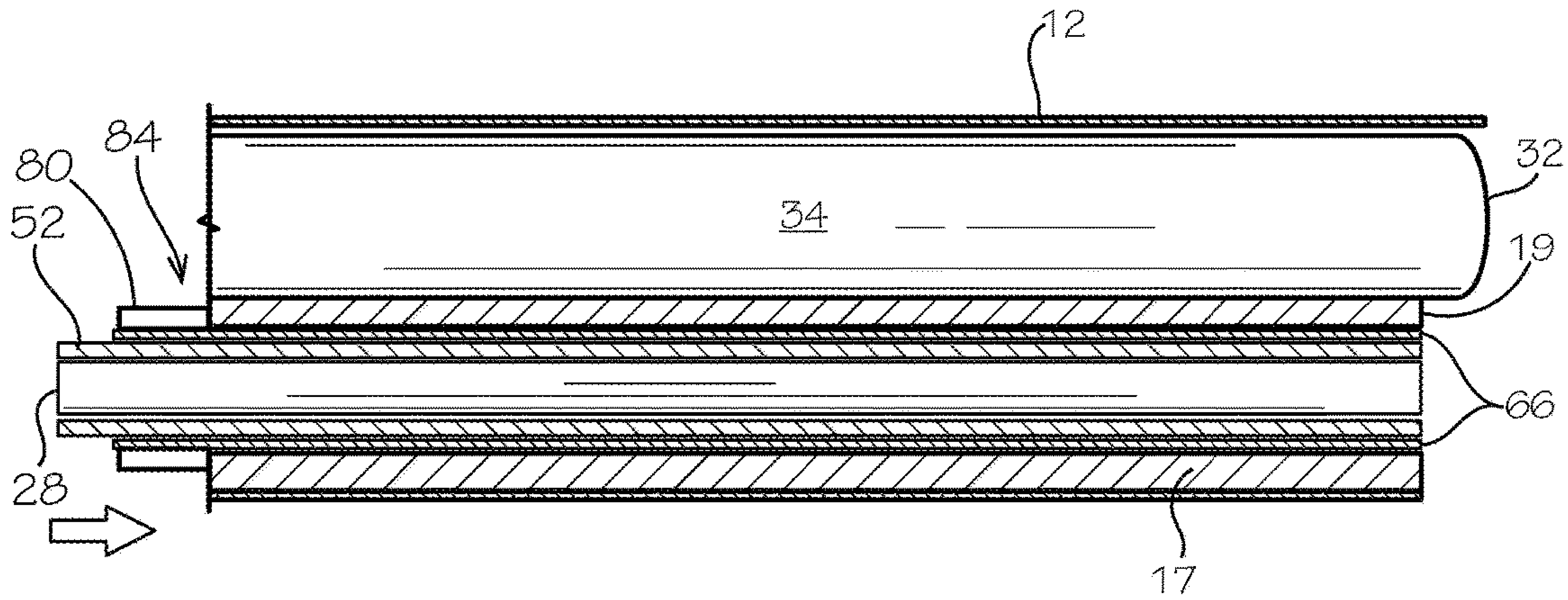

FIG. 17

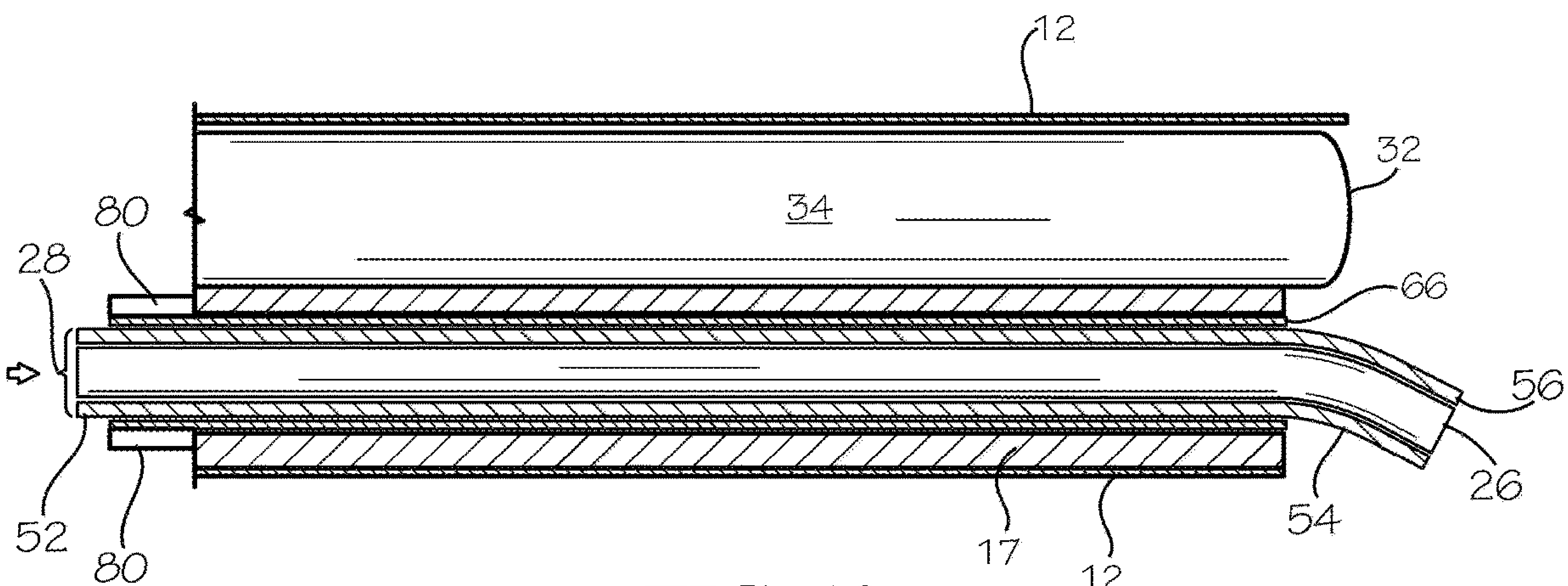

FIG. 18

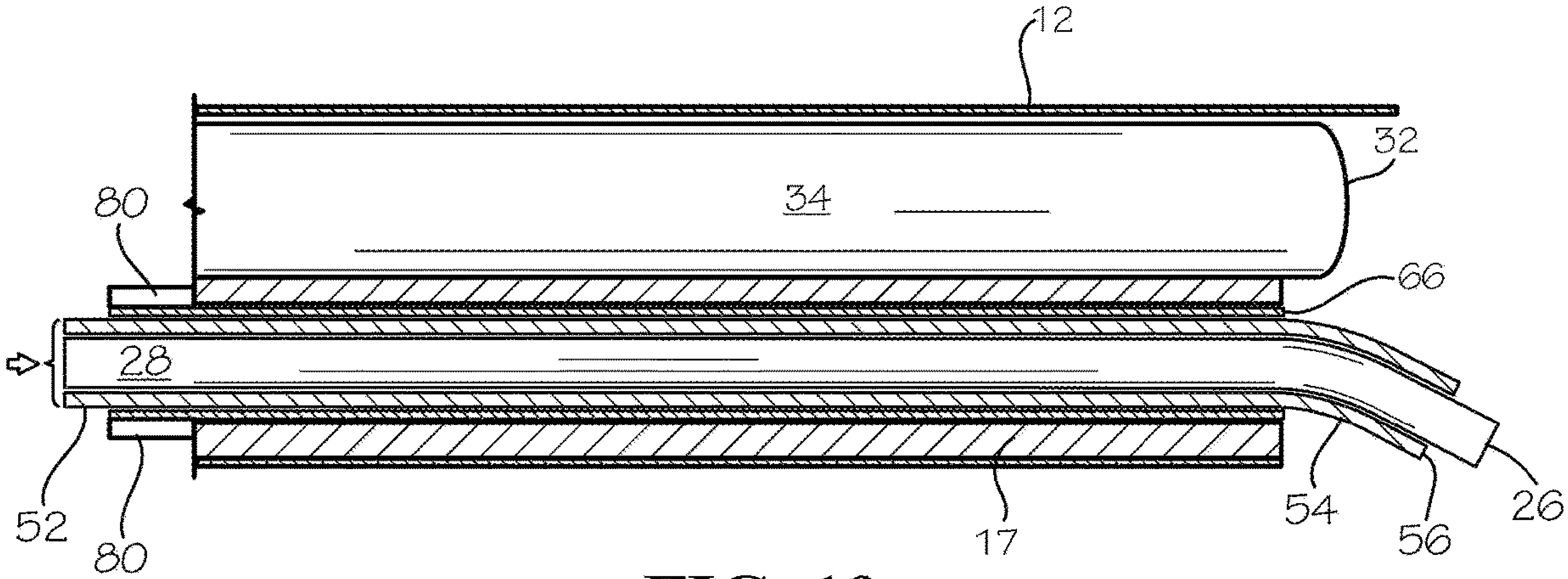
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FIG. 19

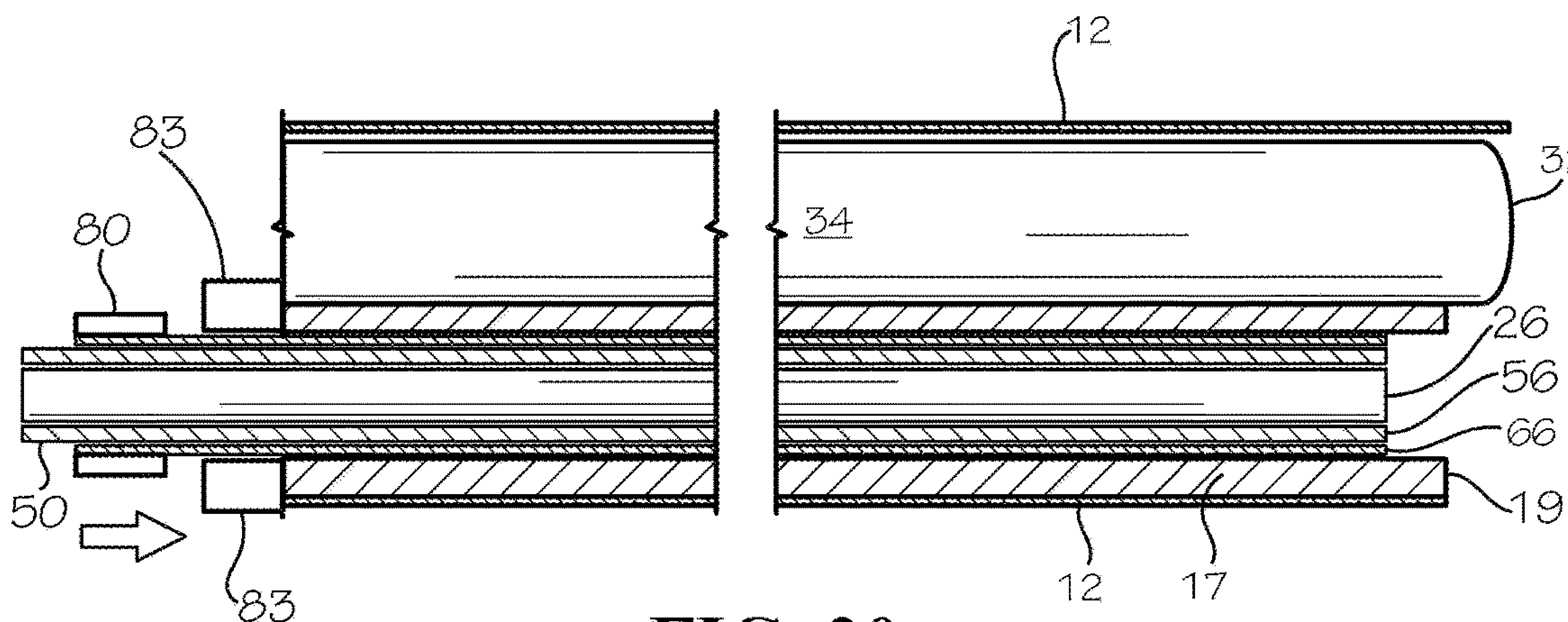
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FIG. 20

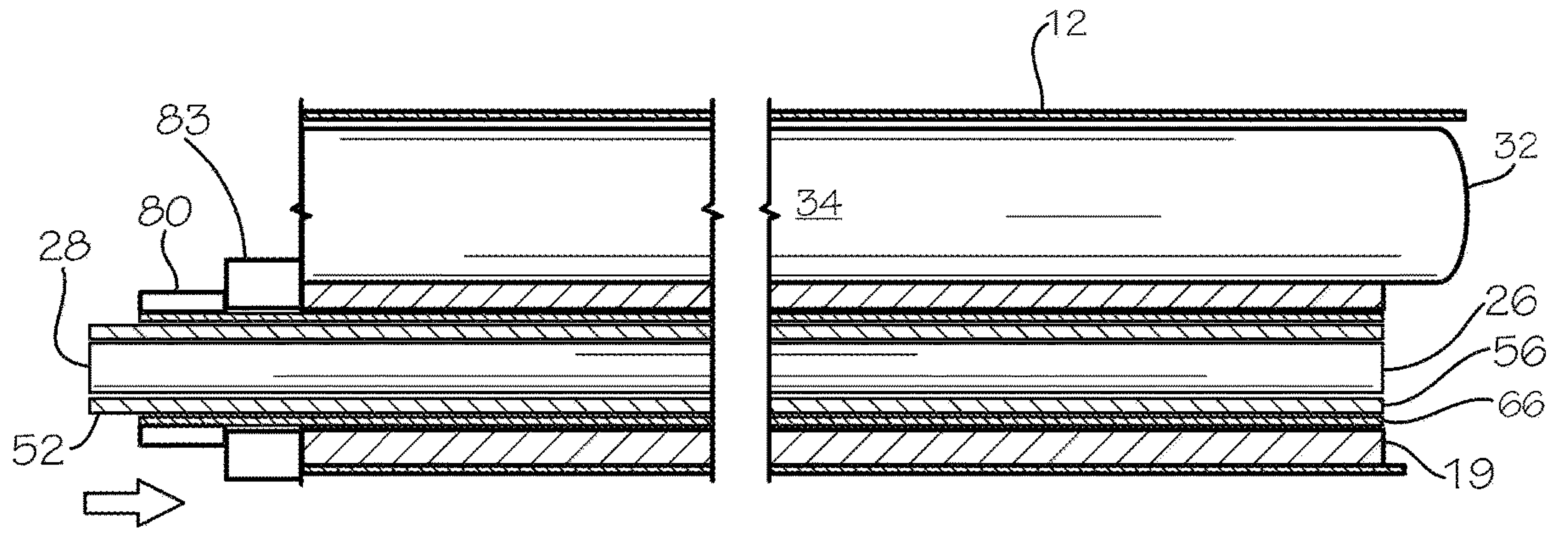
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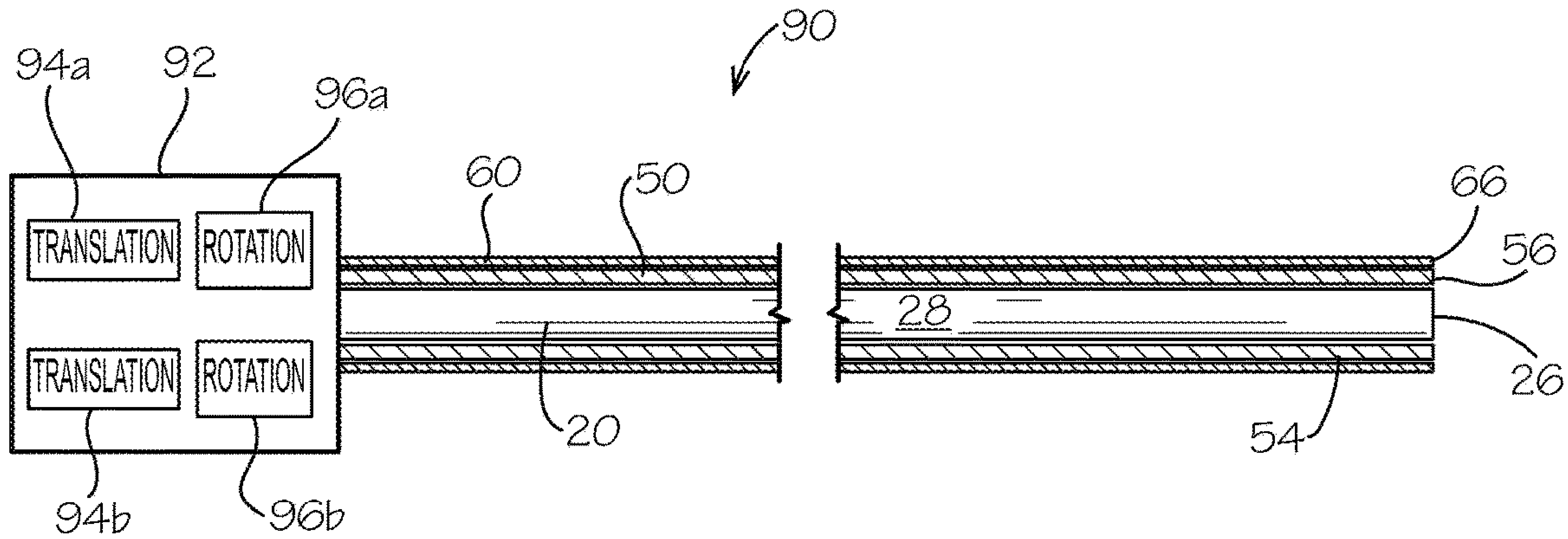
FIG. 21


90
94a
92
96a
TRANSLATION
ROTATION
TRANSLATION
ROTATION
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94b
96b

FIG. 22

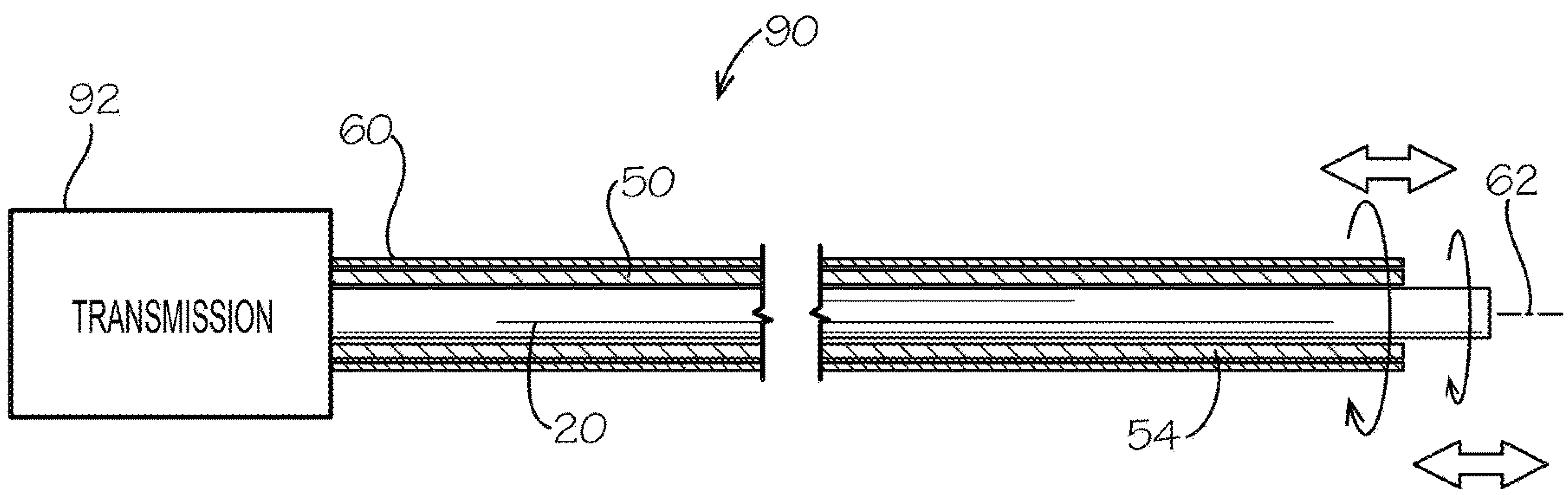


FIG. 23

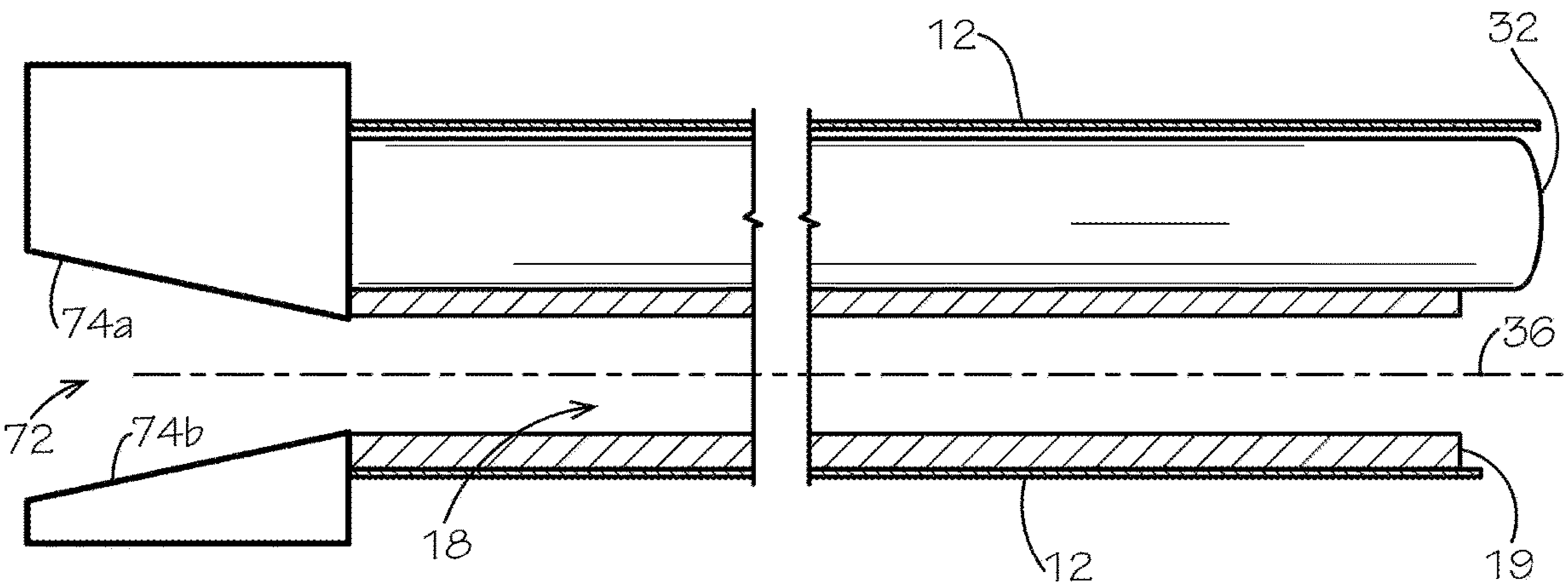


FIG. 24

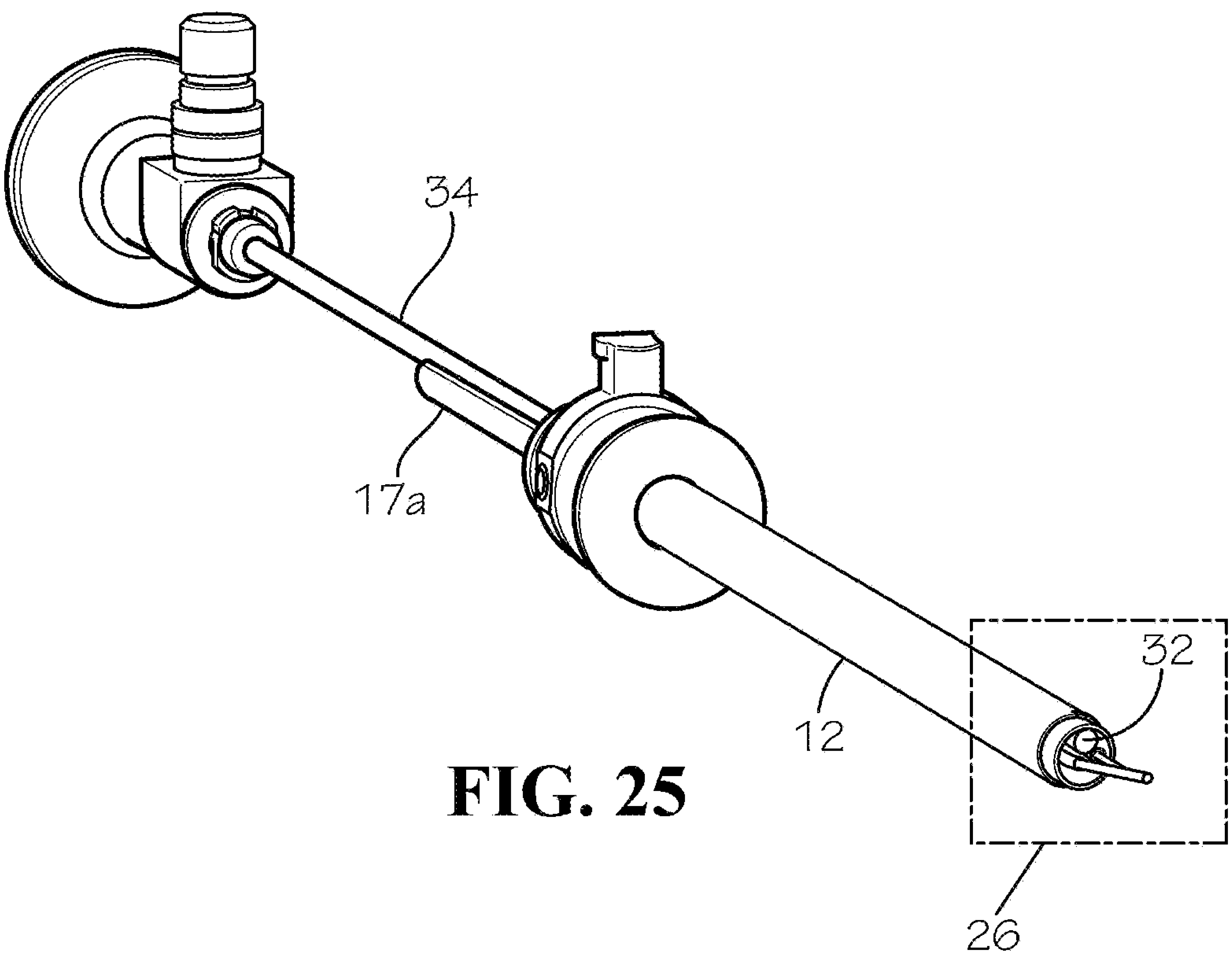


FIG. 25

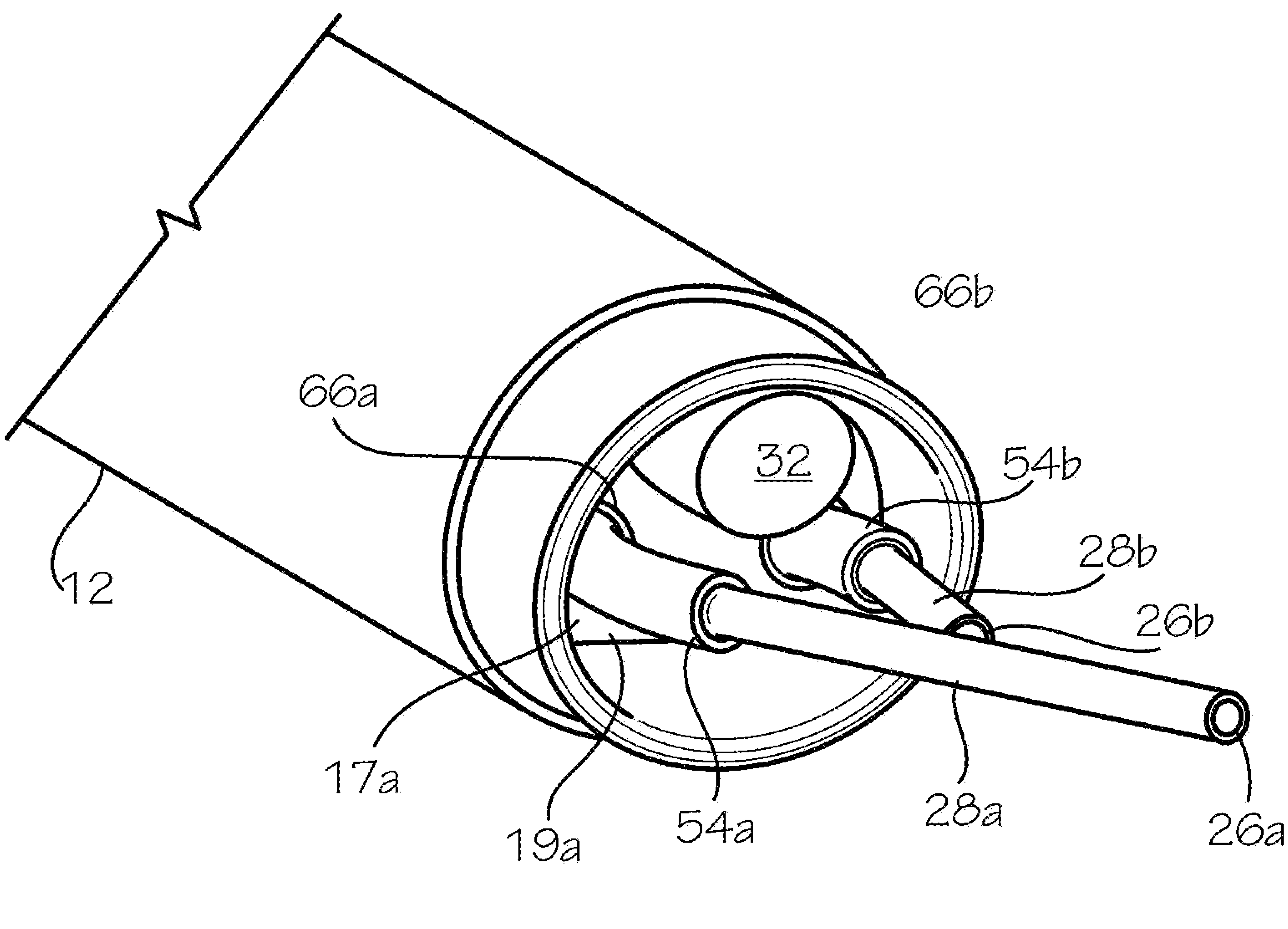
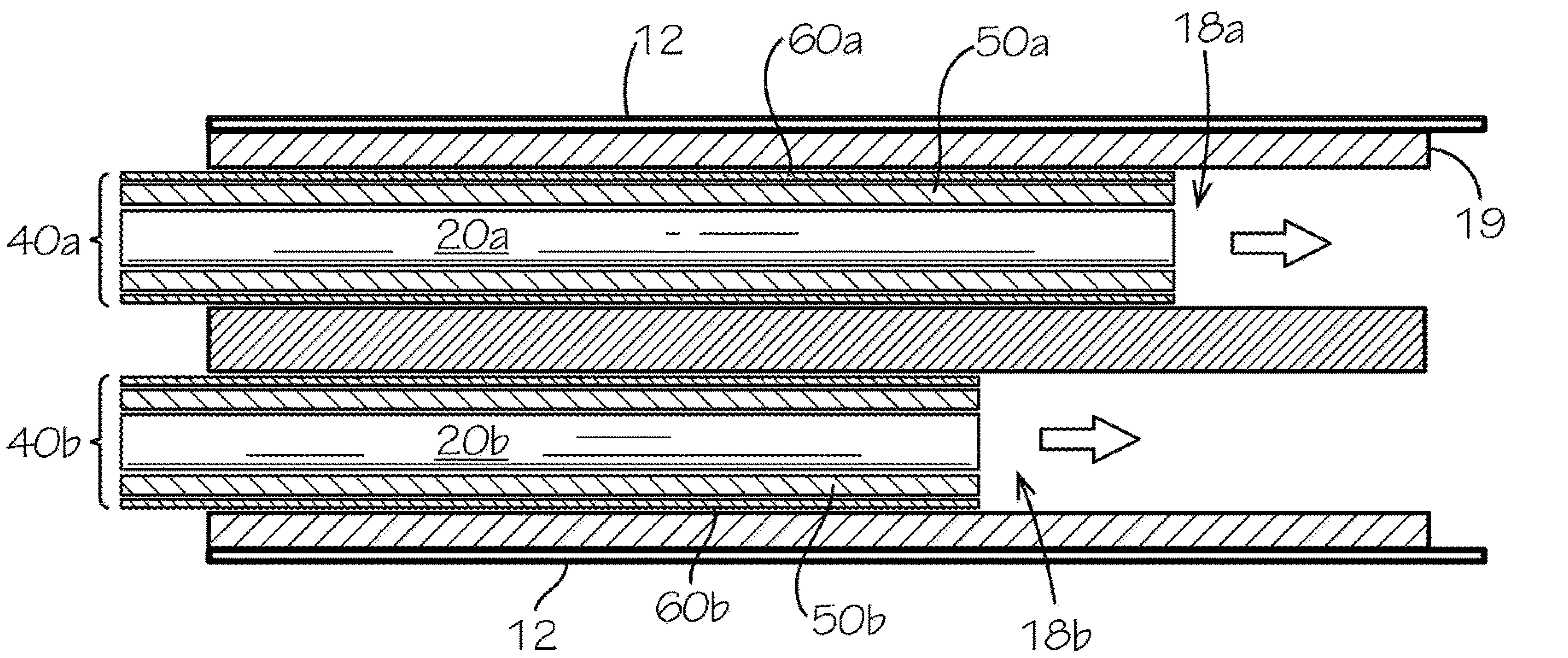


FIG. 26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20b
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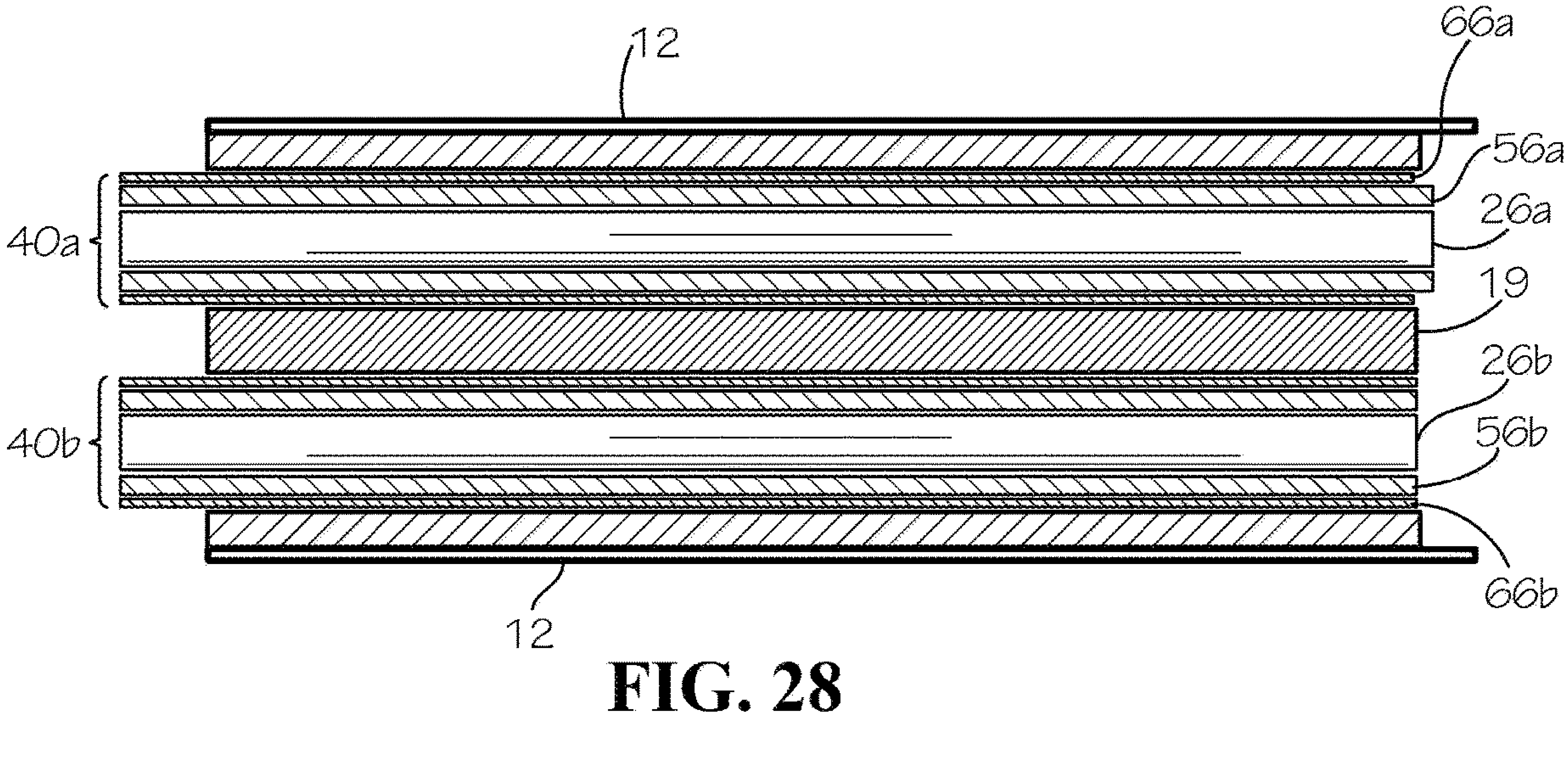
18b

FIG. 27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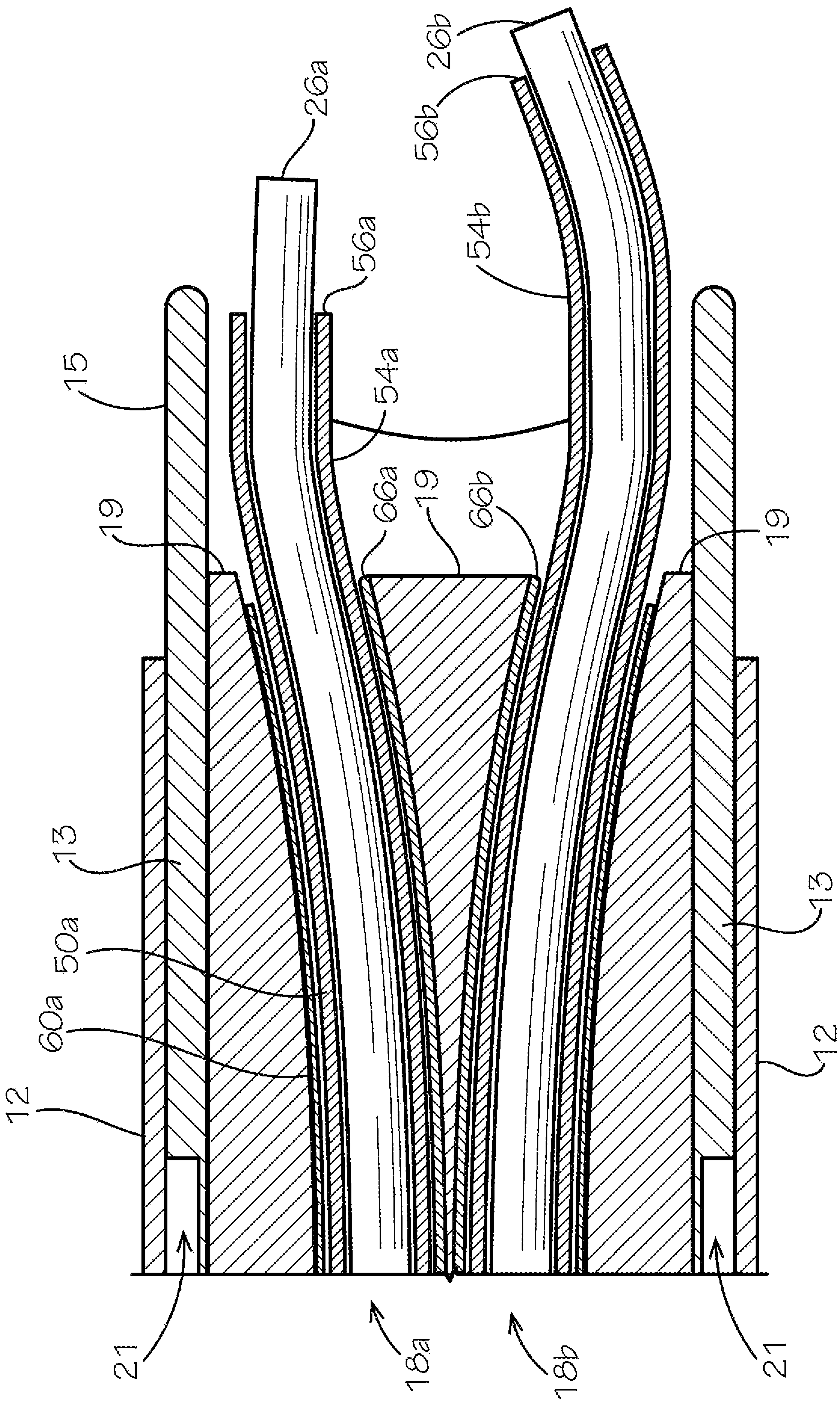
12
66b

FIG. 28


26b
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56a
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66b
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60a
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21
18a
18b
21

FIG. 29

INSERTABLE TUBE SURGICAL ROBOT

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a continuation of, and claims benefit of and priority to, U.S. patent application Ser. No. 16/446,202 filed Jun. 19, 2019 entitled INSERTABLE ROBOT FOR MINIMALLY INVASIVE SURGERY, which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under R44EB024423 awarded by the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

[0003] The present invention relates to surgical instruments and associated methods for performing surgery. More particularly, the present invention relates to tools and methods for minimally invasive surgery using concentric tube robot assemblies.

[0004] Minimally invasive surgery using electromechanical robots is a developing field of medicine. Conventional devices for performing minimally invasive surgery, such as endoscopes and resectoscopes, generally include a distal tip that is inserted through an incision in a patient's body or a natural orifice in a patient's body. The distal tip includes an optical lens which allows a surgeon to see a field of view proximate to the distal tip when placed inside the body. The endoscope will typically have a camera attached to it to display the field of view on an operating room monitor. In some applications the endoscope includes a camera installed on the distal tip of the endoscope. The device also includes a working channel extending through the device. One or more elongated surgical tools may be inserted through the working channel. A tool such as a cutting device, a basket or a laser optic may be included on the surgical tool. The distal end of the surgical tool protrudes from the distal tip of the device, thereby allowing the surgeon to visually observe operation of the tool inside the patient's body during an operation.

[0005] Conventional surgical tools for use through the narrow working channel of an endoscope or resectoscope are generally limited in size, and are particularly limited in the maximum effective outer diameter. Because such tools must be passed through the working channel to reach the surgical site inside the body, the tools must be small enough in outer diameter to be inserted axially into the bore of a working channel in an endoscope or resectoscope. The working channel diameter in an endoscope or resectoscope is generally in the range of about one to twenty millimeters, but the devices may have different inner diameters outside of this range depending on the application. Thus, a surgical tool to be inserted through the working channel must include a similar, or a smaller, effective outer diameter to be smoothly inserted through the channel to reach the surgical site.

[0006] During a surgical procedure, it may become necessary to change a surgical tool. For example, a laser cutting fiber may need to be removed from the endoscope or resectoscope via the working channel, and a mechanical manipulator may need to be inserted through the working channel. Manipulators allow a surgeon to move the distal end of the surgical tool protruding from the distal tip of the endoscope without actually moving the endoscope. This may reduce trauma on the patient in some applications.

[0007] When a surgical tool is changed during a procedure, a first tool may be slid axially out of the working channel in a direction away from the patient, and a second tool may be slid axially into the working channel, or inserted into the working channel, in a direction toward the patient. The second tool is inserted until the distal end of the working tool is in a position to advance toward the surgical site. However, if the first or second surgical tool has a highly curved distal end, or a distal end with a large expanded profile, the second tool may not properly fit into the working channel. Thus, it may be difficult or impossible to insert the surgical tool with a curved or large profile tip into the working channel toward the patient.

[0008] What is needed then are improvements in devices and methods for performing robotic surgery.

BRIEF SUMMARY

[0009] The present invention relates generally to devices and methods for performing minimally invasive surgery. In some embodiments, the present invention includes a surgical robot apparatus including a guide tube with a curved working end housed inside a straightening tube, wherein the straightening tube at least partially straightens the curved working end of the guide tube such that the guide tube and straightening tube may be inserted simultaneously as a combined assembly through the small diameter working channel of the shaft on an endoscope, resectoscope or trocar. In various embodiments, the assembly may include additional tubes, such as an inner tube passing through the guide tube in addition to the surgical tool.

[0010] Following insertion of the guide tube and straightening tube into the working channel, the guide tube may be axially translated through the straightening tube toward a patient's body allowing the curved working end to extend from the distal end of the straightening tube and assume its naturally biased curved orientation. A surgical tool such as a laser optic, cutting tool, forceps, basket or other instrument is passed axially through the guide tube extending from the distal tip of the guide tube. The curvature of the guide tube allows a surgeon improved range of motion for the surgical tool inside the patient's body, when compared with traditional straight surgical tools. The guide tube is coupled to a transmission that allows the guide tube to be translated or rotated during a procedure to steer the surgical tool to desired tissue.

[0011] In some embodiments, the present invention includes a concentric tube robot apparatus for performing minimally invasive surgery. The apparatus includes a tube array with a guide tube and a straightening tube. The guide tube includes a curved working end. The guide tube may be translated and rotated relative to the straightening tube such that the curved working end is housed inside and constrained by the straightening tube, thereby allowing the tube array to be inserted into a narrow working channel of an endoscope, resectoscope or trocar. A transmission is also coupled to the tube array in some embodiments, providing an interchangeable cartridge configuration that can be installed or removed as a complete unit on a surgical robot during a procedure.

[0012] One objective of the present disclosure is to provide a surgical robot apparatus that allows a user to change surgical tools during surgery without removing the endoscope, resectoscope or trocar shaft from the patient's body.

[0013] Another objective of the present disclosure is to provide a surgical robot apparatus that allows a guide tube with a highly curved working end to be inserted axially through a narrow working channel on an endoscope, resectoscope or trocar.

[0014] A further objective of the present disclosure is to provide a surgical robot apparatus that includes a modular tube array with an integrated surgical tool that can be quickly changed during a surgical procedure by sliding the tube array into or out of a longitudinal straight or slightly curved working channel on a stationary endoscope, resectoscope or trocar.

[0015] Numerous other objects, features and advantages of the present invention will be readily apparent to those skilled in the art upon a reading of the following disclosure when taken in conjunction with the accompanying drawings and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. **1** illustrates a perspective view of a prior art embodiment of an endoscope including a surgical tool with an end effector protruding from the distal tip.

[0017] FIG. **2**A illustrates a detail perspective view of a prior art embodiment of an endoscope distal tip with a lens and a working channel opening below the lens.

[0018] FIG. **2**B illustrates a detail cutaway perspective view of the prior art embodiment of an endoscope of FIG. **2**A with a surgical tool and end effector protruding from the distal tip.

[0019] FIG. **3** illustrates a perspective view of a prior art embodiment of an endoscope with separate concentric tube manipulator assemblies protruding from the distal tip.

[0020] FIG. **4** illustrates a perspective view of an embodiment of a guide tube with a curved distal end.

[0021] FIG. **5** illustrates a partial perspective view of an embodiment of a guide tube with a distal end being positioned inside a straightening tube.

[0022] FIG. **6** illustrates a partial perspective view of the embodiment of a guide tube in FIG. **5** positioned inside the straightening tube such that a portion of the curved distal end of the guide tube is received inside and straightened by the straightening tube.

[0023] FIG. **7** illustrates a cross-sectional view of an embodiment of a guide tube with a curved distal end housed inside a straightening tube.

[0024] FIG. **8** illustrates a cross-sectional view of an embodiment of a guide tube with a curved distal end partially protruding from the straightening tube.

[0025] FIG. **9** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly partially inserted through the working channel.

[0026] FIG. **10** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel to a ready position.

[0027] FIG. **11** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel, with the guide tube and surgical tool partially extending from the straightening tube.

[0028] FIG. **12** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel, with the guide tube and surgical tool partially extending from the straightening tube.

[0029] FIG. **13** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel, with the guide tube extending from the straightening tube, and the surgical tool extending from the guide tube.

[0030] FIG. **14** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel, with the guide tube and surgical tool partially extending from the straightening tube and rotated about the working channel axis.

[0031] FIG. **15** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly inserted through the working channel, with the guide tube partially extending from the straightening tube and rotated about the working channel axis and the surgical tool extending from the guide tube.

[0032] FIG. **16** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly partially inserted through the working channel with an axial stop positioned to limit translation of the straightening tube to a desired position in the working channel.

[0033] FIG. **17** illustrates a partial cross-sectional view of the embodiment of an endoscope, resectoscope or trocar of FIG. **16** including a straightening tube, guide tube and surgical tool assembly inserted through the working channel with the axial stop limiting translation of the straightening tube to a desired position in the working channel.

[0034] FIG. **18** illustrates a partial cross-sectional view of the embodiment of an endoscope, resectoscope or trocar of FIGS. **16** and **17** including a straightening tube, guide tube and surgical tool assembly inserted through the working channel with the axial stop limiting translation of the straightening tube to a desired position in the working channel and the guide tube and surgical tool extending from the straightening tube.

[0035] FIG. **19** illustrates a partial cross-sectional view of the embodiment of an endoscope, resectoscope or trocar of FIGS. **16**, **17** and **18** including a straightening tube, guide tube and surgical tool assembly inserted through the working channel with the axial stop limiting translation of the straightening tube to a desired position in the working channel, the guide tube extending from the straightening tube, and the surgical tool extending from the guide tube.

[0036] FIG. **20** illustrates a partial cross-sectional view of an alternative embodiment of an endoscope, resectoscope or trocar including a straightening tube, guide tube and surgical tool assembly partially inserted through the working channel with an axial stop positioned to limit translation of the straightening tube to a desired position in the working channel.

[0037] FIG. **21** illustrates a partial cross-sectional view of the embodiment of an endoscope, resectoscope or trocar of FIG. **20** including a straightening tube, guide tube and surgical tool assembly inserted through the working channel with the axial stop limiting translation of the straightening tube to a desired position in the working channel.

[0038] FIG. **22** illustrates a partial cross-sectional schematic view of an embodiment of a robotic assembly with a surgical tool, a guide tube and a straightening tube coupled to a transmission including guide tube translation and rotation and surgical tool translation and rotation drives.

[0039] FIG. **23** illustrates a partial cross-sectional view of an embodiment of a tube array with a transmission for insertion into a working channel.

[0040] FIG. **24** illustrates a partial cross-sectional view of an embodiment of an endoscope with an insertion port at the proximal end of the working channel.

[0041] FIG. **25** illustrates a perspective view of an embodiment of a resectoscope including an optical lens partially inserted into the shaft.

[0042] FIG. **26** is a detail perspective view of Section **26** from FIG. **25**.

[0043] FIG. **27** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including first and second working channels and tube arrays.

[0044] FIG. **28** illustrates a partial cross-sectional view of an embodiment of an endoscope, resectoscope or trocar including first and second working channels and tube arrays.

[0045] FIG. **29** illustrates a partial cross-sectional view of an embodiment of surgical robot assembly including first and second tube arrays positioned in first and second working channels, each having a curved working end partially extended from its corresponding straightening tube.

DETAILED DESCRIPTION

[0046] Referring now to the drawings, various views of embodiments of devices and methods for performing minimally invasive surgery are illustrated. In the drawings, not all reference numbers are included in each drawing, for the sake of clarity. The devices shown in the illustrations are not intended to illustrate all possible embodiments of the claimed invention, but are rather included as examples. A person of skill in the art will understand the devices and methods of the claimed invention may include different configurations and orientations not shown in the figures.

[0047] The present disclosure provides an insertable concentric tube assembly for minimally invasive surgery. During conventional minimally invasive surgery, a surgical instrument such as an endoscope, resectoscope or trocar includes a distal tip inserted into a patient's body through a small incision. A surgical tool including an end effector such as a cutting tool, probe, forceps, basket, laser fiber or other surgical tool protrudes from the distal tip for performing an operation on patient tissue. An optical lens positioned proximate the distal tip allows a surgeon to visually observe the surgical tool in vivo during the operation.

[0048] An example of a conventional endoscope device **10** for performing minimally invasive surgery is shown in FIG. **1**. The device **10** includes a longitudinal shaft **12** having a distal end **14** and a proximal end **16**. The longitudinal shaft **12** includes a hollow interior allowing the passage of one or more surgical instruments **20**. Surgical instrument **20** includes a surgical tool with an end effector **22**, such as a cutting tool or forceps, disposed on the distal tool end **26** as shown in FIG. **1**. The surgical instrument **20** includes a tool actuator **24** on one end and a tool shaft **28** extending from the tool actuator. The tool shaft **28** is inserted into the longitudinal shaft **12** of the endoscope device **10** such that the distal tool end **26** and the end effector **22** protrude from an opening at the distal end **14** of the of the device **10**.

[0049] During surgery, the distal end **14** of the device **10**, together with the distal tool end **26** and end effector **22** are inserted into a patient's body. The tool actuator **24** may then be manipulated to activate the end effector **22**, for example to perform a cutting operation to remove patient tissue from within the body. During this procedure, the surgical tool **20** may be manipulated relative to the device **10** by moving the surgical tool axially such that the tool shaft translates within the longitudinal shaft **12**, thereby moving the longitudinal position of the end effector **22** relative to the distal end **14** of the device **10**. Additionally, the surgical instrument **20** may be rotated angularly about the longitudinal axis of the shaft **12**, thereby causing the end effector **22** to rotate relative to the distal end **14** of the device **10**.

[0050] During minimally invasive surgery, it is beneficial for a surgeon to be able to visually observe the position of the end effector **22** relative to the tissue undergoing operation. As shown in FIG. **1**, endoscope device **10** in some embodiments includes an optical port **30** for a camera or optic to be inserted into the device **10** such that the camera or optic extends through the interior of the longitudinal shaft **12** alongside the tool shaft **28**.

[0051] An example of a distal end **14** of a tubular, hollow longitudinal shaft **12** of a conventional endoscope, resectoscope or trocar is shown in FIGS. **2**A and **2**B. The longitudinal shaft **12** includes an end opening **19** at the distal end **14**. A hood **15** surrounds the end opening **19** in some embodiments. A working channel **18** is defined through the hollow interior of the longitudinal shaft **12**, and one or more tools may be passed through the working channel **18** toward the end opening **19**. An optical lens **32** is positioned proximate the end opening **19** in some embodiments. The optical lens **32** is coupled to an optical fiber **34** to provide imaging capabilities to a surgeon. The optical fiber **34** extends through the working channel **18** of the longitudinal shaft **12**.

[0052] Also shown in FIGS. **2**A and **2**B, a conventional tool shaft **28** extends through the working channel **18** toward the end opening **19** at the distal end **14** of the longitudinal shaft **12**. The tool shaft **28** is part of a surgical instrument that may be manipulated manually by a surgeon or teleoperated by a surgeon using a robotic interface to actuate end effector **22** and to move distal tool end **26** axially or angularly relative to tool shaft axis **29**. During a procedure, tool shaft **28** may be axially translated in and out of end opening **19** manually or using a mechanized transmission linkage coupled to the tool shaft **28**. Additionally, during a procedure, tool shaft **28** may also be rotated angularly about tool shaft axis **29** manually or using a transmission linkage coupled to the tool shaft **28**.

[0053] Referring to FIG. **3**, in some embodiments, it is desirable to include two surgical tools **20***a*, **20***b* protruding from end opening **19**. Each tool includes an end effector that may be positioned using one or more concentric tubes **25***a*, **25***b*, **25***c*, **25***d*. Such configurations are known in the art for allowing a surgeon to position and steer the end effectors to a desired location at the surgery site. However, such multiple concentric tube configurations are generally fixed and are not insertable through a working channel in an endoscope, resectoscope or trocar due to the relatively large effective diameter of each concentric tube working end caused by the curvature of each tube. As such, conventional concentric tube assemblies for surgical robotics are not amenable to be interchanged by insertion and removal through a small diameter working channel in an endoscope, resectoscope or trocar.

[0054] An example of an elongated tube for guiding a surgical tool through a working channel of an endoscope, resectoscope or trocar is shown in FIG. **4**. The various tubes illustrated herein are not drawn to scale, and may include various aspect ratios, lengths, inner diameters, outer diameters, wall thicknesses and curvature profiles not shown. Person of skill in the art will readily understand that the tubes disclosed herein may take many different embodiments in practice. A guide tube **50**, or inner tube, is shown in FIG. **4**. Guide tube **50** includes a guide tube body **52** and a curved working end **54** at the distal end of the guide tube body **52**. Guide tube **50** includes a hollow interior and may comprise any suitable material such as a metal or metal alloy. In some embodiments, guide tube **50** comprises a nickel-titanium, or Nitinol, alloy. Guide tube **50** is generally used to steer a surgical tool to a desired location at a surgical site at the distal tip of an endoscope, resectoscope or trocar. The surgical tool may be axially housed inside the guide tube **50**, and the surgical end effector may be deployed or retracted in vivo through the guide tube distal end opening **56**.

[0055] The curved working end **54** of the guide tube **50** is pre-shaped to have a desired curvature profile. In some embodiments, the curvature profile of the curved working end **54** is optimized to provide maximum steerability of the surgical end effector in the field of view of the optical lens **32**.

[0056] One drawback of having a curved working end **54** on a guide tube **50** is the curvature profile of the guide tube curved working end **54** causes the guide tube **50** to have an effective outer dimension, or effective diameter, W. In most applications, the guide tube effective diameter W is greater than a corresponding working channel inner diameter on an endoscope, resectoscope or trocar. Thus, it can be difficult or impossible to insert or remove a guide tube **50** with a curved working end **54** axially through the working channel.

[0057] As shown in FIGS. **5** to **7**, in some embodiments, an outer tube or straightening tube **60** may be positioned over the outside of the guide tube **50**. Straightening tube **60** includes a cylindrical tube with a hollow interior. The inner diameter of the straightening tube **60** is slightly larger than the outer diameter of the guide tube **50** such that the guide tube **50** fits closely inside the straightening tube **60** yet is still able to translate axially and rotate relative to the straightening tube **60**. As shown in FIG. **5**, straightening tube **60** includes a straightening tube distal end **66** and a straightening tube distal end opening **68**. The guide tube **50** is received in the straightening tube distal end opening **68**. When the curved working end **54** of the guide tube **50** is translated into the straightening tube **60**, the curved working end **54** is deflected or strained away from its biased curved position toward the guide tube axis **51**. When the curved working end **54** of the guide tube **50** is fully seated inside the straightening tube **60**, as shown in FIG. **7**, the guide tube distal end opening **56** is axially aligned with the straightening tube distal end **66**. In this position, the curved working end **54** is also constrained by the straightening tube such that the curved working end **54** is significantly straightened. In such embodiments, the overall effective outer diameter of the straightening tube distal end **66** and the curved working end **54**, D, is substantially equal to the outer diameter of the straightening tube **60**.

[0058] In some embodiments, the curved working end **54** may impart a force on the straightening tube distal end **66** causing the straightening tube distal end **66** to flex slightly. However, the strain placed on the straightening tube is generally not significant enough to prevent the straightening tube **60** from being able to be inserted through a working channel.

[0059] As shown in FIG. **8**, the guide tube **50** may be translated axially inside the straightening tube **60** to expose a portion of the curved working end **54** from the distal end of the straightening tube **66**. As the guide tube **50** is axially translated causing the curved working end **54** to protrude out of the straightening tube distal end **66**, the curved working end **54** returns to its pre-curved biased position away from the straightening tube axis **62**. The orientation of the guide tube distal end opening **58** is controlled by precise translation and rotation of the guide tube **50** and the straightening tube **60**.

[0060] Referring to FIGS. **9** and **10**, guide tube **50** includes a guide tube body **52** and guide tube curved working end **54** housed inside a straightening tube **60**. The guide tube and straightening tube assembly **50**, **60** together includes a dimensional profile allowing the assembly to be inserted through the working channel **18** defined by working channel inner wall **17**. Working channel **18** includes an inner working channel diameter **38** formed in the longitudinal shaft **12** of the endoscope, resectoscope or trocar. Working channel **18** includes a distal end **19** including an opening formed at the distal tip of the working channel. The guide tube and straightening tube assembly **50**, **60** may be inserted through the working channel at the same time, as shown in FIG. **9**. Additionally, during insertion of the guide tube and straightening tube assembly **50**, **60**, a surgical tool having a surgical tool shaft **28** and surgical tool distal end **26** may also be housed inside the guide tube **50**. During insertion of the guide tube and straightening tube assembly **50**, **60**, the guide tube distal end **56** and straightening tube distal end **66** are axially aligned with the surgical tool distal end **26** in some applications.

[0061] As shown in FIG. **10**, the guide tube and straightening tube assembly **50**, **60** is inserted through the working channel **18** until the guide tube distal end **56** and straightening tube distal end **66** are axially aligned with the working channel distal end **19**. In this position, the surgical tool distal end **26** is also axially aligned with the guide tube distal end **56** and straightening tube distal end **66**. At this ready position, forward translation of the straightening tube **60** is limited; however, the guide tube **50** and surgical tool **20** may be translated in tandem or independently axially relative to the stationary straightening tube **60** as shown in FIG. **11**. The forward translation of the guide tube distal end **56** and straightening tube distal end **66** are controlled by a manual actuator or an electro-mechanical transmission linkage coupled to the tubes. As the guide tube distal end **56** and straightening tube distal end **66** advance axially out of the opening at the distal end of the straightening tube, the curved working end **54** of the guide tube **50** returns to its pre-shaped curvature in its preferred biased position. In some applications, the straightening tube distal end **66** may extend beyond the working channel distal end **19** into the surgical field to further effect manipulation of the guide tube and surgical tool.

[0062] The guide tube angle **53** is a function of the axial position of the guide tube curved working end **54** relative to the straightening tube **60**. As the guide tube **50** advances forward away from straightening tube **60**, the guide tube angle **53** increases until the curved working end **54** assumes its fully biased curvature profile. When the guide tube **50** is retracted relative to the straightening tube **60**, the guide tube angle **53** decreases toward a limit of zero in some embodiments as the curved working end **54** is drawn into the straightening tube **60**.

[0063] Once the guide tube **50** is translated and rotated into a desired position, for example as shown in FIG. **12**, the surgical tool **20** may be deployed by axially translating the surgical tool shaft **28** through the guide tube **50**. Such translation of the surgical tool shaft **28** causes the surgical tool distal end **26** to protrude beyond the guide tube distal end **56**, as shown in FIG. **13**. In further embodiments, the surgical tool distal end **26** is fixed to the guide tube distal end **56** such that the surgical tool distal end **26** is not translatable axially relative to the guide tube **50**.

[0064] As shown in FIGS. **14-15**, the guide tube may be subsequently rotated and/or translated while also moving the axial position of the surgical tool shaft **28** to maneuver the surgical tool distal end **26** to a desired location. The ability to rotate and translate guide tube **50** relative to straightening tube **60**, combined with the ability to translate surgical tool shaft **28** relative to guide tube **50**, provides a technical solution with multiple degrees of freedom for enhancing steerability of the surgical end effector inside the field of view of the lens **32**.

[0065] Referring to FIGS. **16-19**, in some applications it is desirable to stop the axial translation of the guide tube distal end **56** and straightening tube distal end **66** at the distal end of the working channel. An axial stop **80** may be disposed on or linked to the straightening tube **60**. Axial stop **80** can take many forms, including an annular flange protruding radially from the proximal end of straightening tube **60**. Axial stop **80** interferes with a corresponding mechanical structure on the apparatus when the straightening tube distal end **66** is axially aligned with the distal end of the working channel, as shown in FIG. **17**. The structure engaging axial stop **80** to limit forward travel of straightening tube **60** may include a shoulder on the proximal end of the working channel **82** in some embodiments. When the axial stop **80** approaches and contacts the working channel proximal end at a contact location **84**, forward travel of the straightening tube **60** is stopped. From the position where the straightening tube **60** is limited in forward travel by axial stop **80**, guide tube proximal end **52** may be freely advanced forward relative to stationary straightening tube **60**, thereby allowing the curved working end **54** and surgical tool distal end **26** to advance out of the straightening tube distal end **66** together as shown in FIG. **18**. Once the guide tube curved working end **54** reaches a desired orientation, the surgical tool distal end **26** may be deployed from the guide tube distal end **56** by translating the surgical tool shaft **28** forward. Likewise, the surgical tool distal end **26** may be retracted relative to the guide tube **54** by reversing the translation direction of the surgical tool shaft **28**.

[0066] In further embodiments, as shown in FIGS. **20** and **21**, the axial stop **80** on straightening tube **60** engages a structure **83** outside of the working channel to stop the forward axial translation of the guide tube **50** and straightening tube **60**. When the axial stop **80** contacts structure **83**, the forward translation of straightening tube **60** is stopped. In some embodiments, the relative locations of axial stop **80** and structure **83** are positioned such that when contact is made, the straightening tube distal end **66** and the guide tube distal end **56** are axially aligned with the working channel distal end **19**. From this position, the guide tube **50** may be translated forward to extend the curved working end of the guide tube and to deploy the surgical tool distal end **26**.

[0067] In some applications, during a surgical procedure, it is desirable to remove a surgical tool from the endoscope, resectoscope or trocar through the working channel while the device is positioned inside a patient's body without removing the endoscope, resectoscope or trocar. For example, a different surgical tool may be needed for a different stage of an operation. To accommodate this, in some embodiments the present invention provides a concentric tube robot apparatus **90** including a transmission **92** coupled to a tube array. The tube array includes a guide tube **50** with a curved working end **54** housed inside a straightening tube **60**. The guide tube **50** is straightened at least partially by the straightening tube **60** so that the tube array may be axially inserted into or removed from a working channel on an endoscope, resectoscope or trocar.

[0068] Concentric tube robot apparatus **90** also includes a surgical tool with a shaft and an end effector housed within the guide tube **50**. The guide tube **50** may be axially translated and rotated relative to the straightening tube **60**. The axial translation and rotation of the guide tube **50** is driven by a guide tube translation drive **94*a*** and a guide tube rotation drive **96*a***. Each of the guide tube translation drive **94*a*** and guide tube rotation drive **96*a*** are mechanically coupled to guide tube **50** inside transmission **92**. The guide tube translation drive **94*a*** controls axial translation of guide tube **50** relative to straightening tube **60**. The guide tube rotation drive **96*a*** controls angular rotation of guide tube **50** relative to straightening tube **60**. Each guide tube drive may be driven manually or using an electro-mechanical actuator such as a gear box or motor.

[0069] Also shown in FIGS. **22** and **23**, in some embodiments, transmission **92** also includes a surgical tool translation drive **94*b*** and a surgical tool rotation drive **96*b***. The axial translation and rotation of the surgical tool **20** relative to the guide tube **50** is controlled by the translation and rotation drives **94*b***, **96*b***, respectively.

[0070] When it is desired to change a surgical tool, a removable concentric tube robot apparatus **90**, forming a removable cartridge, may be removed as a single unit from the device by sliding the tube array out of the working channel. During removal, the straightening tube **60** is operable to constrain the curved working end of the guide tube enough to facilitate removal of the tube array through the longitudinal working channel. A second concentric tube robot apparatus may be inserted through an insertion port, **72**, shown in FIG. **24**, at the proximal end of the endoscope, resectoscope or trocar. The insertion port **72** provides an opening for insertion of the tube array and surgical tool assembly on the concentric tube robot apparatus **90**. In some embodiments, insertion port **72** includes a ramped surface including first and second ramps **74***a*, **74***b*. In other embodiments, insertion port **72** includes an axisymmetric funnel shaped to feed the distal tip of the tube array into the proper location along the working channel longitudinal axis **36** for insertion into and through the working channel **18**.

[0071] Referring to FIGS. **25** and **26**, in additional embodiments, an endoscope, resectoscope or trocar includes a shaft **12** with a hollow interior. The shaft **12** receives an optic element **34** such as a rod lens or optical fiber that extends longitudinally through the shaft **12**. Alternatively, optic element **34** can include a cable to a chip-tip style camera positioned on the distal end of the working channel including lens **32**. A working channel may be defined through the interior region on the shaft below the optical element **34** in some embodiments. In other embodiments, the working channel is defined in a cannula, or working channel insert **17***a* positioned inside the hollow interior of shaft **12**. Additionally, as shown in FIG. **26**, in some applications it is desirable to include two surgical tools with surgical tool distal ends **26***a*, **26***b* positioned in the field of view of lens **32**. Each surgical tool is housed within a corresponding guide tube. First surgical tool distal end **26***a* and tool shaft **28***a* extend from first guide tube curved working end **54***a*. Second surgical tool distal end **26***b* and tool shaft **28***b* extend from second guide tube curved working end **54***b*. As shown in FIG. **26**, first and second tube arrays are positioned in separate working channels formed in a working channel insert **17***a* having a working channel insert distal end **19***a*. The first tube array includes a straightening tube with a first straightening tube distal end **66***a* axially aligned with the distal end **19***a* of the working channel insert **17***a*. Similarly, the second tube array includes a straightening tube with a second straightening tube distal end **66***b* axially aligned with the distal end **19***a* of the working channel insert **17***a*. As such, the first and second straightening tube distal ends **66***a*, **66***b* do not extend from the working channel openings at the distal end of the working channel insert. A first guide tube curved working end **54***a* protrudes from the first straightening tube distal end **66***a*, and a second guide tube curved working end **54***b* protrudes from the second straightening tube distal end **66***b*. Each guide tube and straightening tube may be rotated and translated. In some embodiments, each guide tube and straightening tube may be rotated together. A first surgical tool distal end **26***a* may be translated in and out of first guide tube curved working end **54***a*, and second surgical tool distal end **26***b* may be translated in and out of second guide tube curved working end **54***b*.

[0072] A partial cross-sectional view of an embodiment of a shaft with first and second tube arrays is shown in FIGS. **27** and **28**. Referring to FIG. **27**, a first tube array **40***a* is inserted in a first working channel **18***a*, and a second tube array **40***b* is inserted in a second working channel **18***b*. The first and second tube arrays **40***a*, **40***b* each include a straightening tube **60***a*, **60***b*, a guide tube **50***a*, **50***b* and a surgical tool **20***a*, **20***b*, respectively. First and second tube arrays **40***a*, **40***b* may be inserted or removed independently of the other. In some embodiments, the first straightening tube **60***a* of first tube array **40***a* may be inserted to a position where the first straightening tube distal end **66***a* is aligned with the working channel distal end **19**. From this position, the first guide tube distal end **56***a* and first surgical tool distal end **26***a* may be translated beyond the first straightening tube distal end **66***a* to deploy the first curved working end and first surgical tool end effector. Similarly, the second straightening tube **60***b* of the second tube array **40***b* may be inserted to a position where the second straightening tube distal end **66***b* is aligned with the working channel distal end. From this position, the second guide tube distal end **56***b* and second surgical tool distal end **26***b* may be translated beyond the second straightening tube distal end **66***b* to deploy the second curved working end and second surgical tool end effector.

[0073] Referring further to FIG. **29**, in some embodiments a device for performing minimally invasive surgery includes a shaft **12** including shaft liner **13**. A plenum **21** is defined between the shaft **12** and the shaft liner **13**. In some embodiments, plenum **21** is used as a duct for suction or irrigation. First and second working channels **18***a*, **18***b* are defined inside the shaft. A first tube array is inserted in first working channel **18***a*, and a second tube array is inserted in second working channel **18***b*. The first tube array includes a first straightening tube **60***a* and a first guide tube **50***a* positioned at least partially inside the first straightening tube. The first guide tube includes a first curved working end **54***a* that is both axially translatable and angularly rotatable relative to the first straightening tube **60***a*. First guide tube **50***a* provides a guide to steer the positioning of first surgical tool distal end **26***a*. Depending on the axial position and angular position of the first guide tube **50***a*, first surgical tool distal end **26***a* may be repositioned with precision in three-dimensional space.

[0074] The second tube array includes a second straightening tube **60***b* and a second guide tube **50***b* positioned at least partially inside the second straightening tube. The second guide tube includes a second curved working end **54***b* that is both axially translatable and angularly rotatable. Second guide tube **50***b* provides a guide to steer the positioning of second surgical tool distal end **26***b*. Depending on the axial position and angular position of the second guide tube **50***b*, second surgical tool distal end **26***b* may be repositioned with precision in three-dimensional space.

[0075] As shown in FIG. **29**, in some embodiments, first and second straightening tube distal ends **66***a*, **66***b* do not extend beyond the distal end **19** of first and second working channels. In some other embodiments, first and second straightening tube distal ends **66***a*, **66***b* extend slightly beyond the distal end **19** of first and second working channels, but do not extend beyond the distal end of hood **15**.

[0076] In further embodiments, the present invention includes a method of performing a surgical procedure, including the steps of (a) providing a concentric tube robot including a guide tube with a curved tip and a straightening tube; (b) positioning the curved tip of the guide tube inside the straightening tube; (c) inserting the guide tube and straightening tube together into a working channel on an endoscope shaft; (d) translating the guide tube relative to the straightening tube to deploy the curved working end of the guide tube; and (e) translating a surgical tool through the guide tube curved working end to a surgical site. The method further includes the steps of rotating the guide tube relative to the straightening tube to reposition the surgical tool. In some embodiments, the method further includes a step of retracting the curved working end of the guide tube into the straightening tube and removing the tube assembly from the working channel.

[0077] Thus, although there have been described herein particular embodiments of the present invention of new and useful devices and methods for robotic surgery, it is not intended that such references be construed as limitations upon the scope of this invention except as set forth in the following claims.

What is claimed is:

1. A surgical robot apparatus, comprising:

an endoscope having a longitudinal working channel including a proximal end opening and a distal end opening, the working channel including a working channel longitudinal axis;

a guide tube configured for insertion into the working channel, the guide tube including a curved working end at the distal end of the guide tube, the curved working end having a pre-shaped curvature biased away from a longitudinal axis of the guide tube when the guide tube is in a resting orientation; and

a straightening tube disposed on the guide tube such that the curved working end of the guide tube is positioned inside the straightening tube when the combined guide tube and straightening tube are inserted axially into the working channel,

wherein the straightening tube mechanically constrains the curved working end of the guide tube inside the straightening tube from its resting orientation toward a longitudinal axis of the straightening tube such that the guide tube and the straightening tube, when combined together, may be inserted axially through the working channel.

2. The apparatus of claim **1**, further comprising a surgical tool disposed in the guide tube.

3. The apparatus of claim **2**, wherein the surgical tool is axially moveable in translation relative to the guide tube during surgery.

4. The apparatus of claim **3**, wherein the surgical tool is angularly moveable in rotation relative to the guide tube during surgery.

5. The apparatus of claim **4**, wherein the surgical tool comprises forceps.

6. The apparatus of claim **4**, wherein the surgical tool comprises a basket.

7. The apparatus of claim **4**, wherein the surgical tool comprises a laser fiber.

8. The apparatus of claim **4**, wherein the surgical tool comprises a cutting tool.

9. The apparatus of claim **1**, wherein the guide tube is axially moveable in translation relative to the straightening tube during surgery.

10. The apparatus of claim **9**, wherein the guide tube is axially moveable in translation relative to the working channel during surgery.

11. The apparatus of claim **10**, wherein the guide tube is angularly moveable in rotation relative to the working channel during surgery.

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