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(54) **SYSTEM INCLUDING GUIDEWIRE FOR DETECTING FLUID PRESSURE**

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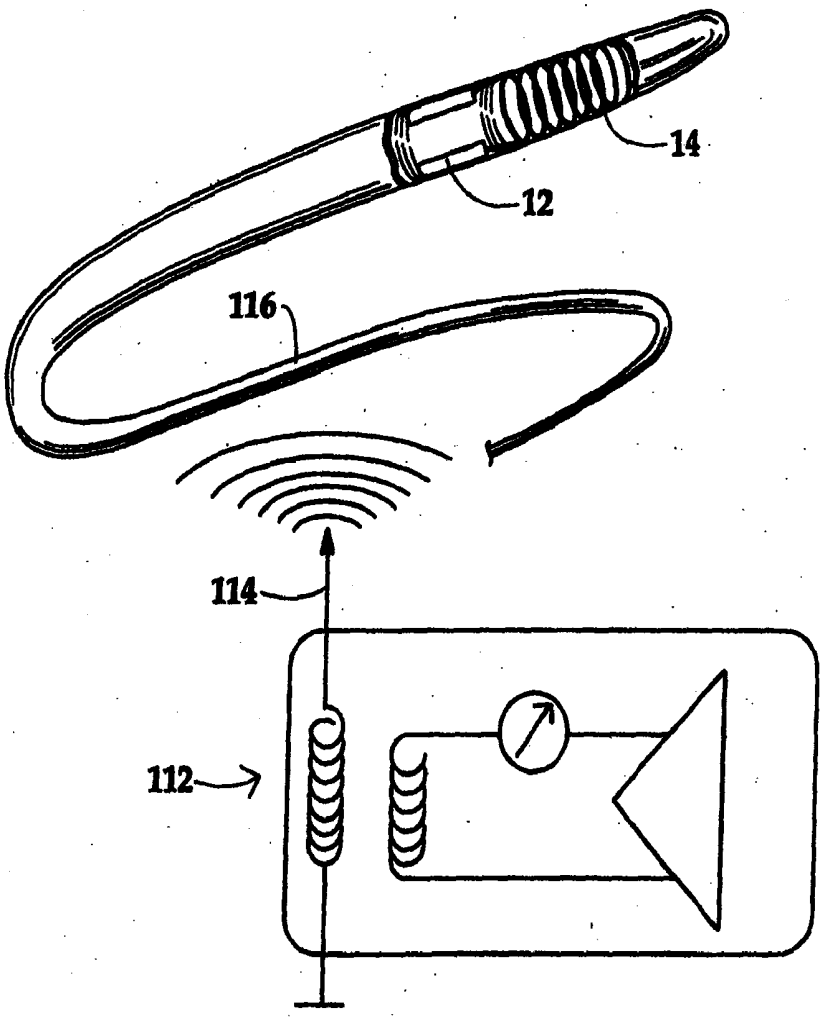
A61B 5/00 (2006.01)

(52) **U.S. Cl.**
CPC ***A61B 5/0215*** (2013.01); ***A61B 5/6851*** (2013.01); *A61B 2562/0214* (2013.01)

(57) **ABSTRACT**

A system for detection of blood pressure in a blood vessel includes a guide wire and a LC resonance circuit provided at a distal end of the guide wire. The resonance circuit may be a non-LC resonance circuit responsive to changes in pressure of fluid external to the guide wire such that the resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid.



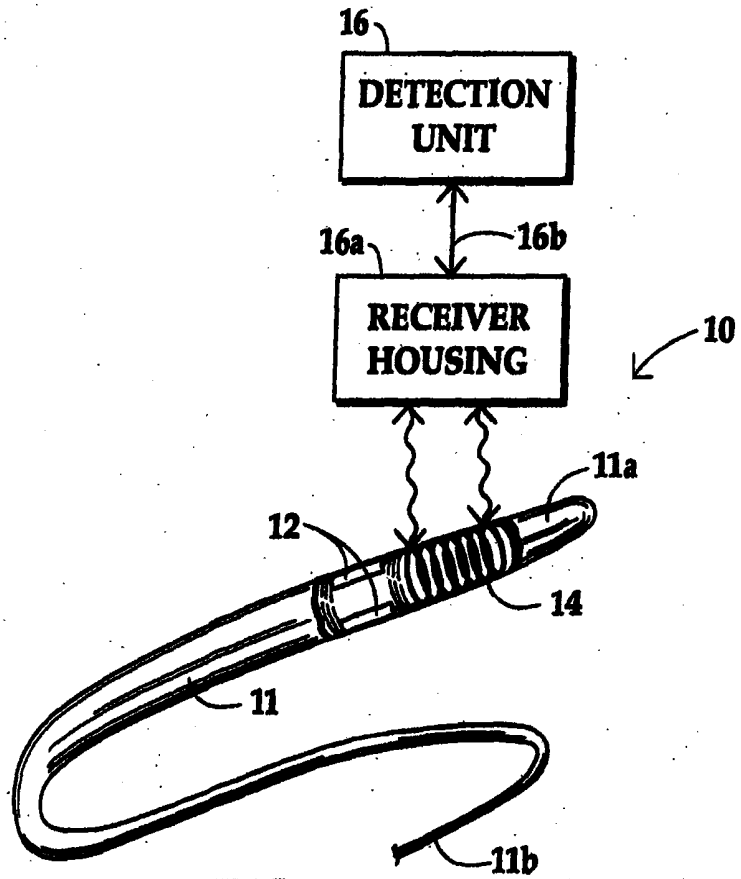


FIG. 1

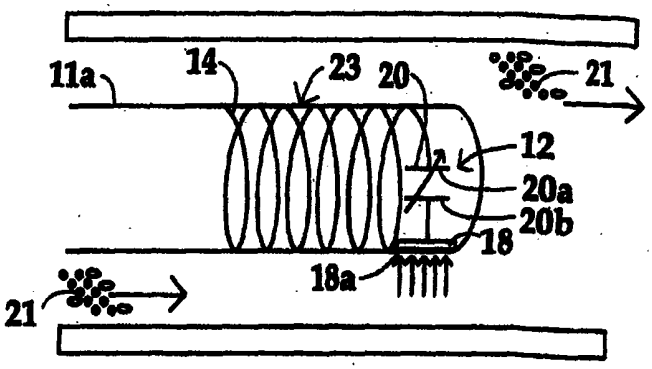


FIG. 2

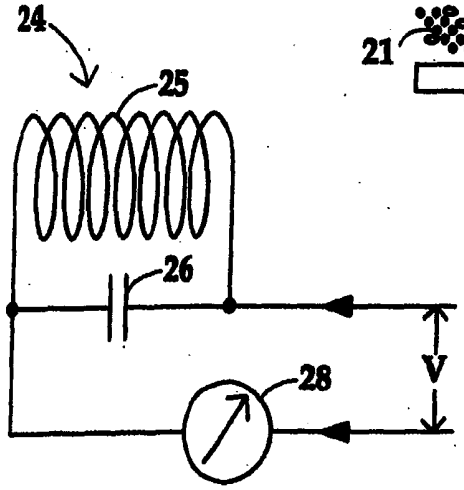


FIG. 3

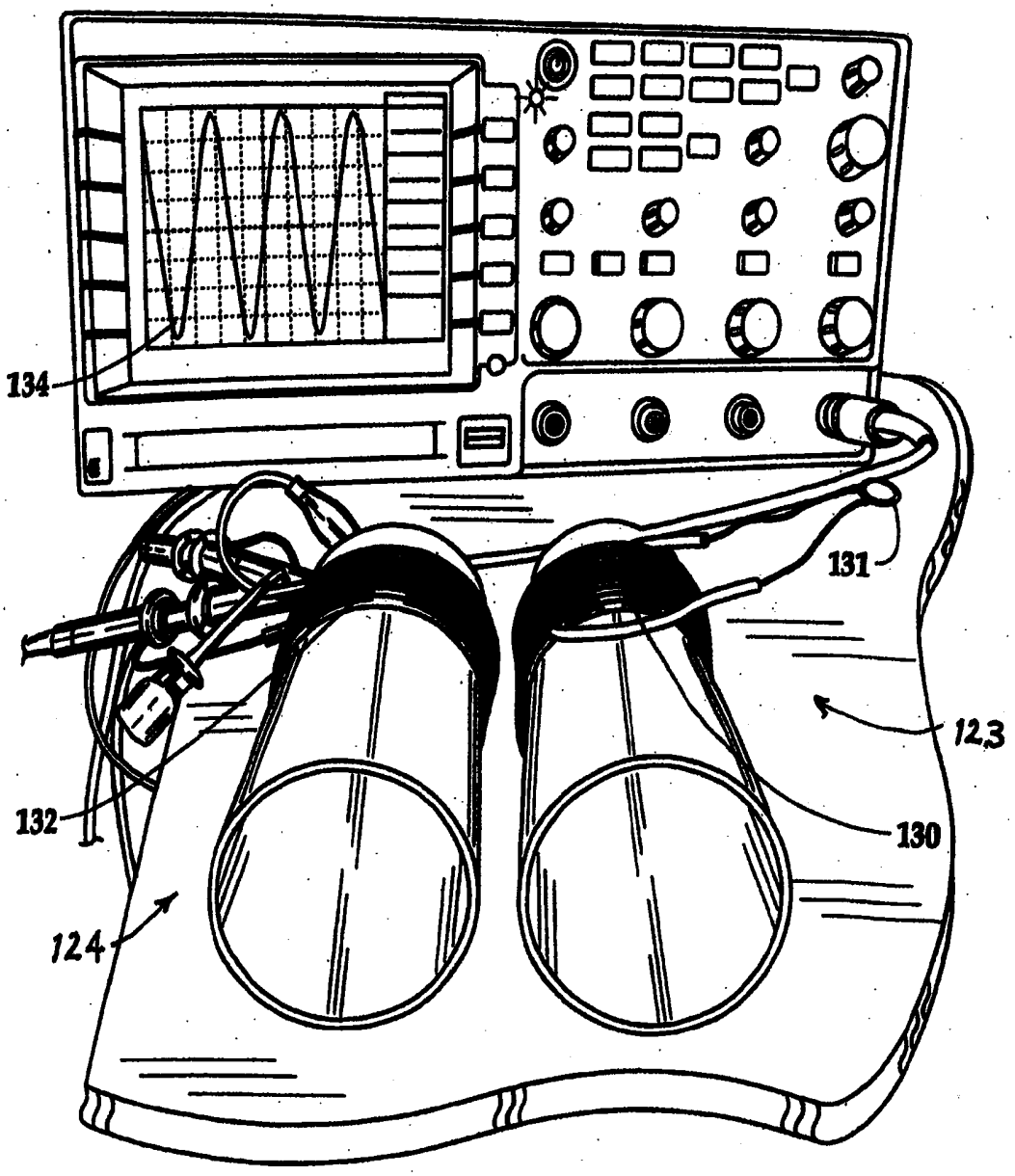


FIG. 4A

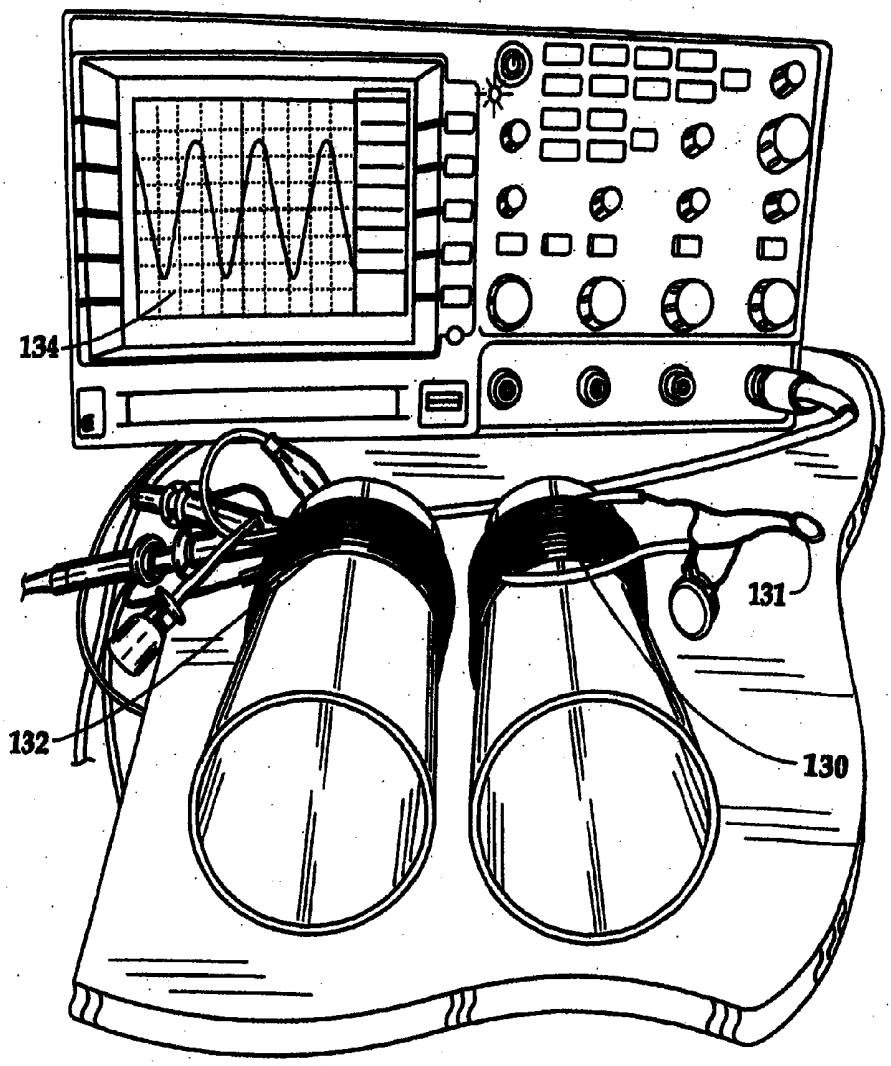


FIG. 4B

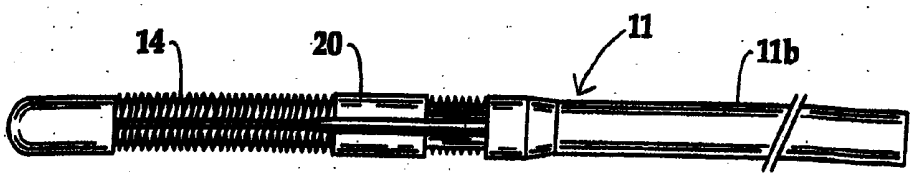


FIG. 5

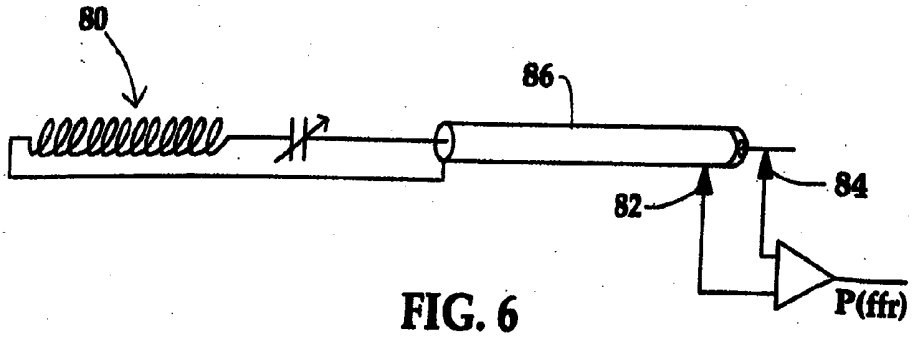


FIG. 6

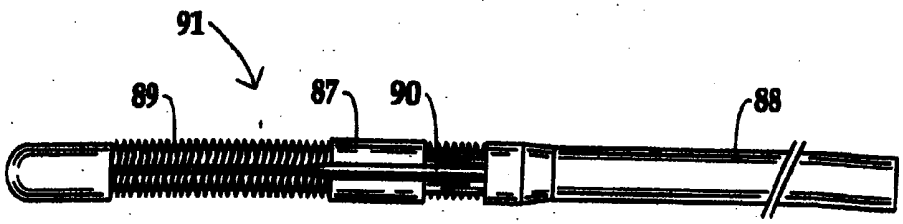


FIG. 7

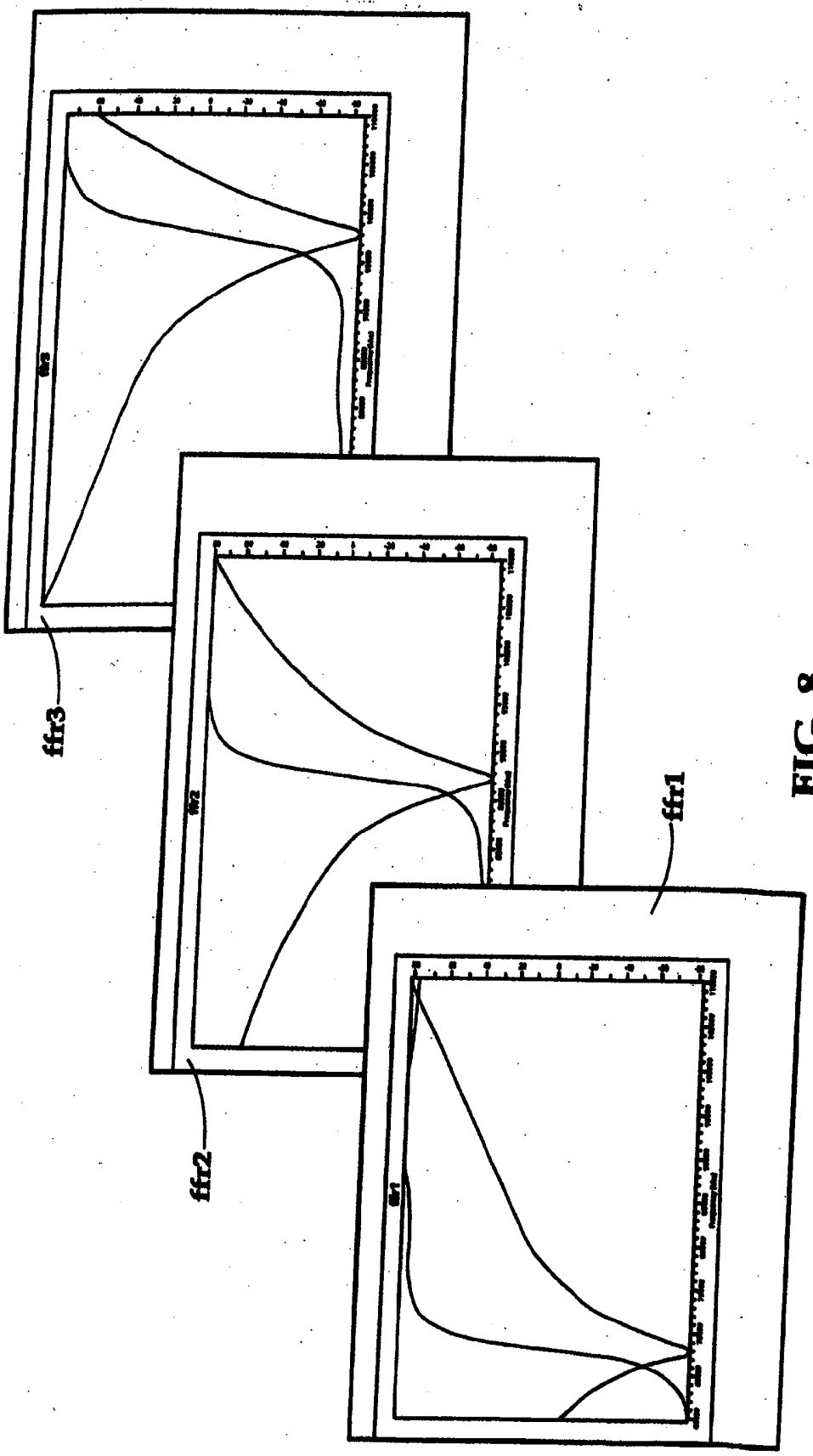


FIG. 8

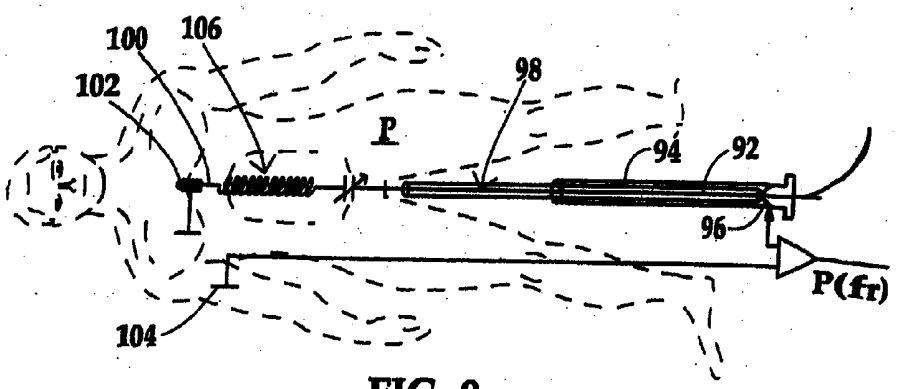


FIG. 9

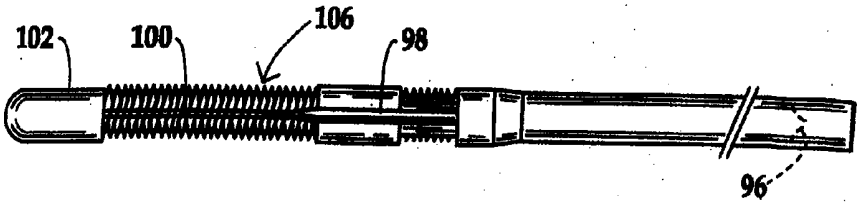


FIG. 10

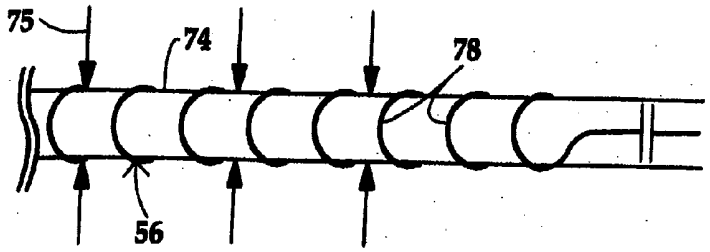


FIG. 11A

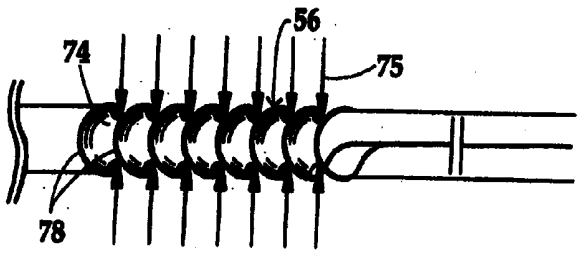


FIG. 11B

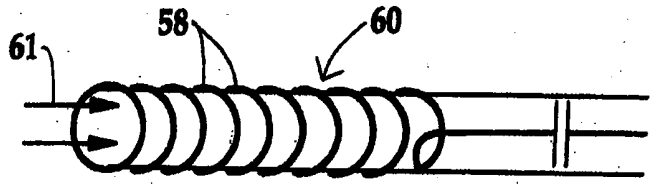


FIG. 12A

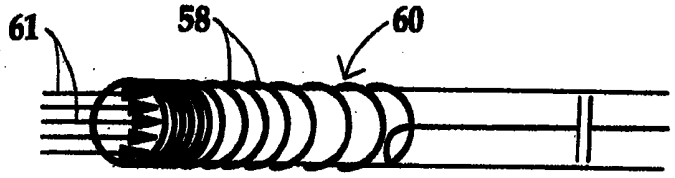


FIG. 12B

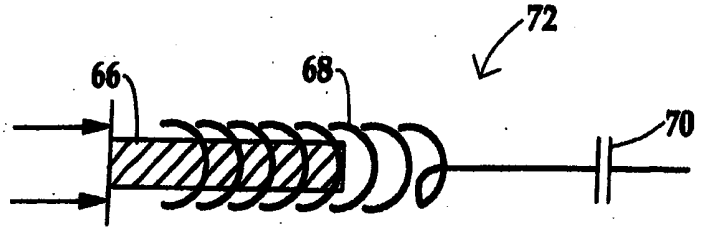


FIG. 13A

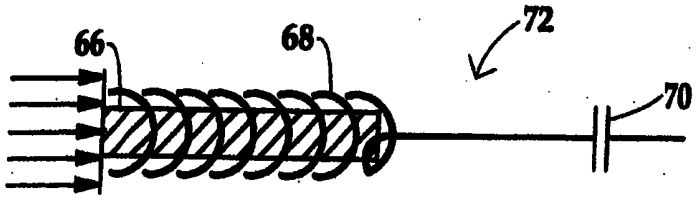


FIG. 13B

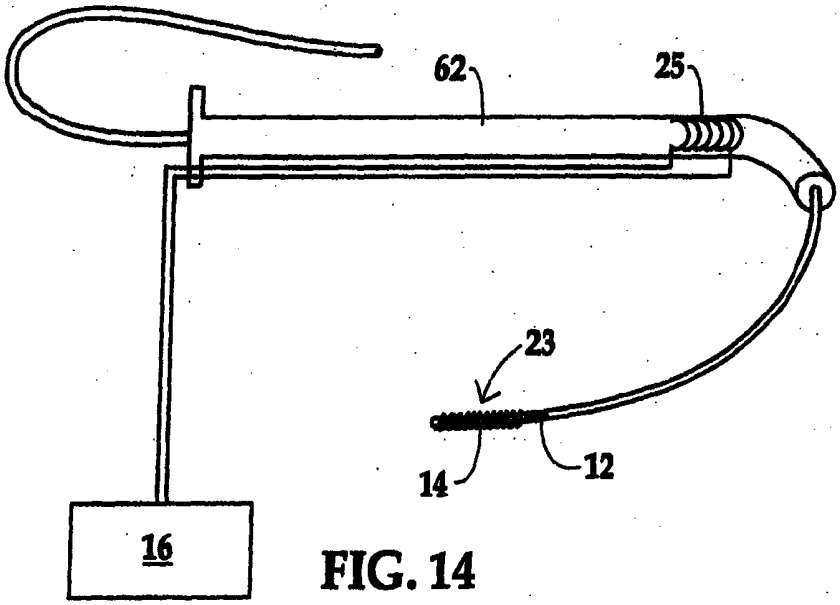


FIG. 14

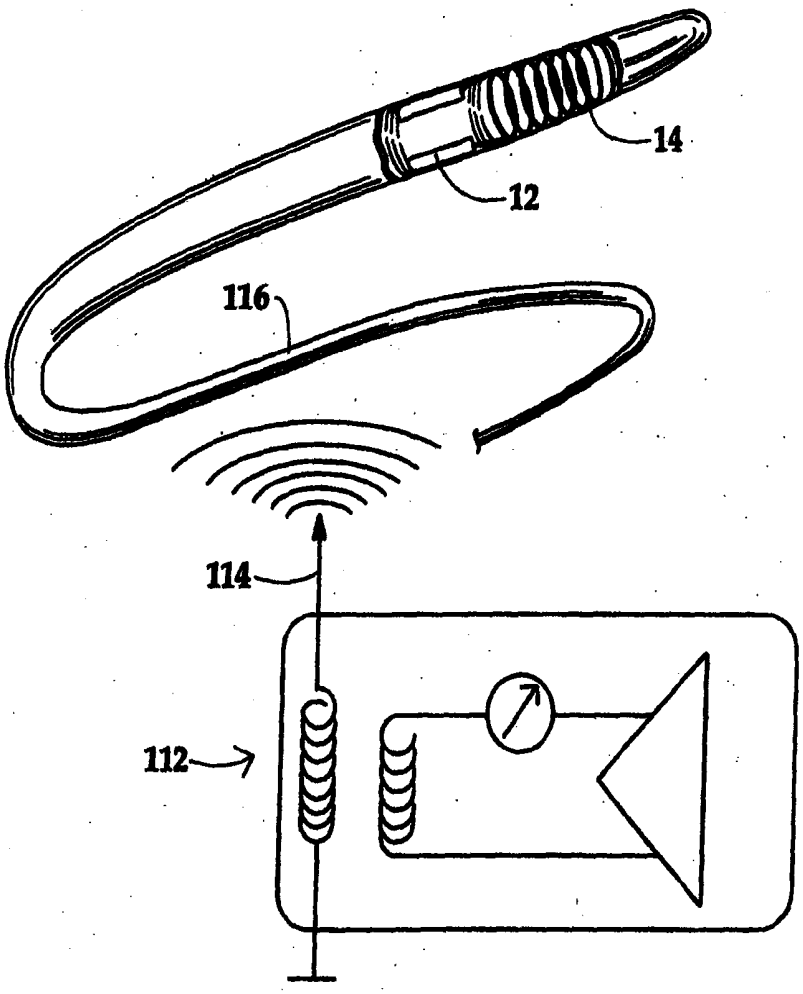


FIG. 15

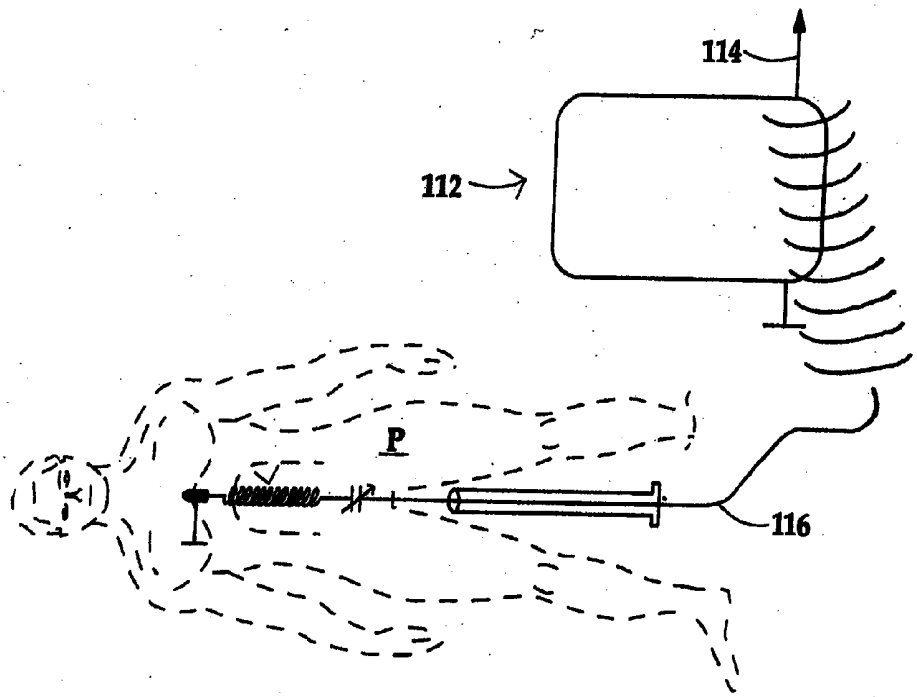


FIG. 16

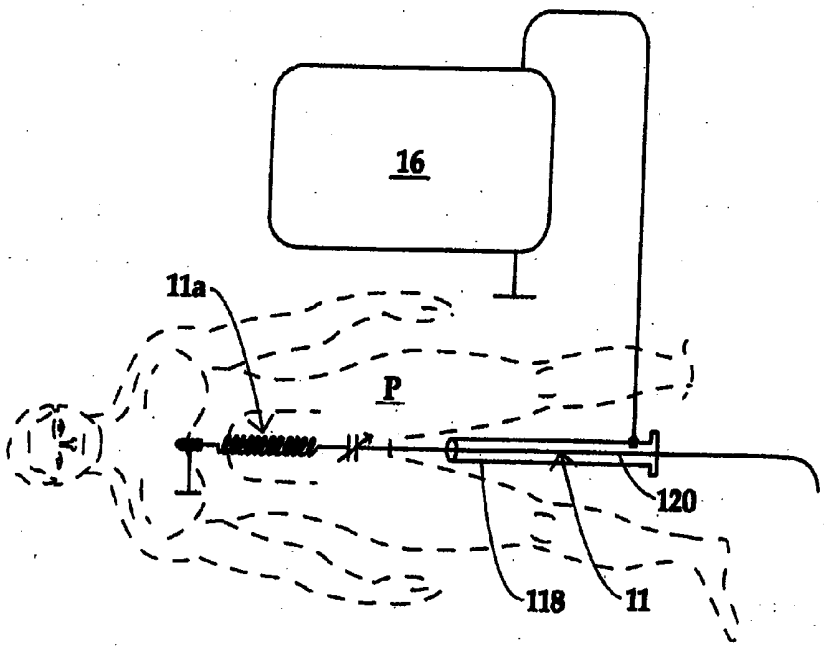


FIG. 17

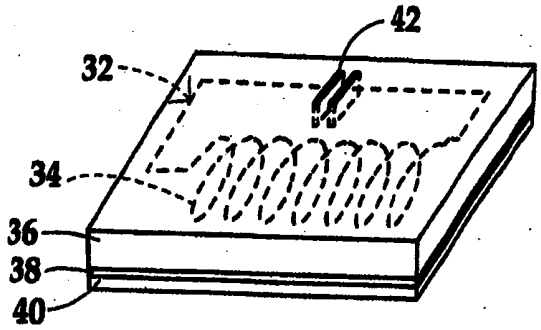


FIG. 18

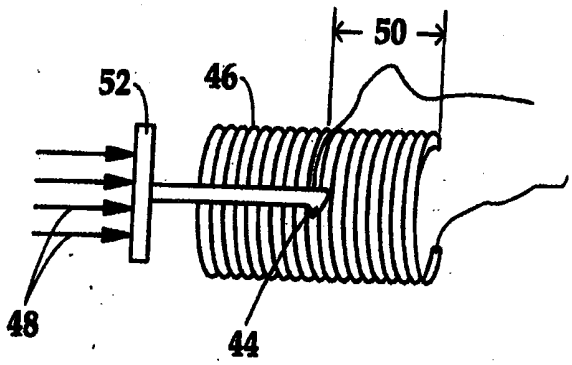


FIG. 19

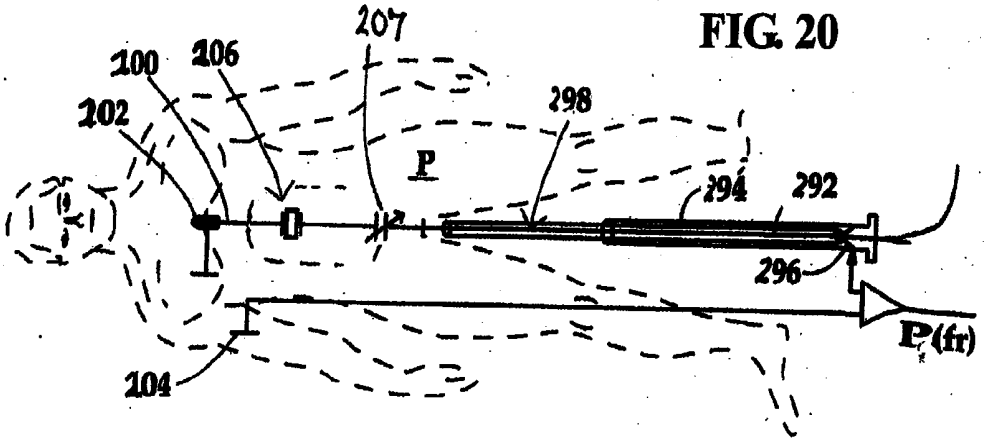

207
100
106
202
298
P
294
292
296
P(fr)
104

FIG. 20

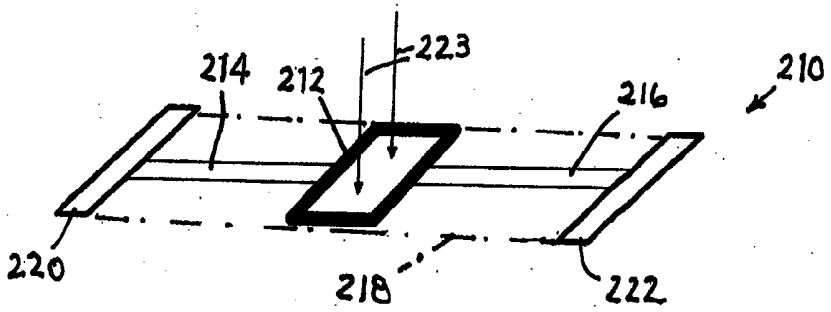

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FIG. 21

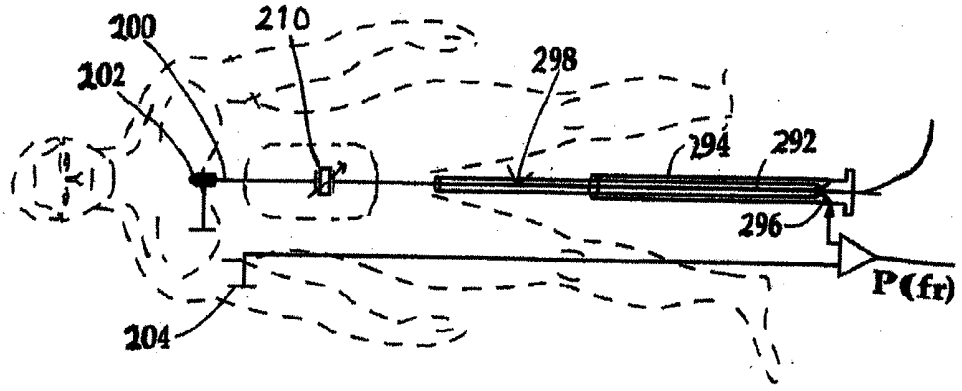


FIG. 22

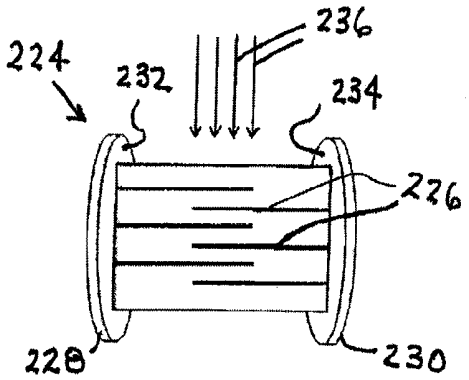


FIG. 23

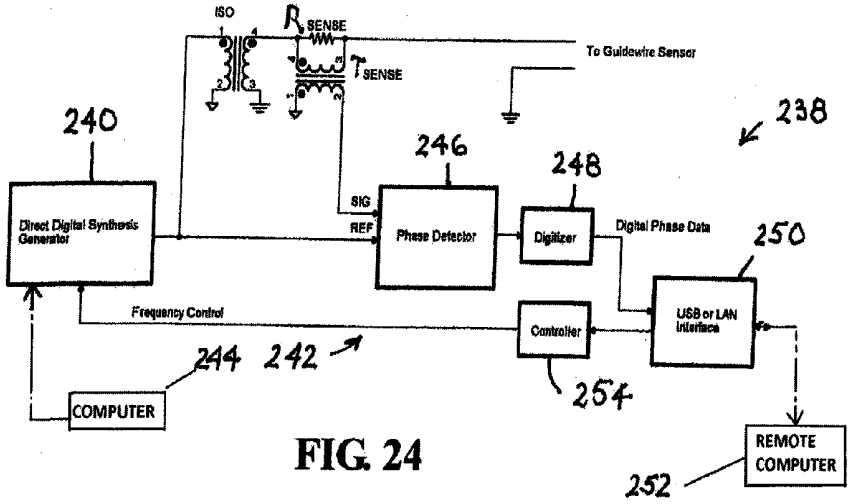

ISO
R SENSE
T SENSE
To Guidewire Sensor
240
238
246
248
Direct Digital Synthesis Generator
SIG
REF
Phase Detector
Digitizer
Digital Phase Data
250
Frequency Control
Controller
USB or LAN Interface
244
242
254
COMPUTER
REMOTE COMPUTER
252

FIG. 24

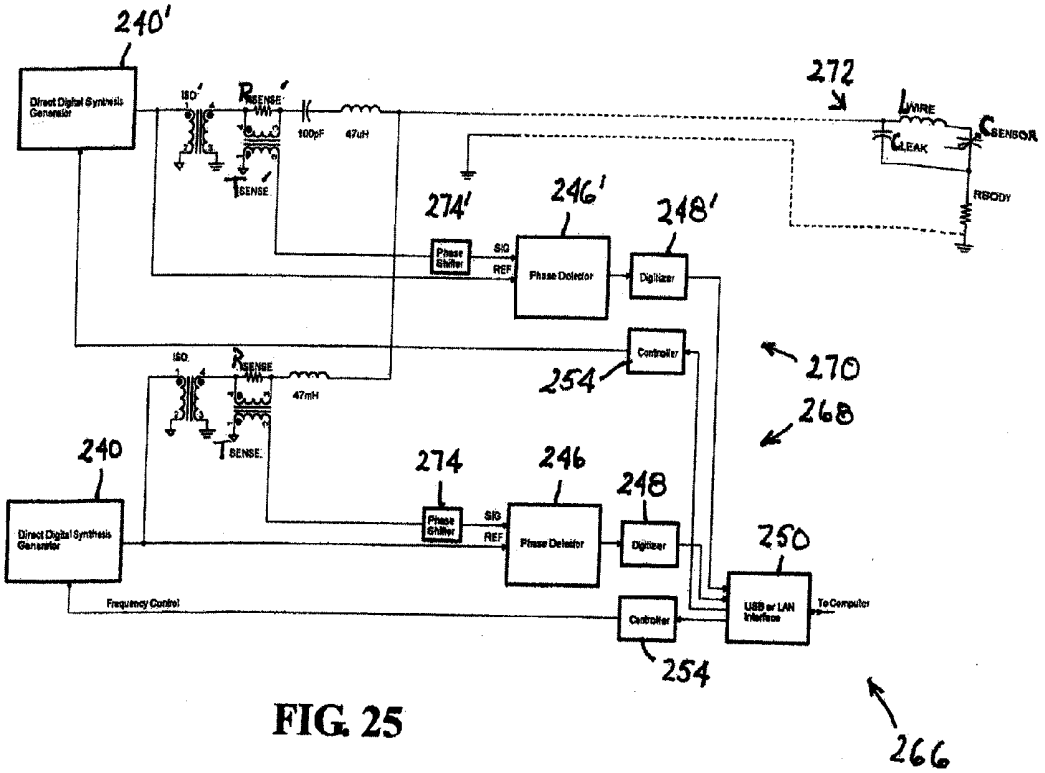

240'
Direct Digital Synthesis Generator
ISO'
R SENSE'
100pF
47uH
T SENSE'
272
L WIRE
C LEAK
C SENSOR
R BODY
274'
246'
248'
Phase Shifter
SIG
REF
Phase Detector
Digitizer
Controller
254
270
268
47mH
240
274
246
248
250
Frequency Control
To Computer
266

FIG. 25

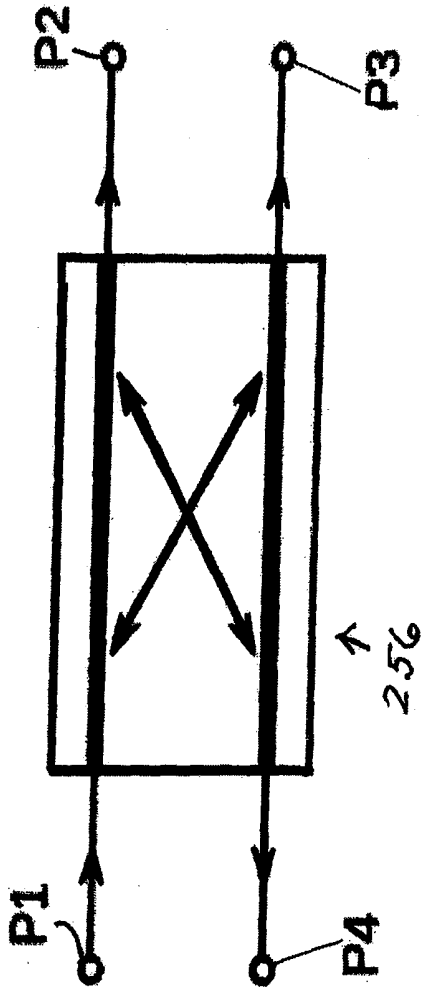


FIG. 26

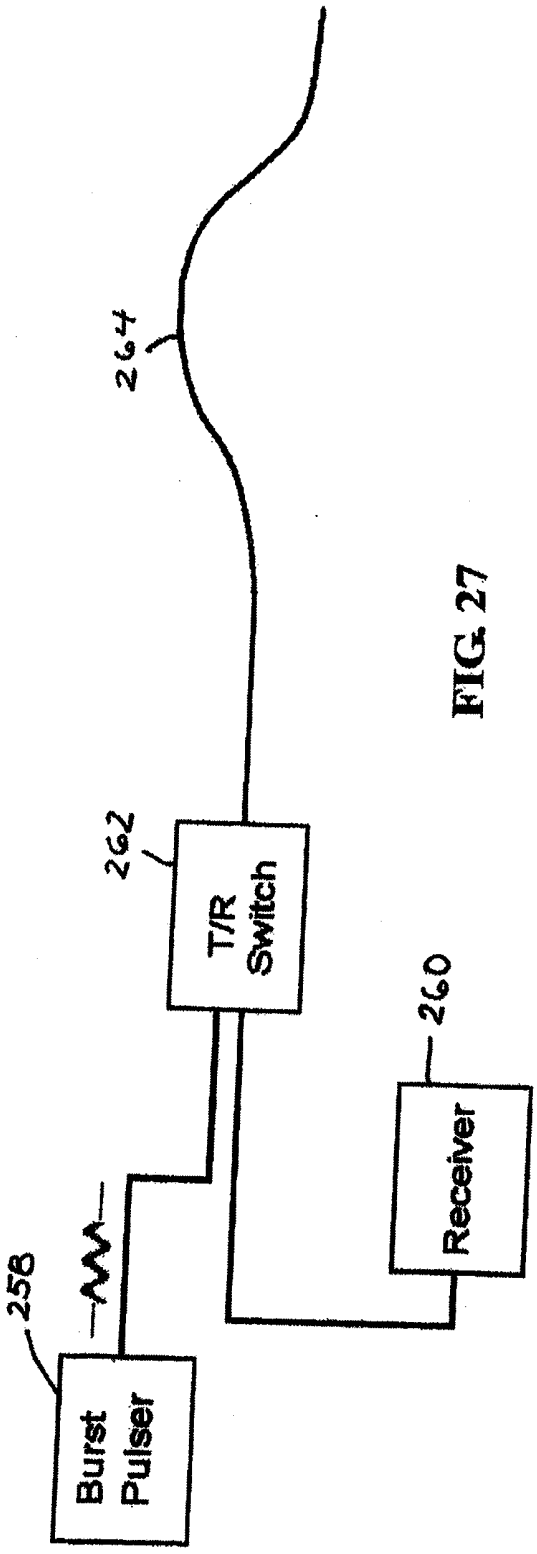


FIG. 27

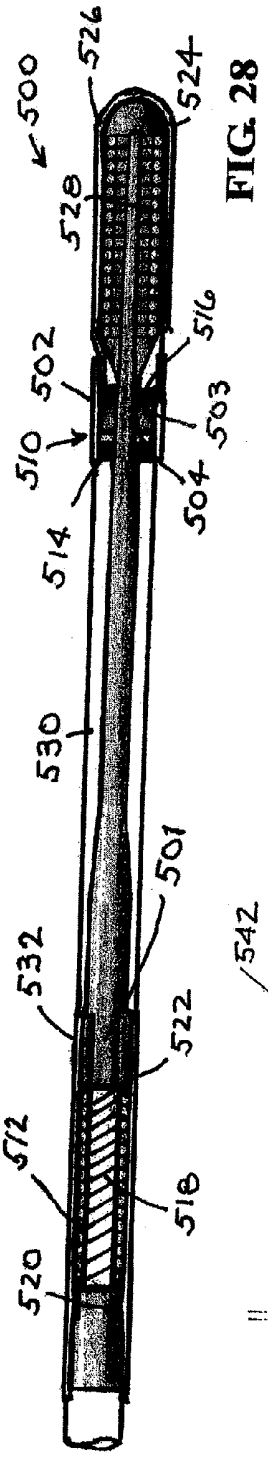


FIG. 28

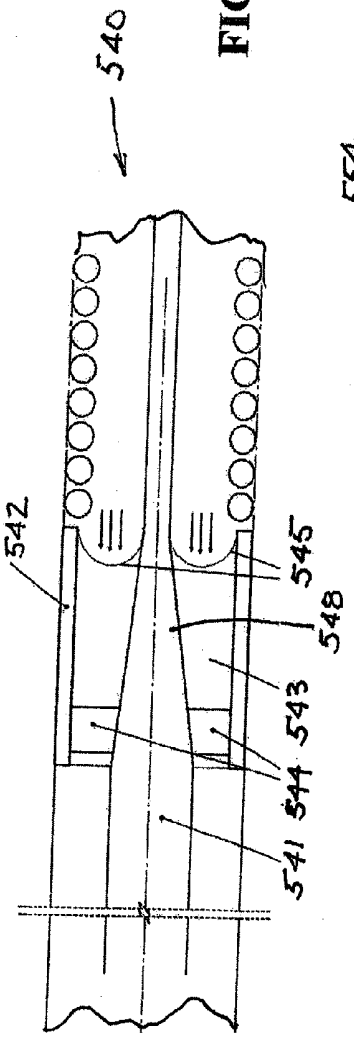


FIG. 29

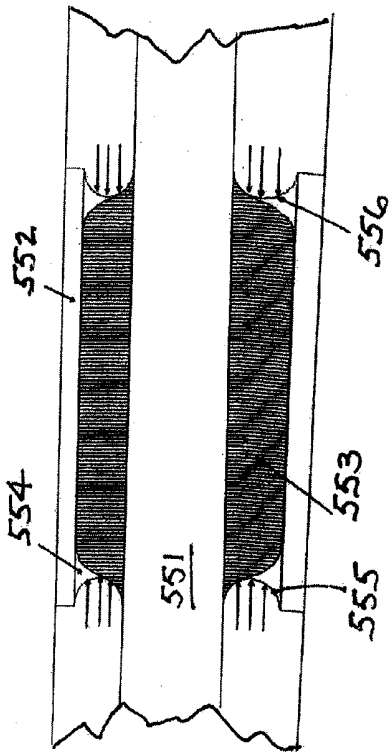


FIG. 30

FIG. 31

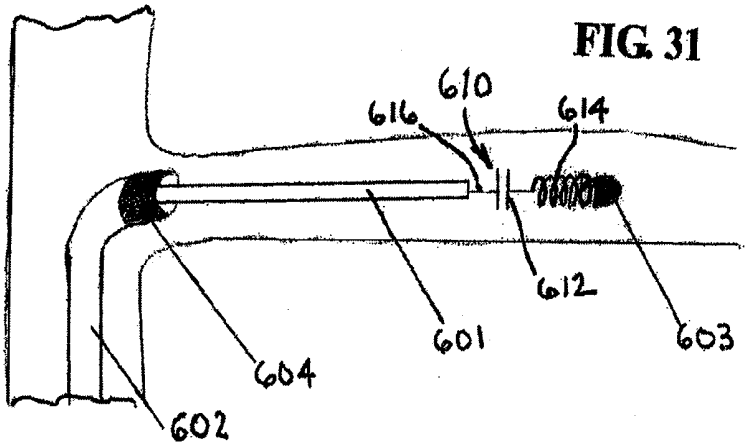


FIG. 32

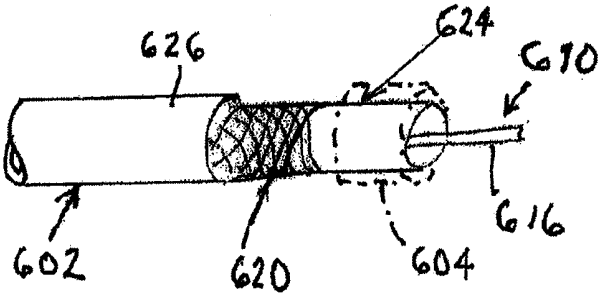
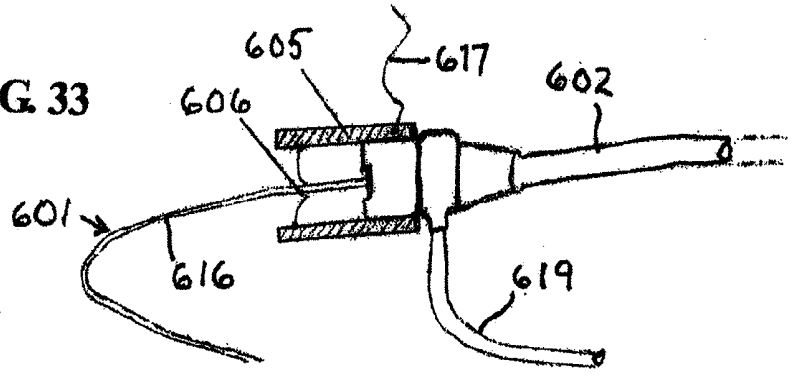


FIG. 33



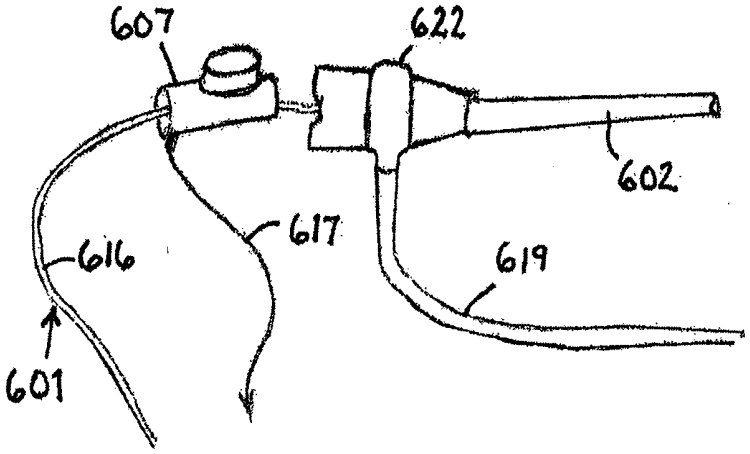


FIG. 34

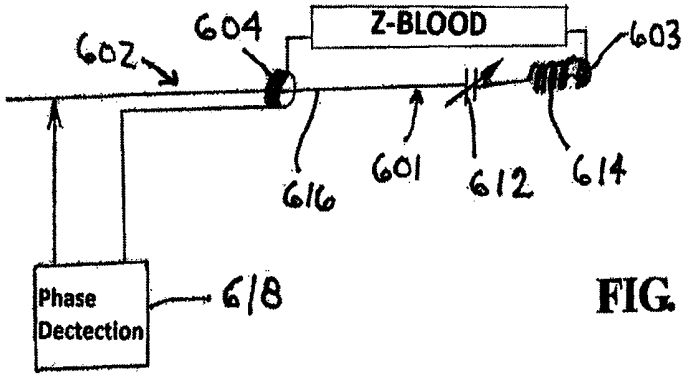


FIG. 35

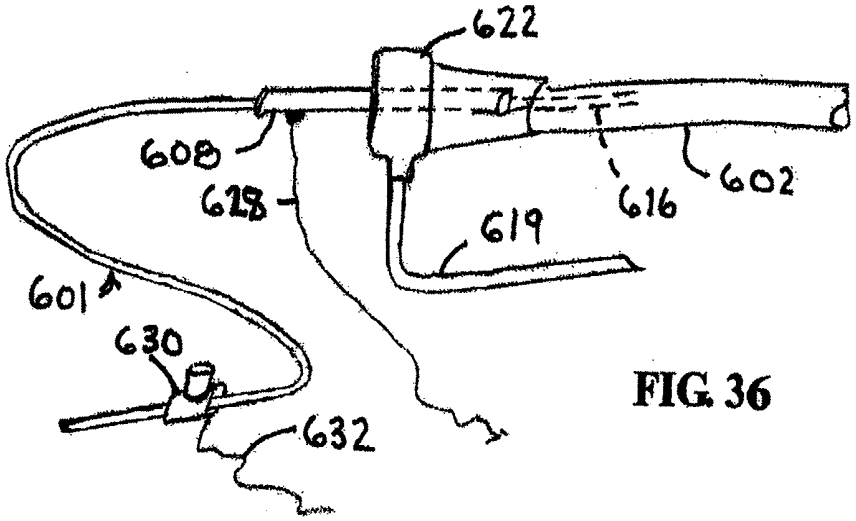


FIG. 36

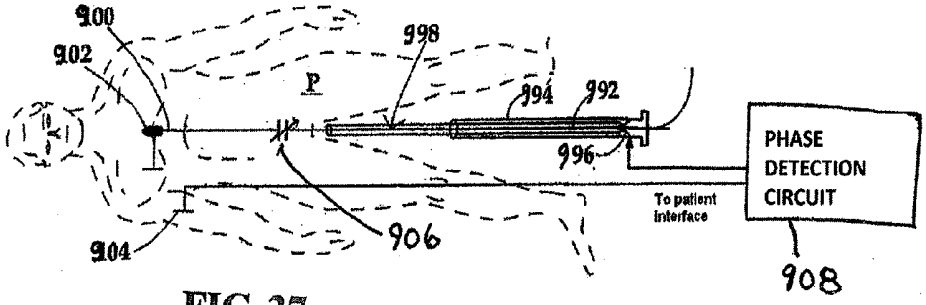

900
902
P
998
994
992
996
PHASE
DETECTION
CIRCUIT
To patient
interface
906
904
908

FIG. 37

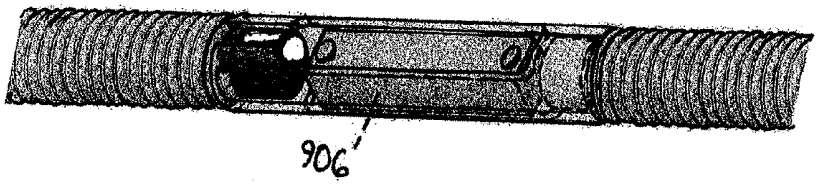

906'

FIG. 38

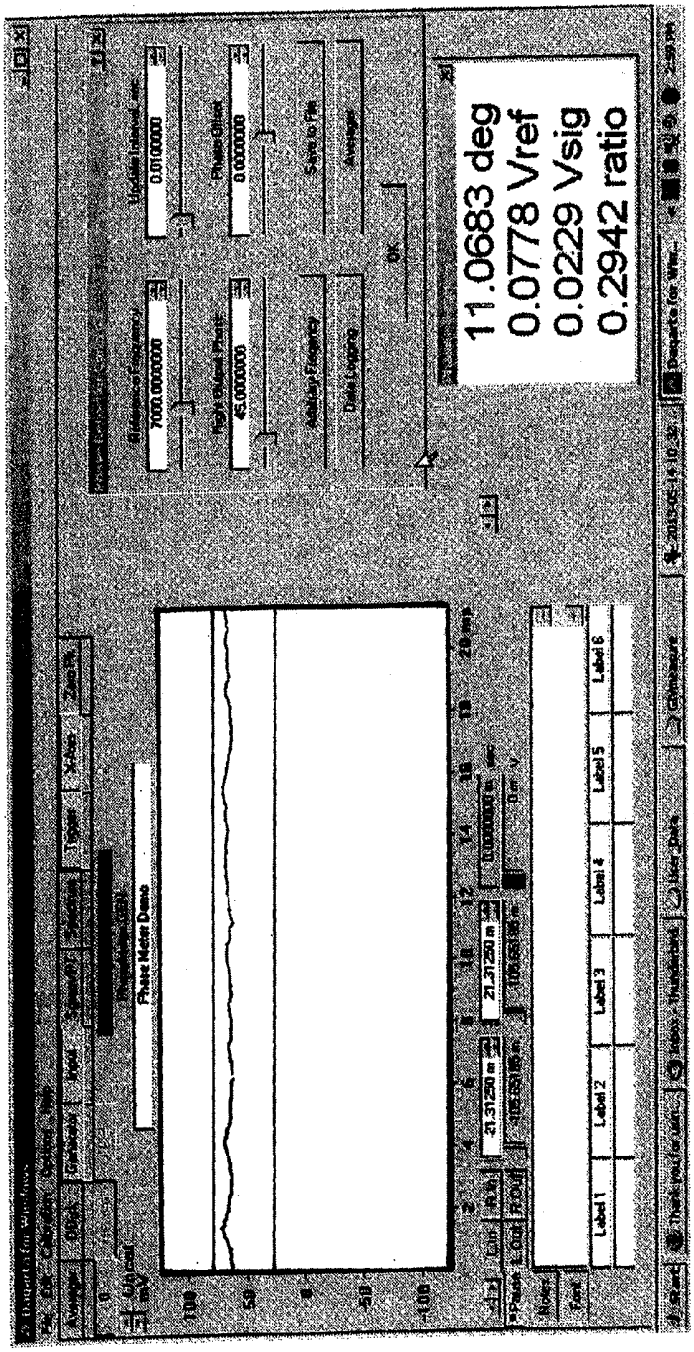

11.0683 deg
0.0778 Vref
0.0229 Vsig
0.2942 ratio
Phase Meter Demo

FIG. 39

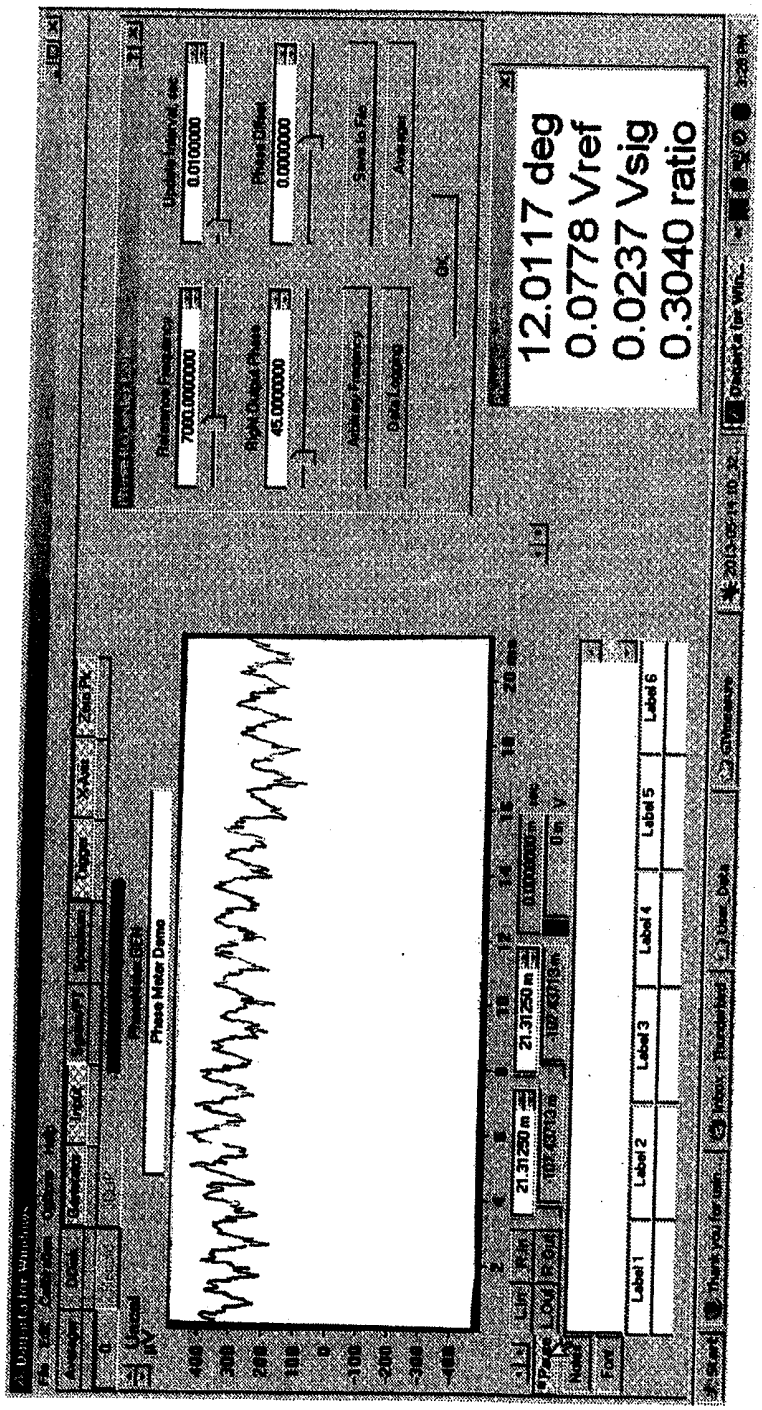

12.0117 deg
0.0778 Vref
0.0237 Vsig
0.3040 ratio
Phase Meter Demo
Label 1
Label 2
Label 3
Label 4
Label 5
Label 6

FIG. 40

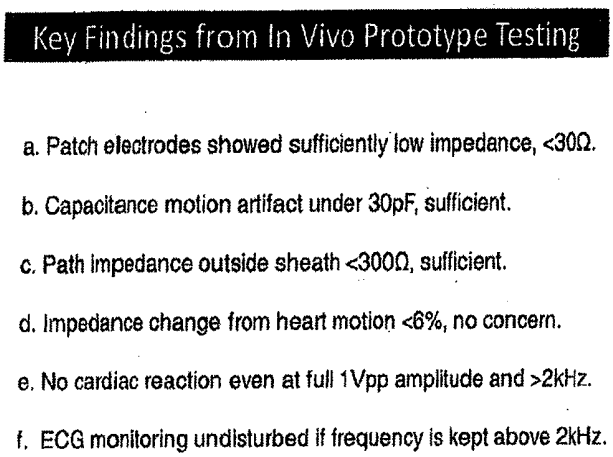

Key Findings from In Vivo Prototype Testing
a. Patch electrodes showed sufficiently low impedance, <30Ω.
b. Capacitance motion artifact under 30pF, sufficient.
c. Path impedance outside sheath <300Ω, sufficient.
d. Impedance change from heart motion <6%, no concern.
e. No cardiac reaction even at full 1Vpp amplitude and >2kHz.
f. ECG monitoring undisturbed if frequency is kept above 2kHz.

FIG. 41

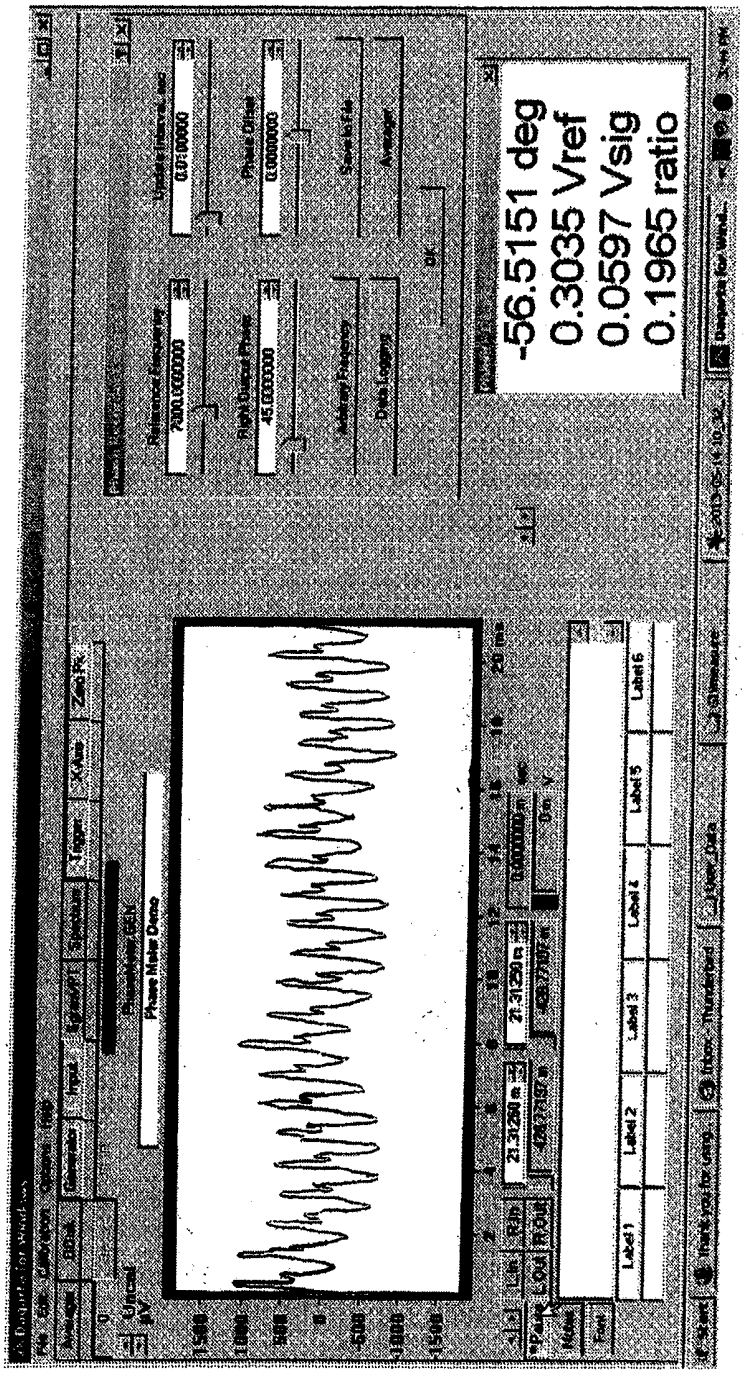
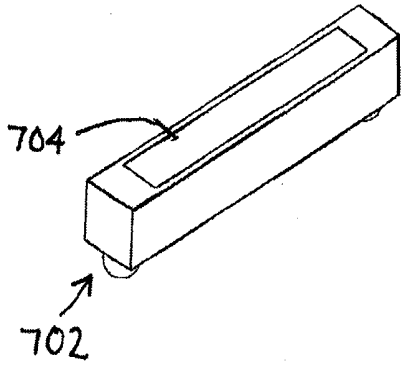


FIG. 42

FIG. 43



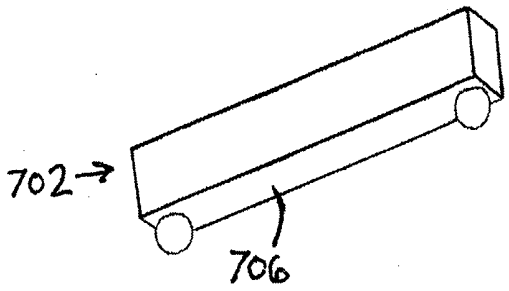
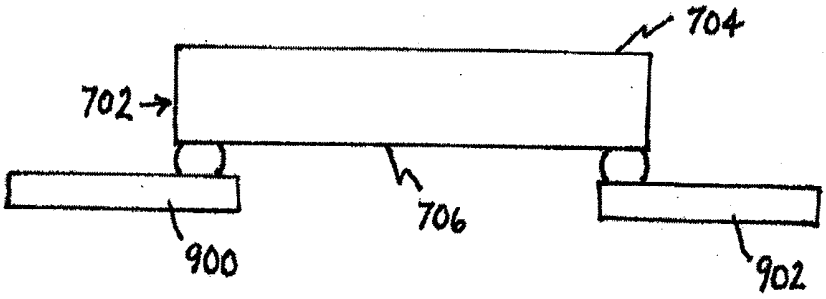


FIG. 44

FIG. 45


704
702
706
900
902

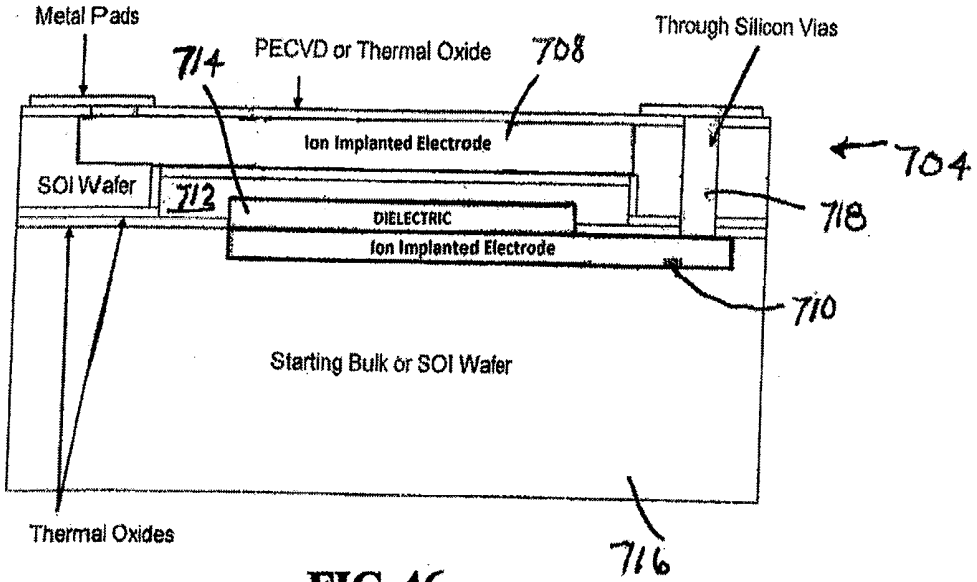

Metal Pads
714
PECVD or Thermal Oxide
708
Through Silicon Vias
Ion Implanted Electrode
704
SOI Wafer
712
DIELECTRIC
718
Ion Implanted Electrode
710
Starting Bulk or SOI Wafer
Thermal Oxides
716

FIG. 46

SYSTEM INCLUDING GUIDEWIRE FOR DETECTING FLUID PRESSURE

FIELD OF THE INVENTION

[0001] The present invention relates to several methods of extracting local pressure information inside a human body, animals, or other environments with restricted accessibility. The invention is particularly useful in obtaining blood pressure measurements.

BACKGROUND OF THE INVENTION

[0002] In interventional cardiology measurements of pressure such as blood pressure are obtained through a guidewire. The technique called Fractional Flow Reserve or FFR seeks to determine the pressure ratio proximal and distal to a blood vessel obstruction. This ratio is used to decide how the obstruction should be treated. The issue with current sensors is the required miniaturization to fit the sensors into a $^{14}/_{1000}$ inch guidewire. Described are sensing methods as well as corresponding electronic circuitry to extract a signal that is proportional to pressure.

[0003] Instead of utilizing a guide wire as a strictly mechanical or guiding tool, pressure and flow wires are being promoted as dual function guide wires, providing mechanical guidance and hemodynamic information at the same time. Based on the results of the FAME study, FFR measurements are becoming popular and in several countries reimbursed. Currently there are 2 types of pressure wires commercially available: Radi (acquired by STJ) and Volcano. Both FFR guide wires use an IC pressure sensor (strain gage type) connected through a push on handle with 3 electrical contacts at the proximal wire end. In case of the Radi guide wire, the connector handle is wirelessly transmitting the pressure values to the display system. This is an improvement over a cable connection, but is still very cumbersome, since for every catheter insertion the connector handle needs to be disconnected from the proximal wire end before the catheter can be advanced over the wire.

[0004] As described in International Patent Application No. PCT/US2012/023130 filed Jan. 30, 2012 (see FIGS. **1-19** herein), a resonant circuit to detect blood pressure changes can be utilized where only two electrical connections need to be made. If the patient body is used as a ground return path the guide wire itself can be utilized as electrical connector. It may also be possible to use the capacitance between sheath (guide catheter) and guidewire in order to provide a high-frequency electrical connection at the port where the guidewire enters the sheath. This has advantages over current strain gage approaches, which require at least 3 electrical connections since a supply voltage is required. With 3 electrical connections wire construction and therewith wire handling is impacted significantly. The wire does not handle like a standard guide wire and is expensive to manufacture. This is overcome in the applications referenced above. However, small capacitive sensors fitting a $^{14}/_{1000}$ inch guide wire with enough sensitivity to drive a significant load (body capacitance) are difficult to construct. Therefore a need exists for miniature passive pressure sensors with high sensitivity capable of driving a low impedance load and for sensitive FFR detector systems.

[0005] The active powering of the currently marketed FFR wires requires electrical wiring to run the entire length of the wire which significantly compromises the integrity and therewith handling characteristics of a standard guide wire. U.S. Patent Application Publication No. 2001/0051769A1 (RADI) describes how to reduce the number of contacts to one proximal wire contact by utilizing an internal and external ground electrode on (or) respectively an electrode inside the patient. However, again, this proposed solution relies on actively powered sensors with significant electrical currents flowing through the patient body to power the pressure sensor. Therefore, a need remains for an improved sensing and connection scheme with a passive pressure sensing capacitive element.

SUMMARY OF THE INVENTION

[0006] The present invention aims to optimize and facilitate in vivo fluid pressure measurements. The invention contemplates attaining such an aim in part by minimizing contacts that a measurement circuit has to a patient of subject. The invention also seeks a modification of the measurement apparatus so that the method of use is simplified and therefore expedited.

[0007] Accordingly, the present invention aims in part to provide a system (apparatus and method) for a one-contact detection of blood pressure in a blood vessel. Concomitantly, the invention aims in part to provide an apparatus and method for a quasi wireless detection of blood pressure in a blood vessel. The invention also aims to provide an improved sensing and connection scheme with a passive pressure sensing capacitive element.

[0008] The present invention contemplates a system having a guide wire with a capacitive electrolyte sensor for sensing pressure of the blood, and a system using same, through only one contact, monitoring the blood pressure sensed. The invention also contemplates a system having a guide wire with a sensor for sensing pressure of the blood, and a system using the same through two contacts, hidden from the user, to monitor the blood pressure sensed.

[0009] A transmission through a sheath contact of pressure data from the resonance circuit at the distal end of the wire to the pressure monitoring system would greatly enhance clinical utility because catheters can be inserted over the wire without having to disconnect a handle. This way the wire truly functions as a mechanical guide for catheter insertions and a hemodynamic measurement tool. The one contact version also has the advantage over current wires that the guide wire characteristics are not compromised through electrical wires running inside the guide wire since the inner core wire will be utilized as electrical conductor. This results in superior wire handling compared to current FFR wires and lower manufacturing costs.

[0010] A system for detection of blood pressure in a blood vessel comprises, in accordance with the present invention, a guide wire and a resonance circuit provided at a distal end of the guide wire. The resonance circuit is responsive to changes in pressure of fluid external to the guide wire such that the resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid.

[0011] In one embodiment of the present invention, the resonance circuit is a non-LC resonance circuit. The resonance circuit may include a resonator element and at least one pressure-sensitive element serving as a sensor. The most distal element can either be the resonating element or the sensor, functionally the two configurations being identical. Placing the sensor most distal will often be preferable.

[0012] The resonator element is preferably a ceramic element and the pressure-sensitive element is preferably a capacitor. The resonator element and the capacitor are coupled to each other to form the resonance circuit. The capacitor is responsive to changes in pressure of fluid external to the guide wire such that the resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid.

[0013] Pursuant to another embodiment of the present invention, the pressure-sensitive element includes a pressure plate mechanically connected to the resonator element, the resonator element being configured for mechanical deformation in response to movement of the pressure plate. The pressure-sensitive element may further include a membrane fastened to the pressure plate.

[0014] In accordance with a further feature of the present invention, the system additionally comprises an electronic signal processing circuit configured for monitoring electrical-current phase changes. The signal processing circuit preferably includes an oscillator, a current sensor, a phase detector, a digitizer and an interface, the interface being operatively connectable to a computer device. The oscillator may be a direct digital synthesis generator.

[0015] In accordance with another feature of the present invention, the signal processing circuit includes a first circuit or subcircuit for compensating for measurement error arising from changes in positioning of the resonance circuit at a fluid-containing site, the signal processing circuit further including a second circuit or subcircuit for detecting changes in pressure of fluid at the site. Where the resonance circuit includes a capacitor, the first circuit is configured to compensate for changes in leakage capacitances that occur between the guide wire and the fluid-containing site. Where the first circuit is configured for operating in a first frequency range and the second circuit is configured for operating in a second frequency range, the second frequency range being much lower than the first frequency range, the second circuit is configured to be insensitive to frequencies in the first frequency range.

[0016] A system for detection of blood pressure in a blood vessel comprises, also in accordance with the present invention, (a) a guide wire, (b) a coil provided at a distal end of the guide wire, and (c) a capacitor provided at a distal end of the guide wire, the coil and the capacitor being coupled to each other to form a resonance circuit, at least one of the coil and the capacitor being responsive to changes in pressure of fluid external to the guide wire such that the resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid, the capacitor taking the form of a multi-layer ceramic capacitor.

[0017] A system for detection of blood pressure in a blood vessel comprises, also pursuant to the present invention, a guide wire and a resonance circuit provided at a distal end of the guide wire, the resonance circuit being responsive to changes in pressure of fluid external to the guide wire such that the resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid. An electronic signal processing circuit is configured for measuring resonance frequency changes of the resonance circuit, the signal processing circuit including a first circuit for compensating for measurement error arising from changes in positioning of the resonance circuit at a fluid-containing site, the signal processing circuit further including a second circuit for detecting changes in pressure of fluid at the site. Further features of this invention are discussed above.

[0018] A method for measuring fluid pressure comprises, in accordance with the present invention, (a) inserting a distal end portion of an elongate wire into fluid at a predetermined site, where the distal end portion is provided with a non-LC resonance circuit, (b) detecting a resonance frequency of the resonance circuit while the circuit is in the fluid at the site, (c) determining a fluid pressure value from the detected resonance frequency.

[0019] Where the resonance circuit includes a resonator and a pressure sensor, the resonator having a resonance frequency varying in accordance with pressure of the fluid at the site, the method further comprises monitoring the resonance circuit for a change in the resonance frequency induced by a change of pressure in the fluid; determining a second pressure value from the changed resonance frequency.

[0020] In another embodiment of the present invention, a pressure measuring system has a guide wire having a distal portion with a coil and pressure sensitive capacitive element providing a resonance circuit which varies in its resonance frequency and phase responsive to the pressure from blood external the guide wire when in a blood vessel of a patient's body. In one embodiment the resonance frequency or phase shift will be read through one brush contact inside the sheath, the guide wire is inserted through and a ground electrode on the patient. In another embodiment a clip at the proximal wire end provides for the electrical contact. A wire torquer can be utilized as such clip.

[0021] The pressure sensitive capacitive element of the resonance circuit represents a variable capacitive element with at least one pressure sensitive membrane which varies the capacitance responsive to the amount of pressure applied external of the guide wire onto the membrane. These pressure sensitive capacitors are well known and described in Journal of Micromechanics and Micro-engineering, Volume 17, July 2007: A fast telemetric pressure and temperature sensor system for medical applications; R Schlierf, U Horst, M Ruhl, T Schmitz-Rode, W Mokwa and U Schnakenberg; Sensors and Actuators A: Physical, Volume 73, issues 1-2, March 1999: Low power integrated pressure sensor system for medical applications; C Hierold, B Clasbrummel, D Behrend, T Scheiter, M Steger, K Oppermann, H Kapels, E Landgraf, D Wenzel and D Etzrodt; 2010 IEEE International Solid-State Circuits Conference: Mixed-Signal Integrated Circuits for Self-Contained Sub-Cubic Millimeter Biomedical Implants; Eric Y Chow, Sudipto Chakraborty, William J Chappell, Pedro P Irazoqui). However, due to the size restrictions inside a $^{14}/_{1000}$ inch guidewire the sensors need to have a size of only about 200 microns widths×1 mm length×200 microns thickness. Such small sensors as referenced above are typically based on membranes separated by air or vacuum and do not provide enough capacitive change over the physiological blood pressure range to be detected through ground impedance and wire/body parallel capacitance. The typical capacitive change obtainable with the above referenced pressure sensor is in the 10% range which equates to 1 pF or less given a base capacitance of 10 pF or less. Such small capacitive change cannot be detected directly without amplifying the signal first at the sensor site because of a shunt capacitance of 1000 pF or higher between guide wire and surrounding blood. A much higher capacitive change in the order of 100% and a base capacitance around 1000 pF would be desirable in order

to enable direct detection through ground and sheath (brush or capacitive) or clip contact without having to add active electronic circuitry.

[0022] The droplet capacitor as described in the journal article "Droplet-based interfacial capacitive sensing," Lab Chip, 2012, v. 12, p. 1110-1118: Baoqing Nie et al. (copy appended hereto as Exhibit A) would offer a much higher base capacitance and the desired sensitivity. The current invention describes ways to size reduce such droplet capacitors and to mount them into a 14/1000 of an inch guide wire.

[0023] The present invention also contemplates a system having a guide wire having a distal portion with a coil and pressure sensitive capacitive element providing a resonance circuit which varies in its resonance frequency responsive to the pressure from blood external the guide wire when in a blood vessel of a patient's body. The floppy tip a typical guide wire consists of at the distal end may serve as the coil or inductor of the resonance circuit. Alternatively a miniaturized coil can be incorporated into the guide wire. This way only up to two small additional electrical components need to be integrated and the wire maintains its original mechanical handling characteristics. In other embodiments a ceramic resonator replaces the inductor or the inductor and capacitive sensor. The resonance frequency will be read through one brush contact attached to the sheath or guide catheter or alternatively through capacitive coupling to a metalized layer inside the guide catheter or sheath the guide wire is inserted through and a ground electrode incorporated into the distal sheath or guide catheter end.

[0024] Unlike the device and method described in US Patent Application Publication No. 2001/0051769A1 this embodiment of the invention utilizes a completely passive sensor with an order of magnitude lower current flowing through the patient's body. Also, there is no need for a ground electrode affixed to the patient's skin since a ground electrode on the distal sheath or guide catheter end is used to close the electrical circuit. This has the advantage that the electrical current flow, through the patient, is limited to the blood stream, with significantly better conductivity than tissue.

[0025] The present invention contemplates a further system comprising a guide wire having a distal portion with a pressure sensitive capacitive element providing a phase shift signal which varies in response to the pressure from blood external the guide wire when in a blood vessel of a patient's body. The floppy distal tip of a typical guide wire may serve as the location for the capacitive pressure sensor in order to minimize the impact on wire handling by leaving the proximal wire portion unaltered. In this way only one small additional electrical component needs to be integrated and the wire maintains its original mechanical handling characteristics.

[0026] The pressure sensitive capacitive element may take the form of a variable capacitive element with at least one pressure sensitive membrane which varies the capacitance responsive to the amount of pressure applied external of the guide wire onto the membrane. These pressure sensitive capacitors are well known and described in Journal of Micromechanics and Micro-engineering, Volume 17, July 2007: A fast telemetric pressure and temperature sensor system for medical applications; R Schlierf, U Horst, M Ruhl, T Schmitz-Rode, W Mokwa and U Schnakenberg; Sensors and Actuators A: Physical, Volume 73, issues 1-2, March 1999: Low power integrated pressure sensor system for medical applications; C Hierold, B Clasbrummel, D Behrend, T Scheiter, M Steger, K Oppermann, H Kapels, E Landgraf, D Wenzel and D Etzrodt; 2010 IEEE International Solid-State Circuits Conference: Mixed-Signal Integrated Circuits for Self-Contained Sub-Cubic Millimeter Biomedical Implants; Eric Y Chow, Sudipto Chakraborty, William J Chappell, Pedro P Irazoqui).

[0027] However, due to the size restrictions inside a 14/1000 inch guidewire the sensors must have a size no larger than about 200 microns in width, about 1 mm in length and about 200 microns thick. Conventional small capacitive sensors are typically based on membranes separated by air or vacuum and do not provide enough capacitive change over the physiological blood pressure range to be detected through ground impedance and wire/body parallel capacitance. The typical capacitive change obtainable with the above referenced pressure sensor is in the 10% range which equates to 1 pF or less given a base capacitance of 10 pF or less. Such small capacitive change cannot be detected directly without amplifying the signal first at the sensor site because of a shunt capacitance of 1000 pF or higher between guide wire and surrounding blood. A much higher capacitive change on the order of 100% and a base capacitance around 1000 pF would be desirable in order to enable direct detection through ground and sheath (brush or capacitive) or clip contact without having to add active electronic circuitry.

[0028] As mentioned herein above, a phase shift signal may be read through one brush contact attached to the sheath or guide catheter. Alternatively the phase shift may be monitored through a contact clip at the proximal wire end and a ground electrode attached to the patient body or incorporated into the distal sheath or guide catheter end.

[0029] A transmission through a patch ground electrode on the patient and a simple clip at the proximal guide wire end to the pressure monitoring system, as in one embodiment of the present invention, greatly enhances clinical utility because catheters can be inserted over the wire without having to disconnect a bulky connector handle first. In this way the guide wire really functions as a mechanical guide for catheter insertions and simultaneously as a hemodynamic measurement tool. The chance of erroneous pressure signal readings due to contaminated slip ring contacts is also minimized because the present invention does not require slip-ring contacts embedded into the guide wire.

[0030] A capacitive sensor as used in the present invention may be manufactured using semiconductor techniques. In particular the capacitive sensor may take the form of a MEMS capacitive pressure sensor with a size of 0.2×0.2×1.2 mm (width, depth, length) or less and a capacitance of 0.5-5 nF. A capacitive MEMS pressure sensor may be made up of two capacitors in parallel fabricated using multiple silicon wafers that are micro-machined, stacked and bonded together. One capacitor is on the top side of the device (capacitor **1**) and the other capacitor is on the bottom side of the device (capacitor **2**) separated by bulk silicon. The capacitors are connected in parallel and the electrical signals are brought to one side of the sensor via through silicon vias. In the fabrication process, SOI (silicon on insulator) wafers may be used to precisely control etching steps and provide a robust handling means during fabrication. Metal pads on one side of the wafer may be used for solder, wire bonds or other form of electrical interconnection to the guide wire and the core wire thereof. Such a MEMS type capacitive sensor is designed to achieve 0.5-5.0 nF capacitance (total) when the two capacitors connected in parallel. In the first capacitor, two plates are separated by a specified gap and one plate of the capacitor is held fixed

(bottom plate) while the other plate deflects with applied pressure (top plate). In between the two plates are an air or vacuum gap and a dielectric with a high dielectric constant. As pressure is applied the top plate deflects through the air or vacuum gap until it makes contact with the dielectric. Once the top plate makes contact with the dielectric the capacitor turns on. As pressure is increased, the area of contact of the top plate with the dielectric increases. The purpose of the dielectric is to significantly increase the capacitance achievable between the top and bottom electrode. The capacitance prior to top plate and dielectric contact is negligible. The minimum pressure range of the device is specified by a minimum area of contact between the top plate and dielectric. The maximum capacitance is defined when a saturation pressure is reached and maximum area of contact is achieved. As the area of contact changes between the top plate and the dielectric, the capacitance changes and this change in capacitance is proportional to applied pressure. This physical phenomenon is identical for the second capacitor. The high level of capacitance is needed to ensure the electrical signal can be channeled outside of the body while maintaining a high signal to noise ratio when wires are attached. Hence the device can be used to measure pressure internal to the body.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] FIG. **1** is partially a schematic perspective view and partially a block diagram of a wireless pressure sensing system in accordance with the present invention.

[0032] FIG. **2** is partially a schematic cross-sectional view and partially a circuit diagram of a distal portion of a guide wire in an artery of a patient, in accordance with the present invention.

[0033] FIG. **3** is a circuit diagram of an external circuit of the wireless pressure sensing system of FIG. **1**.

[0034] FIGS. **4**A and **4**B are two perspective views illustrating the operation of two resonance circuits which may represent a sensor circuit and a detector circuit of the present invention, where FIG. **4**A shows the sensor circuit and the detector circuit in resonance and accordingly a high current on an oscilloscope, and FIG. **4**B shows the sensor circuit detuned with an additional capacitor which reduces the current into the detector circuit and therewith the current on the oscilloscope.

[0035] FIG. **5** is a schematic side elevational view of a distal end portion of a guide wire in accordance with the present invention, showing a coil implementing a floppy tip and utilized as the inductor of a pressure sensing resonance circuit and further showing the position of a variable-capacitance capacitor completing the resonance circuit, in accordance with the present invention.

[0036] FIG. **6** is a circuit diagram showing a 2 contact version of a pressure-sensing guide wire system in accordance with the present invention.

[0037] FIG. **7** is a schematic side elevational view of the 2 contact version of the pressure-sensing guide wire, demonstrating how a core wire and a hypotube are utilized as electrical conductors.

[0038] FIG. **8** is a series of three different resonance curves representing different capacitance values and concomitantly different pressure values.

[0039] FIG. **9** is essentially a circuit diagram of a sheath contact version of a pressure sensing guide wire system in accordance with the present invention.

[0040] FIG. **10** is a schematic side elevational view of the sheath-contact pressure wire depicted as a circuit diagram in FIG. **9**.

[0041] FIG. **11**A is a diagram of a sensor resonance circuit in a distal portion of a guide wire, where the circuit includes a fixed value capacitor and a pressure sensitive inductor.

[0042] FIG. **11**B is a diagram similar to FIG. **11**A, showing the inductor with a shorter length owing to contraction in response to an increase in surrounding pressure.

[0043] FIG. **12**A is a diagram of another resonance circuit in the distal portion of a guide wire with a fixed value capacitor and a pressure sensitive inductor.

[0044] FIG. **12**B is a diagram similar to FIG. **12**A, showing the inductor with a shorter length owing to contraction in response to an increase in surrounding pressure.

[0045] FIG. **13**A is a diagram of yet another resonance circuit in the distal portion of a guide wire with a fixed value capacitor and a pressure sensitive inductor by virtue of a shiftable ferromagnetic inductor core.

[0046] FIG. **13**B is a diagram similar to FIG. **12**A, showing the core inserted to a greater extent inside an inductor coil in response to an increase in surrounding pressure.

[0047] FIG. **14** is partially a schematic perspective view and partially a block diagram of another wireless or practically wireless pressure sensing system in accordance with the present invention, showing an external detection unit connected to an external coil located at a distal end of an insertion sheath.

[0048] FIG. **15** is partially a schematic perspective view and partially a circuit diagram of another contactless pressure sensing system in accordance with the present invention, where an external detector includes a radio transmitter.

[0049] FIG. **16** is a schematic diagram of the contactless configuration of FIG. **15**, showing how a proximal guide wire end acts as an opposite (receiver) antenna.

[0050] FIG. **17** is a schematic diagram of another contactless configuration wherein a detector and guide wire are coupled capacitively through an insertion sheath.

[0051] FIG. **18** is a schematic perspective view of an adhesive patch carrying a resonance circuit inductor in accordance with the present invention.

[0052] FIG. **19** is a schematic side elevational view of an inductor or coil having a number of active windings that varies in accordance with external fluid pressure.

[0053] FIG. **20** is essentially a circuit diagram of a pressure sensing guide wire system in accordance with the present invention, schematically showing deployment thereof in a human patient for purposes of measuring blood pressure.

[0054] FIG. **21** is a diagram of a tuning-fork-type MEMS resonator device for fluid pressure measurement in accordance with the present invention.

[0055] FIG. **22** is a circuit diagram similar to FIG. **20** but incorporating the tuning-fork-type MEMS resonator device of FIG. **21**.

[0056] FIG. **23** is a schematic side elevational view, partly in cross-section, of a multi-layer ceramic capacitor utilizable in an LC pressure measurement device as disclosed herein with reference to FIGS. **1**-**19**.

[0057] FIG. **24** is a block diagram of an electronic signal processing circuit as a component part of a pressure sensing guide wire system in accordance with the present invention.

[0058] FIG. **25** is a block diagram of another electronic signal processing circuit as a component part of a pressure sensing guide wire system in accordance with the present invention.

[0059] FIG. **26** is a block diagram of a directional coupler showing connections for an electronic amplitude monitoring circuit for a resonator-incorporating resonance circuit in accordance with the present invention.

[0060] FIG. **27** is a block diagram of a pressure-measuring resonance circuit for operating in the time domain, in accordance with the present invention.

[0061] FIG. **28** is a drawing showing another embodiment of the present invention, with components mounted inside a $^{14}/_{1000}$ of an inch guide wire.

[0062] FIG. **29** is a diagram of the distal portion of the guide wire of FIG. **28** showing a different configuration for the sensor.

[0063] FIG. **30** is a schematic diagram of the distal portion of the guide wire of FIG. **28** showing another sensor configuration.

[0064] FIG. **31** is essentially a schematic side elevation diagram showing the distal end of a guide catheter inside the aorta with a distal guide wire extending into a coronary vessel, in accordance with the present invention.

[0065] FIG. **32** is a schematic perspective view broken away to show layers of a sheath or guide catheter and an inserted guide wire, in accordance with the present invention.

[0066] FIG. **33** is a schematic elevational view, partially broken away, of a proximal end of a sheath or guide catheter portion (hub), showing an external brush contact attached to in accordance with the present invention.

[0067] FIG. **34** is a schematic elevational view of a proximal end of a sheath or guide catheter portion (hub), showing a guide wire inserted and a wire torquer attached to the proximal end of the guide wire, electrically connecting the guide wire with an FFR system, pursuant to the present invention.

[0068] FIG. **35** is an electrical diagram of a resonance circuit of FIG. **31** connected to a phase detection system through the core wire of the guide wire and with ground electrodes connected through the blood stream.

[0069] FIG. **36** is a schematic elevational view of a proximal end of a sheath or guide catheter portion (hub), showing a circuit connection through a tubular ground electrode connecting the FFR system to the patient's blood stream, which does not require sheath modifications.

[0070] FIG. **37** is a diagram of a guide wire with a capacitive sensor inside a patient and electrical connections established through a sheath contact and ground electrode, pursuant to the present invention.

[0071] FIG. **38** is a schematic perspective view, partially broken away, of the guide wire of FIG. **37**, showing the position of the capacitive sensor in a floppy tip section of the guide wire.

[0072] FIG. **39** shows a computer display screen with in vivo phase measurement of the parasitic wire/body capacitance.

[0073] FIG. **40** shows a display screen recording in vivo phase measurement of the parasitic capacitance variations with breathing and heart cycle.

[0074] FIG. **41** is a table of key findings from in vivo measurements of impedance parameters.

[0075] FIG. **42** shows a display screen with an amplitude measurement of bloodstream impedance changes with cardiac and breathing cycles.

[0076] FIGS. **43** and **44** are perspective views of a capacitive sensor utilizable in a pressure sensing system in accordance with the present invention, showing top and bottom sides, with first and second capacitors in parallel and solder bumps as one form of electrical interconnect.

[0077] FIG. **45** is a schematic side elevational view, on an enlarged scale, which shows the capacitive sensor of FIGS. **43** and **44** connected to wires which make the electrical connection to a distal and proximal guide wire portion.

[0078] FIG. **46** shows a cross-section view of 1 of 2 capacitors of the capacitive sensor of FIGS. **43-44**, depicting dielectric and conductive layers building up the MEMS capacitive sensor.

DETAILED DESCRIPTION

[0079] As illustrated in FIG. **1**, a pressure sensing guide wire system **10** comprises a guide wire **11** having a sensor **12** and coil **14** at its distal end portion **11***a*. FIG. **5** shows the mechanical arrangement of a floppy tip coil **14** and a capacitive sensor **20** forming a pressure sensing resonance circuit. The guide wire **11** may be inserted into the cardiovascular system of a patient. Small flexible devices, called catheters, may be guided over the guide wire **11** inserted through blood vessels and vascular structures of the patient, such as to the site of a damaged or diseased blood vessel, as typically performed in interventional cardiology. A detection unit **16** has a receiver housing **16***a* disposable external of the patient's body in the vicinity of the resonance circuit consisting of sensor **12** and coil **14**. In a typical embodiment, receiver housing **16***a* carries an inductor **25** (FIG. **3**) that may take the form of a flat coil, particularly a printed coil, attachable to the patient's side roughly at the location of the heart in case of coronary artery interventions. Such printed circuit coils are preferably disposable. The receiver housing **16***a* may be in contact with the patient's skin surface or introduced within the patient. Information from the sensor **12** is wirelessly detected by the receiver (detection resonance circuit **24**, see FIG. **3**) through the human body (soft or hard tissue). The body **11***b* of the guide wire **11**, which is integrated with the sensor **12** and the coil **14**, may be a typical guide wire used in interventional cardiology or interventional radiology (i.e., composed of non-corrosive biocompatible material(s)) and of a diameter and sufficiently flexibly and bendable to pass through blood vessel(s) or vascular structure(s) to a surgical or diagnostic target site in the patient (see also FIG. **5**). The sensor **12** and detection unit **16** provide wireless detection of a physical variable, in particular blood pressure at such site, thus eliminating the need for a mechanical connection between the sensor and external detection equipment of the prior art.

[0080] FIG. **2** shows the distal portion **11***a* of the guide wire **11** in more detail. The distal portion **11***a* is a cone integrated to the body **11***b* at the distal end of the guide wire. The sensor **12** comprises a pressure sensitive element **18** mounted in the guide wire to detect the blood pressure surrounding the wire **11**, and further comprises a variable capacitor **20**, which is referred to herein as a pressure sensitive capacitive element. Pressure sensitive element **18** is connected to or part of a variable capacitor **20** whose capacitance value varies with amount of pressure upon element **18** from the blood about the distal portion **11***a*. The pressure sensitive element **18** has an outer surface **18***a* exposed to blood **21** about the distal wire portion **11***a*, and may be biased, such as by a spring, away from capacitor **20**. Increased or decreased pressure upon the outer surface **18***a* moves the pressure sensitive element

towards or away, respectively, from the capacitor, the change in distance resulting in a change in the capacitive value of capacitor **20** and hence the resonance frequency of the resonance circuit **23** (FIG. **2**) consisting of capacitor **20** connected to coil **14**. More specifically, capacitor **20** may include a first plate element **20***a* and a second plate element **20***b*, where the latter is movably mounted relative to plate element **20***a* and guide wire **11** and coupled or entrained to pressure sensitive element **18** so that motion of the pressure sensitive element causes a change in the distance between plate **20***b* and **20***a*. Other capacitive pressure sensors may also be used, such as described for example in Sensors and Actuators A: Physical Vol 73, Issues 1-2, 9 Mar. 1999, Pages 58-67 or as shown in FIG. **46** hereof.

[0081] The position of the coil **14** and sensor **12** in the distal portion **11***a* of the guide wire may either be as shown in FIG. **1**, in which the coil is more distal than the sensor **12**, or vice versa, as shown in FIG. **2**.

[0082] The coil **14** provides an inductance which may utilize the coil tip (or sections thereof) at the distal end of the guide wire, often referred to as the floppy tip. This inductor **14** and pressure sensitive capacitor **20** form a resonance circuit **23** with a resonance frequency varying with blood pressure fluctuations. In other embodiments, the capacitor can be of fixed value while the inductance of the coil changes according to the surrounding blood pressure. This can be accomplished by changing the length of a coil **56** or **60** according to surrounding blood pressure as shown in FIGS. **11**A and **11**B or FIGS. **12**A and **12**B. In the approach of FIGS. **12**A and **12**B, windings **58** of coil **60** are pressed in a longitudinal or axial direction of the guide wire in response to fluid pressure **61** exerted in that direction. Inductance changes can also be related to the surrounding blood pressure by changing the number of active windings of a coil or by changing the position of a ferromagnetic core **66** inside the coil as shown in FIGS. **13**A and **13**B.

[0083] In the embodiment of the wireless pressure sensing guide wire system of FIGS. **1-3**, an external or extracorporeal electro-magnetic field is created in response to an applied voltage by an external resonance (or detector) circuit **24** of the detection unit **16**, comprising a capacitor **26** and an inductor (or coil) **25** as shown in FIG. **3**. When both resonance circuits **23** and **24** are tuned to the same resonance frequency, a maximum energy transfer will take place from the external circuit **24** to the internal circuit **23**, which is mounted inside the guide wire **11**. Detuning of the circuit **23** through capacitance changes (caused by blood pressure variations) will vary the amount of transmitted energy to the external circuit **24**. By recording the changes of transmitted energy, a blood pressure recording is provided, as via a current sensor **28**. Thus, pressure values are detected without making an electrical connection by wire at the proximal guide-wire end or by switching the detector unit **16** into a receive-only mode relying on very weak signals being emitted from a free oscillation of the sensor circuit **12** after the power to the detector circuit **16** has been cut, as described in U.S. Pat. No. 6,517,481.

[0084] The detection circuit **24** may be disposed in housing **16***a* and electronically connected (e.g., via wires **16***b*) to the detection unit **16** which supplies power and varies the frequency of resonance circuit **24** in the operative frequency range of circuits **23** and **24**, and a change in power/current monitor **28** detects the resonance frequency when circuits **23** and **24** are in resonance.

[0085] Optionally, in order to improve the coupling between sensor circuit **23** and detector circuit **24**, the coil **25** of detector circuit **24** may be located in an insertion sheath **62** rather than housing **16***a* as shown in FIG. **14**. During use of the pressure sensing guide wire system of FIG. **14**, the sheath **62** may be located inside the aorta of the patient and the distal sheath end at the aortic arch and all devices (guide wire **11**, balloon catheters etc) are advanced through the sheath. This has the advantage of better coupling between sensor circuit **23** and detector circuit **24**. The guide wire **11** may contain a core wire which may be fabricated out of a ferromagnetic material to even further improve coupling, since sensor coil **14** and detector coil **25** surround the same ferromagnetic core as shown in FIG. **14**.

[0086] Only one LC circuit **23** is provided in the guide wire **11**: an inductance L consisting of wire windings or coil **14** in the floppy tip **11***a* of the wire **11** and a capacitor **20** which changes capacitance C with blood pressure.

[0087] The inductance L of a distal pressure-sensing coil or inductor may be varied by moving, in response to blood pressure, a ferromagnetic core member **66** inside a guide wire coil **68** which is connected together with a fixed-value capacitor **70** in a resonance circuit **72**, as shown in FIGS. **13**A and **13**B. Alternatively, the resonance frequency of an LC circuit may be varied in accordance with blood pressure by changing the number of active windings of a variable-inductance coil. This change in the number of active windings may be accomplished by shifting a winding-contact element and the coil relative to one another. Pursuant to another approach, depicted in FIGS. **12**A and **12**B, the inductance is adjusted by compressing, through blood pressure, the coil **60** as shown in FIGS. **12**A and **12**B. Changing the length of the coil **60**, in response to a blood pressure-induced axial force serves to vary the inductance of the coil. In another embodiment, shown in FIGS. **11**A and **11**B, a membrane **74** surrounding the coil **56** is compressed in a transverse or radial direction by the surrounding blood pressure **75**. With windings **78** of coil **56** movably mounted relative to the guide wire and with the membrane **74** connected to the windings, the inward distortion of the membrane **74** causes the windings **78** to move laterally towards one another, in the longitudinal direction of the guide wire, thus modifying the active length of the coil **56** and varying the inductance proportional to blood pressure changes.

[0088] In system **10** of the present invention contact-less detection of a remote sensor is accomplished by detecting the resonant frequency of the sensor circuit **23** while the external detector circuit **24** is being powered up. The detection operation works as follows: the external high frequency oscillator sweeps across a frequency band. An electromagnetic field of different frequencies is generated while the power consumption of the external high-frequency oscillator is being monitored. The sensing LC circuit **23** absorbs a portion of the RF power of external high frequency oscillator mainly at its resonant frequency. The power, with which the external oscillator is supplied, will exhibit a change when the external circuit **24** and the sensing circuit **23** are in resonance. This change in power consumption of the external high frequency oscillator represents the resonance frequency of the LC sensor **12** which in turn is indicative of the blood pressure.

[0089] The detection unit **16** may have electronics for detecting when the power change occurs and displaying the corresponding blood pressure reading on a display. Such electronics may have a programmed controller or microprocessor

(or other logic device), which calculates (or lookups up in a table in a memory) the corresponding blood pressure for the detected resonance frequency for output to the display. The relationship of resonance frequency to blood pressure may be in accordance with an equation, or calibrated with circuits **23** and **24** to provide a curve or look-up-table relating frequency to blood pressure stored in memory of the electronics for later use. See for example, see monitoring material properties in: Butler; Sensors and Actuators A 102 (2002)61-66. The blood pressure monitoring process may be done periodically during interventional procedures or as needed to classify the hemodynamic significance of a lesion, so that the blood pressure about the site of intervention can be accurately measured.

[0090] Detection unit **16** is configured for detecting a change in blood pressure by detecting an absorption of less electromagnetic energy by resonance circuit **23** in response to the change in the inductance or capacitance of the pressure-sensitive LC circuit element. Detection unit may be programmed to calculate, or look up in a table, the pressure corresponding to the amount of reduction of energy absorption. Alternatively, detection unit **16** may induce detector circuit **24** to scan through a range of frequencies about the former resonance frequency, thereby picking up or detecting a new resonance frequency. Detection unit **16** may then report the new blood pressure associated with the newly detected resonance frequency.

[0091] FIGS. **4**A and **4**B are two perspective views illustrating resonance between two resonance circuits illustrating the operation of the present invention providing a sensor circuit **123**, which corresponds to and functions the same way as sensor circuit **23**, and a detector circuit **124**, which corresponds to and functions the same way as detector circuit **24** of system **10**. The sensor circuit **123** for illustrative purposes is not shown in the desired form and configuration described earlier. The detector circuit **124** may also be in a different form than shown. In each FIG., the right circuit illustrates the sensor circuit **123** having a coil **130** connected to capacitor **131**, the left circuit illustrates the detector circuit **124** having a coil **132** connected to a capacitor (not shown), and the oscilloscope's leads are connected to the detector circuit. FIG. **4**A shows the sensor circuit and the detector circuit in resonance and accordingly a high current on the oscilloscope's screen **134** at this frequency. A frequency oscillator (not shown) when such resonance circuits are in the desired form and configuration coupled to the detector circuit was varied until the high current was observed on the oscilloscope (i.e., from a change in power consumption of the detector circuit **24** when the two circuits illustrated are in resonance). To illustrate a pressure change (and hence capacitance), FIG. **4**B illustrates the sensor circuit detuned with an additional capacitor **132** connected to capacitor **131**, which reduces the current in the detector circuit and hence the observed current is now lower on the oscilloscope's screen **134**. The frequency oscillating the detector circuit is now at the different frequency than the new resonance frequency of the sensor circuit due to the combined capacitance of capacitors **132** and **131** in the LC circuit **23** with coil **130**.

[0092] From the foregoing description, it will be apparent that there have been provided a wireless pressure sensing guide wire and detector. Variations and modifications in the herein described apparatus, method, and system in accordance with the invention will undoubtedly suggest themselves to those skilled in the art.

[0093] FIG. **6** is an electric circuit diagram showing the structure of the 2 contact pressure wire version. A resonance sensing circuit **80** at the distal wire end is identical to the one described above for the wireless version. Instead of wirelessly determining the change of the resonance frequency, two contacts **82** and **84** at the proximal wire end **86** are utilized.

[0094] FIG. **8** demonstrates the change in resonance frequencies for capacitive values of about 13 pF in screen ffr**1**, about 8 pF in screen ffr**2** and about 7 pF in screen ffr**3**. A change of about 5 to 6 pF represents the physiological pressure range in this experiment and allows for unmistaken detection of the blood pressure values. FIG. **7** shows typical guide wire components utilized as electrical conductors to avoid having to integrate additional electrical wires into the guide wire structure, which negatively affects wire handling. The compromised wire handling of the commercially available pressure sensing guide wires represents a significant barrier towards widespread use of pressure sensing guide wires. As FIG. **7** demonstrates, the wire handling can be equal to non-pressure sensing guide wires by requiring only 2 electrical conductors in the coaxial form of the standard wire components of hypotube **88** and core wire **90**). Core wire **90** is connected to a capacitor **87** and inductor or coil **89** of an LC pressure-sensing circuit **91**.

[0095] FIG. **9** shows an alternative configuration which to the user appears wireless since a proximal guide wire end **92** does not need to be connected with a connector handle. Instead a sheath **94**, which is part of any interventional procedure, contains a brush contact **96** to connect to the proximal end **92** of the guide wire **98**, while a distal end **100** of the wire is in electrical contact via an electrode **102** with the patient P, who in turn is connected to ground potential through a ground electrode **104**. This grounding technique is widely utilized in RF ablation procedures with a typical impedance of about 100 Ohms from RF electrode to ground. As can be seen in FIG. **8**, the resonance frequencies, for the pressure wire configurations described here, are in the 10^{th} of MHz range (vs. KHz range for RF ablations), which reduces the serial impedance to ground to negligible values since the mostly capacitive impedance of the patient body is proportional to 1/f. An LC resonance circuit **106** at the distal wire end **100** is connected through electrode **102** at the distal tip of the wire **98** to the patient P who is connected to ground potential through the ground electrode **104**. The other end of the resonance circuit **106** is connected to the proximal wire body **98**, either the hypotube and or core wire or a solid proximal wire portion. The proximal end portion **92** of the wire **98** is not insulated in order to make contact with the contact brush **96** within the sheath as shown in FIG. **10**. This has the same advantage as in the two contact version that wire handling is not compromised since standard wire components (hypotube and or core wire) are utilized as electrical conductor avoiding the insertion of additional electrical wires.

[0096] In another embodiment, a wireless coupling is accomplished with an external radio transmitter **112**, as shown in FIG. **15**. An antenna **114** of the external radio transmitter **112** interacts with the proximal guide wire end **116**, which acts as a receiver antenna, as shown in FIG. **16**. Except for the coupling through antennas this configuration functions as described for the wireless system **10** with the detector unit **16** and the guide wire **11** as shown in FIG. **1**.

[0097] In yet another embodiment, the coupling between detector unit **16** and the resonance circuit **23** in the guide wire

11 is accomplished capacitively as shown in FIG. 17. An insertion sheath 118 might be equipped with a special metallic layer which acts as one capacitive electrode while the proximal guide wire section 120 inserted through the sheath acts as the opposite electrode. Instead of a special metal layer, the metallic braid many sheaths utilize for torqueabilty could be utilized.

[0098] As depicted in FIG. 18, an external or detector resonance circuit 32 may include a printed disposable coil 34 attachable to a patient near an intervention site. Coil 34 may be embedded in a strip 36 of polymeric material that is provided with an adhesive layer 38 and a removable cover sheet 40. A capacitor 42 of the LC resonance circuit 32 may be provided in strip 36 or separately therefrom.

[0099] As shown in FIG. 19, a resonance circuit on a guide wire may have a movable electrical contact 44 shiftable relative to a coil 46 so that changes in pressure 48 of an external fluid (e.g., blood) results in shifting of the contact relative to the coil and changing the active length 50 of the coil, thereby varying an inductance of coil and concomitantly the resonance frequency of the resonance circuit. The movable electrical contact 44 is coupled to a plate or disk 52 that moves relative to the guide wire in response to changes in external fluid pressure 48.

[0100] 1. Resonator with Capacitive Sensor

[0101] FIG. 20 shows a resonator 206 and capacitive sensor 207 connected in close proximity to each other in a distal end portion 200 of a guidewire 298, near a conductive tip 202 of the guidewire.

[0102] The resonator 206 is a ceramic element from aluminum nitride or another ceramic material which produces a resonance similar to a quartz crystal as they are used in precision oscillators. However, in contrast to a quartz crystal the resonance is usually broader and it can be pulled over a wider frequency range via a variable capacitance. Ceramic resonators can also be produced in a smaller form factor, allowing the integration into small $^{14}/_{1000}$ inch guidewires. They are less prone to mechanical damage. Metal in close proximity will not have an adverse effect on the properties of a resonator. It is of little difference whether the sensor 207 or the resonator 206 is the more distal element. The contact to the wire can be as simple as a single pinch contact at the proximal wire end since no active supply voltage is required. The resonator 206 can alternatively be located proximally from the capacitive sensor 207.

[0103] FIG. 20 shows the guide wire 298 as having a proximal end portion 292 inside a sheath 294. A contact point 296 is in the proximal sheath portion (hub), outside the patient P. The resonance circuit includes a body contact ground electrode 204.

[0104] Another embodiment is a parallel resonant circuit where the capacitive sensor 207 is connected in parallel with the resonator 206. This is usually less advantageous than a series connection.

[0105] Yet another embodiment is a connection of the resonant circuit to the system via an additional conductor wire inside or on the guidewire (see further discussion hereinbelow). This eliminates the need to use the patient body for ground return but may make wire production and handling more cumbersome, mainly due to the need for external contacts. The transmission method could be a central core wire coaxially inside a hypotube or it could be a differential scheme with two insulated strands in a spiral-style guidewire.

[0106] The electronic circuitry in the external system acts like a network impedance analyzer. It measures amplitude and phase of the whole guidewire assembly and determines where the resonance is found at any given time. Phase shift of the RF current into the wire versus applied RF voltage is generally a more precise method than measuring only the peak in the amplitude of the current. The location of the resonance in the frequency spectrum indicates the local pressure. Linearization is usually required.

[0107] Pressure exerted on the capacitive sensor 207 will change its capacitance. This in turn will shift the resonance of the resonator. The external system can detect such movement of the resonance by monitoring the RF current into the guidewire for phase, amplitude or both.

[0108] 2. MEMS Resonator for Direct Pressure Sensing

[0109] FIGS. 21 and 22 illustrate a sensor 210 which is of similar material as the sensor in FIG. 20. However, sensor 210 is longer and operates like one or several miniature tuning forks. The example shows a two-fork version similar to that proposed by Sandia National Laboratories (Olsson, December 2012) for use as an accelerometer.

[0110] The present invention intends to use the MEMS (micro-electromechanical system) sensor 210 not as an accelerometer where the mass accelerates sideways and lengthens one tuning fork while shortening the other. Instead, sensor 210 is designed to measure a pressure exerted onto a center plate 212 that holds the two ceramic tuning forks 214 and 216 together. A membrane 218 is provided to prevent contact between the ceramic and the patient's blood. Two electrodes or contacts 220 and 222 provide electrically conductive connection to the guidewire 298.

[0111] The resonance can be measured externally in the same way as discussed hereinabove. No capacitors, inductors or any other components may be necessary in the guidewire 298 when using such a resonator 210. This greatly reduces complexity and cost when producing the guidewire.

[0112] Increasing pressure 223 pushes the center plate 212 farther down which pulls on both tuning fork resonators 214, 216, stretching them. This causes their resonant frequency to shift and such shifts can be detected by the external system. The resonator 210 needs to be of reasonably low impedance so that large parasitic capacitances from the insulated part of the guidewire 298 to the surrounding blood will not weaken the detection of the resonance excessively.

[0113] Another embodiment is a connection of the MEMS sensor to the system via an additional conductor wire inside or on the guidewire (discussed in detail hereinafter). This eliminates the need to use the patient body for ground return but can make wire production and handling more cumbersome. The transmission method could be a coaxial central wire inside a hypotube or it could be a differential scheme with two insulated strands in a spiral-style guidewire.

[0114] 3. Ceramic Pressure Sensing

[0115] FIG. 23 shows a sandwiched ceramic structure 224 having multiple capacitive plates 226 (exemplarily of nickel) in an interleaved array between two conductive epoxy panels 228 and 230 having copper terminations 232, 234, forming a multilayer ceramic capacitor or MLCC. Such a multilayer ceramic capacitor 224 is produced by AVX/Kyocera. A typical ceramic material is barium titanate. Many such capacitors have the undesired side effect of being microphonic. When exposed to an AC voltage they can emit audible noise. Since the effect is reciprocal an external pressure wave 236 can alter the capacitance and also generate an AC voltage. This capaci-

tance change or the voltage can be sensed by electronics in many ways, for instance, either directly as a generated AC signal or indirectly by using the capacitor **224** inside a resonant circuit, where the inductive component can be disposed far away from the capacitor (for example outside of the guidewire inside the detector system) if the capacitance is large enough.

[0116] Due to the proliferation of miniaturized electronics such as cell phones these ceramic structures are being made available in ever smaller and higher capacitance variants, the goal of the industry being to provide a higher density of capacitance per volume. The number of layers is, therefore, increasing. Aiding this trend is the fact that supply voltages of modern ICs are dropping to lower values, thus requiring less breakdown voltage rating of capacitors. That is advantageous for this invention as it reduces the source impedance of the pressure-induced capacitive change signal and thus increases the chance of only needing this one capacitive element in the guidewire as a sensor. The signal could be extracted using the same methods as described above with reference to FIGS. **1-19**. The electronic system could measure capacitance, generated signal, or both.

[0117] Where multilayer ceramic capacitor (MLCC) **224** is used in a guidewire-carried pressure-measuring LC circuit as disclosed above with reference to FIGS. **10-19**, the MLCC **224** is preferably a very high density MLCC with consequently high capacitance. Such a high capacitance requires a large inductance which would be difficult if not impossible to integrate into a small guidewire. A solution is to split off and place the bulk of the inductance outside the guidewire. This same design can be used in any guidewire-mounted circuit having an inductance that need be partially located at the distal end of the guidewire.

[0118] 4. FFR Electronic System

[0119] FIG. **24** depicts one embodiment of an electronic system **238** suitable to detect resonances in a resonator **206**, **210** and also in an inductor-capacitor based FFR guidewire (FIGS. **1-19**). Description below refers specifically to the guidewire systems of FIGS. **20** and **22**. Only important components are shown, support functions such as power supply or computer algorithms being known to engineers skilled in the art.

[0120] A controllable RF generator **240** sends an RF signal of fixed frequency into the guidewire **298** and a sensing circuit **242** measures the phase shift between the oscillator output and the current the wire draws. The generator **240** can be of any kind that can be controlled via an analog or digital system. Phase-locked loop (PLL) used to be common but due to faster control of the frequency direct digital synthesis (DDS) has become a more contemporary method. The current is sensed at RSENSE and sent via transformer TSENSE for safety isolation purposes.

[0121] A computer **244** commands the controllable generator **240** to move to a certain frequency that is guaranteed to be lower than the resonance in the guidewire **298**. Computer **244** then commands generator **240** to increase its frequency incrementally until a desired phase shift between the generator output and the current sense signal tapped off at RSENSE has been reached. This phase shift can later be adjusted again to compensate for capacitive drift in the various leakage capacitances from the guidewire to its surroundings.

[0122] A phase detector **246** measures the phase shift and its analog output is digitized by a converter or digitizer **248**. The phase value moves with pressure but not in a linear relationship. A two-way universal serial bus (USB) or local area network (LAN) interface **250** communicates with a computer **252** (optionally the same as computer **244**). Computer **252** may perform the functions of computer **244** via the interface **250** and a controller **254**. The computer **252** linearizes the phase signal over pressure and displays the pressure in a rolling graph or in any other desired form. A LAN interface **250** may be advantageous because it electrically isolates as well as allows the computer **252** to be at a remote location, for example in a shared control room that often exists between two catheter labs in a hospital. Existing hospital infrastructure can then be used for data transfer. The bandwidth of the data is very low compared to other usual activities, less than 5 kbit/sec.

[0123] Another embodiment of the electronics is to only measure amplitude, by using a directional coupler **256** (FIG. **26**). This can be sufficient when using resonators with very narrow frequency response. The directional coupler **256** is connected at a receive or input port P**1** to a fixed-frequency generator, for instance, of the direct digital synthesis type. At a transmit or output port P**2**, the directional coupler **256** is connected to a guidewire containing a resonator (as shown in FIGS. **20** and **22**). At an isolated port P**4**, the directional coupler **256** is connected to a signal-processing computer for monitoring amplitude changes. Another port P**3** of the directional coupler **256** is not used in this application. Ground return is common to all ports.

[0124] Yet another embodiment (FIG. **27**) of the electronics is to operate in the time domain. Here, a pulse oscillator **258** is used that only sends out bursts. A receiver **260** of the system then listens for the ringing from the resonant circuit in a guidewire (**264**). This method can prove beneficial if there are interference concerns with the above continuous wave method. If the resonance is at a suitable frequency the burst oscillator **258** could operate in a license-free industrial-scientific-medical (ISM) band. FIG. **8** shows burst pulse generator **258** and receiver/processor circuit **260** alternately connectable to the guidewire **264** via a transmit/receiver switch **262**.

[0125] A further electronic processing system **266** shown in FIG. **25** compensates for changes in leakage capacitances that occur naturally between a coated guidewire and the body of a patient or subject. These capacitances change when the wire is moved or pushed back and forth.

[0126] A first section **268** of processing system **266** is, as in the embodiment of FIG. **24**, the phase detection circuit that senses pressure. Phase detection circuit **268** has components identical to those in FIG. **24** and bearing the same reference designations. Processing circuit section **268** is operated at a frequency much lower than that of a second circuit section **270** and is designed to be insensitive to frequencies used in the second section **270**. Wire movements will cause changes in the leakage capacitance C_{LEAK} in a guidewire **272**, resulting in false pressure change indication. Filters to set the spectral sensitivities of the two sections have been omitted from the drawing for clarity and are easy to design by anyone skilled in the art, since essentially they are just LC filters. Phase shifters **274** and **274'** are needed because most ordinary phase detection circuits suffer from ambiguity every 180 degrees and also from inaccuracy when operated too close to 180 degrees in phase shift and multiples thereof.

[0127] The second or upper circuit section **270** in FIG. **25** has components that are analogous to respective components of the circuit of FIG. **24** and bear the same reference desig-

nations with a prime mark. Circuit section **270** runs at a much higher frequency, typically above 1.6 MHz to avoid noise from the AM radio band. Because of the inductor L_{WIRE} in the guidewire **272** the second circuit section **270** will largely be sensitive only to the leakage capacitance C_{LEAK} but not the pressure-measuring capacitance C_{SENSOR}. Therefore, the phase information gathered in the upper or section circuit section **270** will indicate the leakage capacitance C_{LEAK}. This information can then be used in the system software to compensate for the amount of false pressure change information caused by a change in the leakage capacitance C_{LEAK}. This essentially neutralizes changes in pressure measurements due to changes in leakage capacitance C_{LEAK} and greatly improves the pressure reading accuracy of the system in a clinical setting, where wire movements are part of the routine procedure of measuring a fractional flow reserve.

[0128] Because the computational overhead and the data rates are low it is also possible to use a hand-held device such as a smart phone or tablet computer. Even transmission of the data through regular digital voice data channels (cell networks) is feasible. This can open up options if the technology is considered for other purposes such a battlefield use.

[0129] As depicted in FIG. **28**, a capacitive pressure sensing guide wire **500** comprises a guide wire core wire **501** having a tubular capacitive sensor **510** and a coil **512** at its distal end portion. The cylindrical shaped sensor **510** utilizes core wire **501** as the inner sensor electrode. A tubular polymer member **502**, metalized on the inside, acts as the outer electrode and pressure sensing membrane. Preferably this tubular polymer member **502** has a variable wall thickness to enable the cylinder to take an oval or ovoid shape when pressure is applied. This way the sensitivity of the sensor **510** to pressure changes will be increased. Between inner electrode or core wire **501** and tubular outer electrode **502**, an electrolyte **503** is disposed. An air gap **504** allows the areas of contact between the electrolyte **503** and the outer electrode **502** and inner electrode **501** to vary depending on applied pressure at the outside electrode **502**. Electrolyte **503** and air gap **504** are enclosed or bounded by a pair of polymeric spacer rings **514** and **516**. The guide wire **500** may be inserted in the body of a patient or subject through blood vessels and vascular structures, such as to the site of a damaged or diseased blood vessel, as typically performed in interventional cardiology, without having to disconnect a contact handle from the proximal wire portion first. Catheters may be guided over the guide wire in the patient's body.

[0130] As further depicted in FIG. **28**, coil or inductor **512** is provided with a ferrite core **518** and is disposed between separated sections of core wire **501**. Coil **512** is electrically linked to the sections of core wire **501** by connectors **520** and **522**. A distal tip **524** of guidewire **500** have a polymer coating **526** which is metalized for conduction all around the distal tip if warranted. Otherwise the distal tip **524** has the same construction as conventional interventional guide wires, including a floppy coil structure **528**.

[0131] Tubular polymeric member **502**, with its metalized inner diameter, may be cut ant an angle to allow ease of electrical bonding like a pad. Guidewire **501** is provided with a polymer coating **530** at least between coil **512** and capacitive sensor **510** so that the coil on the distal side is only for RO. An outer connection **532** may be a Kapton tube disposed over coil **512** and bonded to core wire **501**.

[0132] FIG. **29** illustrates a differently configured capacitive sensor **540** for the distal portion of the guide wire **500**. Here the capacitive sensor **540** comprises a core wire **541** having a conical portion **548** and forming an inner electrode of the sensor. An outer electrode **542** is a tubular member essentially fixed in shape so as to not deform under surrounding blood pressure. A pressure sensitive membrane **545** is mounted in a transverse or cross-sectional fashion at a distal or front end of the sensor **540**. Pressure **546** applied to this membrane **545** will deform the membrane and thereby modify the volume occupied by electrolyte **543**. Capacitance changes because of variation in the area of electrolyte/electrode contact, variously compressing an air volume **544**. The capacitive change is enhanced through the conical portion **548** of the inner electrode **541** which will cause more surface variation (electrolyte/electrode) per volume movement.

[0133] The position of the coil **512** and sensor **510** or **540** in the distal portion of the guide wire **500** may either be as shown in FIG. **28**, in which the coil **512** is positioned more proximal than the sensor, or vice versa.

[0134] FIG. **30** shows yet a different capacitor configuration **550** with an isometric core wire **551**. Pressure sensing membranes **555**, **556** are mounted proximal and distal of the cylindrical capacitor **550**. The membranes **555**, **556** are variably deformed in accordance with the magnitude of ambient blood pressure, thereby varying the electrolyte volume **553** (vs. the volume of one or more air pockets **554**) to change the area of contact between the electrolyte **553** and electrode **552**. An outer tubular electrode **552**, metalized along an inner surface, does not change its configuration in response to changes in ambient pressures.

[0135] In yet another embodiment the space between an outer electrode and an inner electrode formed by a guide wire core wire is minimized to 100 microns diameter or less and the electrolyte is mainly stored in a pressure sensitive volume section proximal or distal (or alternatively both) to the capacitor. The pressure sensitive volume is connected with the capacitor so that the electrolyte can move into the space between the outer electrode and inner electrode of the capacitor when the pressure sensitive reservoir(s) is compressed. This construction will allow an even further increased sensitivity compared to the structure of FIG. **29**.

[0136] With reference to FIG. **31**, the present invention comprises a guide wire **601** having a resonance circuit **610** consisting of a capacitive sensor **612** and a coil **614** at its distal end portion. The resonance circuit **610** is connected to a conductive tip or ground electrode **603** which electrically connects the resonance circuit with the bloodstream of the patient. Through the bloodstream connection is made to another ground electrode **604** mounted on the distal portion of a sheath or guiding catheter **602**. In this embodiment of the invention, the resistance between the ground electrodes **603** and **604** is minimized since the blood path consists of a relatively short length of approximately 5 to 20 cm depending on lesion location and since blood is a better conductor than tissue. Besides the minimized electrical resistance compared to an approach with an external ground electrode this approach offers the convenience of not having to attach an external ground electrode to the patient making the procedure easier and faster. Last but not least this approach offers the advantage of a short connection through the patient's bloodstream without having vital organs like the heart being part of the conductive path way. This is problematic especially in an approach where the sensor is actively powered as described in US Patent Application Publication No. 2001/0051769/A1 and U.S. Pat. No. 7,645,233 B2. In a different embodiment

the ground electrode (**604**) at the distal sheath or guide catheter end can be mounted on the distal end of a flexible tube which is inserted into the sheath or guide catheter (**602**). This obviously has the advantage that any type of sheath or guide catheter the user prefers can be utilized.

[0137] FIG. **35** shows the electrical connections of the overall system consisting of circuit path Z-Blood between the ground electrodes **603** and **604**, the resonant circuit **610** connected to a core wire **616** of the guide wire **601** on one side and the distal guide wire ground electrode **604** (either mounted distally on the sheath or guide catheter or a tube to be inserted into either the guide ort sheath) on the other side. A phase detection system **618** is connected to the distal ground electrode **604** of the guide catheter or sheath **602** and the core wire **616** of guide wire **601** and is described in detail hereinabove with reference to FIGS. **20-27**.

[0138] FIG. **33** shows one way of connecting the core wire **616** of guide wire **601** with the FFR (Fractional Flow Reserve) system through a brush contact **606** at the proximal end or hub of the sheath or guide catheter **602**. The brush contact **606** is part of an attachment or coupling **605** which is designed to plug onto the hub of the sheath or guide catheter **602**. A lead or wire **617** extends from the attachment or coupling **605** to the FFR system. A liquid conduit or tube **619** extends to the hub **622** for conducting a fluid flush for the proximate pressure sensor.

[0139] Alternatively, the brush contact **606** can be integrated into the hub. In yet another embodiment the brush contact could be mounted proximally into a tube to be inserted into the guide or sheath **602**.

[0140] FIG. **34** shows a different embodiment where the electrical connection to the FFR system is made through a wire torquer **607** attached to the proximal end of the core wire **616** of the guide wire **601**.

[0141] FIG. **32** shows another embodiment of electrically coupling the core wire **616** of guide wire **601** with the sheath or guide catheter **602**. In this case coupling is achieved capacitively, between a stainless steel braid **620** as one capacitor electrode and core wire **616** of guide wire **601** as the opposite capacitor electrode. Braid **620** is sandwiched between an inner layer **624** of polytetrafluoroethylene or other polymeric material and an outer layer **626** of soft nylon or similar polymeric material. Two mutually insulated conductors (not shown) extend along the sheath or guide catheter **602** to the FFR system from the blood electrode **604** and the stainless steel braid **620**, respectively. Instead of utilizing the braid **620** of the sheath or guide **602** a metalized tube (not shown) could be inserted to create the opposite electrode to the core wire **616** of the guide wire **601**.

[0142] The guide wire **601** may be inserted in the body of a patient, for instance, through blood vessels and vascular structures to the site of a damaged or diseased blood vessel, as typically performed in interventional cardiology. Catheters may be advanced over the guide wire so inserted. The capacitive coupling approach from FIG. **32** and the sheath brush contact **606** shown in FIG. **33** allow insertion of catheters without having to disconnect an electrical contact handle from the proximal guide wire end. This allows for the FFR measurement to fit seamlessly into the interventional procedure.

[0143] The position of the coil **614** and capacitive sensor **612** in the distal portion of the guide wire **601** may either be as shown in FIG. **31**, in which the coil **614** is more distal than the sensor **612**, or vice versa. The coil **614** provides an inductance which may utilize the coil tip (or sections thereof) at the distal end of the guide wire **601**, often referred to as the floppy tip (**528**, FIG. **28**). This inductor **614** and pressure sensitive capacitor **612** create the resonance circuit **610** with a resonance frequency varying with blood pressure fluctuations. As described above with reference to FIGS. **28-30**, a typical vacuum or air filled capacitor cannot drive the load represented by body tissue. In order to fit the minimal dimensional requirements of a typical $^{14}/_{1000}$ guide wire and to provide enough capacitive change detectable through body and core wire conduction, an electrolyte capacitor **510**, **540**, **550** is utilized. In another embodiment the capacitor **612** can be of fixed value while the inductance of the coil **614** changes according to the surrounding blood pressure as described hereinabove with reference to FIGS. **1-19**. In yet another embodiment the resonance circuit **610** can be replaced by the ceramic resonator **206** which varies in resonance frequency depending on the surrounding blood pressure as described hereinabove with reference to FIGS. **20-27**.

[0144] The blood pressure monitoring process may be done periodically during interventional procedures or as needed to classify the hemodynamic significance of a lesion, so that the blood pressure about the site of intervention can be accurately measured.

[0145] From the foregoing description of FIGS. **31-36**, it will be apparent that there have been provided a quasi wireless pressure sensing guide wire and detector. Variations and modifications in the herein described apparatus, method, and system in accordance with the invention will undoubtedly suggest themselves to those skilled in the art.

[0146] FIG. **31** demonstrates the utilization of typical guide wire components as electrical conductors to avoid having to integrate additional electrical wires into the guide wire structure which negatively affects wire handling. The compromised wire handling of the commercially available pressure sensing guide wires represents a significant barrier towards widespread use of pressure sensing guide wires. As FIG. **31** demonstrates, the wire handling can be equal to non-pressure-sensing guide wires by requiring only 2 electrical conductors, utilizing the standard wire components, core wire and distal tip.

[0147] FIG. **35** shows the electrical configuration which to the user appears wireless since the proximal guide wire end does not need to be connected with a connector handle. Instead the sheath or guide catheter **602** which is part of any interventional procedure contains a brush contact **606** as shown in FIG. **33**, to connect to the proximal end of the wire **616**, while the distal end of the wire is in electrical contact with the patient who is connected to ground potential through a ground electrode **604** mounted to the distal end of the sheath or guide catheter **602** as shown in FIG. **31**. External patch electrode grounding techniques are widely utilized in RF ablation procedures with a typical impedance of about 100 Ohms from RF electrode to ground. The other end of the resonance circuit **610** is connected to the wire body or core wire **616**. The proximal end portion of the wire **616** is not insulated in order to make contact with the contact brush **606** within the sheath **602** as shown in FIG. **33**. This has the advantage that wire handling is not compromised since standard wire components (core wire and distal tip) are utilized as electrical conductors avoiding the insertion of additional electrical wires.

[0148] FIG. **36** shows yet another configuration where the ground connection is established through a conductive cylin-

der or tube **608** inserted into a sheath or guide hub **622** to make contact with the fluid column inside the sheath or guide **602** and therewith the patient's bloodstream. Compared to the approach shown in FIG. **31**, this has the advantage that the sheath **602** does not need to be modified with a permanent ground electrode (**604**). Cylinder or tube **608** can be either a conductive cylindrical tube advanced over the proximal wire end into the hub of sheath **622** or guide catheter **602** or consists of 2 linked half shells so that the cylinder can be opened and closed around the guide wire. In either case the cylinder or tube **608** is connected through a wire **628** to the ground terminal of the FFR system. FIG. **36** also depicts a coupling through a wire torque **630** electrically linked on the one side to guide wire core wire **616** and on the other side to the FFR system via a wire **632**.

[0149] As depicted in FIG. **37**, the present invention comprises a guide wire **900** having a capacitive sensor **906** (FIG. **38**) at its distal end portion. The capacitive sensor **906** is connected to a conductive tip or ground electrode **902** which electrically connects the capacitive sensor with the bloodstream of the patient. Through the bloodstream connection, is made to an external ground electrode **904** attached to the patient. Proximal to the sensor the guide wire is electrically isolated from the body with a thin layer or coating of insulating material. In this embodiment of the present invention the impedance between the ground electrodes **902** and **904** is on the order of less than 30 Ohms. Values up to several hundred Ohms can be tolerated for this invention so that even smaller patch electrodes than used in ablation procedures are feasible. This serial impedance might be problematic in an approach where the sensor **906** is actively powered as described in US Patent Application Publication No. 2001/0051769 A1 and U.S. Pat. No. 7,645,233 B2 but is not of concern in this invention. Another critical parasitic factor is the wire/body (blood) impedance. The capacitive sensor **906** needs to have about an order of magnitude higher capacitance than the parasitic wire/body capacitance. As can be seen from FIG. **39** this was verified in vivo to be the case with a wire/body capacitance in the 300 to 400 pF range. Also variations of this parasitic capacitance with wire movement on the order of 30 pF (see middle trace in FIG. **39**) are of no concern as long as the sensor is producing a capacitive change in the nF range. FIG. **40** shows the impact of heartbeat and breathing on the parasitic capacitance. This variation is in the pF range and again, will not impact the pressure measurement given a capacitive change in the nF range. FIG. **37** shows the electrical connections of the overall system consisting of the blood-body circuit path Z-Blood/Body between the ground electrodes **902** and **904**, the capacitive sensor **906** connected to the core wire of the guide wire **900** on one side and the distal guide wire ground electrode **902** on the other side. A phase detection circuit component **908** is connected to the external patient ground electrode **904** and the guide catheter or sheath **994** through a contact **996** or directly with the proximal core wire **996** of the guide wire **900**.

[0150] Phase detection circuit **908** essentially operates like a network impedance analyzer to detect the capacitive changes. It measures phase and amplitude in very fast sequence, typically 100 times per second or more. In contrast to a classical impedance analyzer phase detection circuit **908** measures the whole frequency spectrum of interests not in sweeps but simultaneously, typically 2 kHz to 10 kHz. Phase detection circuit **908** uses the complex Fast Fourier Transform method (FFT) or similar calculations.

[0151] FIG. **42** shows the impedance change with cardiac and breathing cycles and is an amplitude instead of a phase measurement. This is useful for two purposes. The system must automatically find a frequency where a change in impedance has the least impact on the displayed pressure value and monitoring this amplitude signal enables it to do so as needed. In addition, this signal allows a basic monitoring of vital signs in the absence of other suitable gear, for example in emergency care.

[0152] The guide wire **900** may be inserted in the body of a patient. Catheters may be guided over the guide wire **900** inserted in the patient's body through blood vessels and vascular structures, such as to the site of a damaged or diseased blood vessel, as typically performed in interventional cardiology. The sheath brush contact **996** shown in FIG. **37** allows insertion of catheters without having to disconnect an electrical contact handle from the proximal guide wire end. This allows for the FFR measurement to fit seamlessly into the interventional procedure. Alternatively a clip contact is easily removed and attached to the proximal wire end. Guide wire torquing handles are also routinely used and these can be employed to simultaneously provide the proximal electrical wire contact.

[0153] The position of the capacitive sensor **906** in the distal portion of the guide wire **900** may either be as shown in FIG. **38** in which the sensor is positioned in the coil section of the guide wire, often referred to as the floppy tip. A typical vacuum or air filled capacitor with capacitive change in the pF range cannot drive the load represented by body tissue. In order to fit the minimal dimensional requirements of a typical $^{14}/_{1000}$ guide wire and to provide enough capacitive change detectable through body and core wire conduction, an electrolyte-containing capacitor is utilized such as capacitor **510**, **540**, or **550**, described hereinabove with reference to FIGS. **28-30**.

[0154] As depicted in FIGS. **43-46**, a MEMS sensor **702** for implementing capacitive sensor **906**, or alternatively any of the variable-capacitance capacitive sensors disclosed herein, comprises two capacitors **704** and **706** in parallel, with exemplary dimensions of 0.2×0.2×1.2 mm (width, depth, length) and a capacitance range to 0.5-5 nF. Improved dielectrics produced over time may result in an even higher capacitance range. Two plates **708** and **710** (FIG. **47**) of the capacitor **704** (FIG. **46**) in the form of ion implanted electrodes are separated by a specified air or vacuum gap **712** and one plate of the capacitor **704** is held fixed (bottom plate **710**) while the other plate deflects with applied pressure (top plate **708**). In between the two plates are disposed air gap **712** (air, vacuum or ideal gas) and a dielectric **714** with a high dielectric constant (2000-15000 or more). The dielectric **714** can be BaTi03, CaCu3Ti4012 or a similar material. As pressure is applied the top plate **708** deflects through the air gap **712** until it makes contact with the dielectric layer **714**. Once the top plate **708** makes contact with the dielectric **714** the capacitor **704** turns on. As pressure is increased, the area of contact of the top plate **708** with the dielectric **714** increases. The purpose of the dielectric **714** is to significantly increase the capacitance achievable between the top and bottom electrodes **708** and **750**. The capacitance prior to top plate and dielectric contact is negligible. The relationship for capacitance with a dielectric is provided by the following equation:

$$\text{Capacitance}=(er*e*A)/h$$

where e is permittivity, er is dielectric constant, A is plate area and h is distance between plates. The minimum pressure range of the device is a specified by a minimum area of contact between the top plate **708** and the dielectric layer **714**. The maximum capacitance is defined when a saturation pressure is reached and maximum area of contact is achieved. As the area of contact changes between the top plate **708** and the dielectric layer **714**, the capacitance changes and this change in capacitance is proportional to applied pressure. This physical phenomenon is identical for the second capacitor **706**.

[0155] The electrodes of the top and bottom plates **708** and **710** can be fabricated by doped silicon, platinum or another suitable material. The top plate **708** is fabricated using a reactive ion etch (RIE) process to etch a diaphragm (0.7-3 micron thick) into the membrane of an SOI (silicon on insulator) wafer. The resulting standoffs create the separation between the two plates and define the gap **712** between the top plate electrode **708** and dielectric layer **714**. An alternative method to creating the standoffs is depositing or growing an oxide layer and patterning it via photo lithography and etching means. The handle portion of the SOI wafer is present to improve handling robustness during sensor fabrication and is greater than 100 microns in thickness but in a preferred embodiment is about 300 microns thick. The bottom plate **710** and the dielectric layer **714** are located on a bulk or SOI silicon wafer **716**. The bottom plate electrode **710** is fabricated by doping the silicon wafer or depositing a platinum or other suitable metal on the wafer. The dielectric layer **714** is deposited over the bottom plate electrode **710**. The first wafer containing the top plate **708**, electrode and standoffs is then bonded to the second wafer containing the bottom plate **710**, electrode and dielectric layer **714**. A similar procedure is followed to fabricate the second capacitor **706** with the added steps of fabricating the through silicon vias for electrical interconnection.

[0156] In a preferred embodiment, a fusion bond is used to bond the two wafers creating a single capacitive sensor **702**. In order to create a good fusion bond, a thin oxide layer is grown on both the first (top) and secondary (bottom) wafers. This oxide layer is preferably 500 angstroms or less. However alternate means such as glass frit or elastomeric materials can be used to bond the two wafers together.

[0157] In the preferred embodiment the top plate electrode is fabricated by doping the silicon membrane via ion implantation or diffusion after the first and second capacitors **704** and **706** are fusion bonded together and the handle wafers and oxide have been removed via dry or wet etch. This can be accomplished because the membrane is, for example, 1-2 microns thick. This is repeated for the second capacitor. An alternative to doping silicon for the top electrodes is depositing platinum or other suitable conductive material prior to fusion bonding.

[0158] In the preferred embodiment, electrical interconnects are on one side (top or bottom) of the sensor. A suitable metallization and barrier is deposited or plated for wire bonding, solder bumps, silver epoxy other electrical interconnect means. An alternative to using electrical interconnects is a wireless communication system such as but not limited to an inductive coil and needed electrical circuitry for resonance frequency shift telemetry as described above.

[0159] On the opposite side of the electrical interconnects, the oxide from the SOI wafer is left intact on the edges of the sensor with the center portion over the capacitor diaphragm removed. This creates a short standoff that will prevent mounting tools like a vacuum tip from touching the sensitive diaphragm when the sensor is attached to the guide wire or other medical tools. The capacitors **704** and **706** are connected in parallel and their electrical signal is channeled to one or two sides of the sensor **702** by through silicon vias **718**.

[0160] In yet another embodiment the capacitive sensor **906** can take the form of a ceramic resonator, that is, a multilayer ceramic capacitor **224** or MLCC as discussed above with reference to FIG. **23**. Such a multilayer ceramic capacitor is produced by AVX/Kyocera. A typical ceramic material is barium titanate. Many such capacitors have the undesired side effect of being microphonic. When exposed to an AC voltage they can emit audible noise. Since the effect is reciprocal an external pressure wave can alter the capacitance and also generate an AC voltage. This capacitance change or the voltage can be sensed by electronics in many ways. Either directly as a generated AC signal or indirectly by using this capacitor inside a resonant circuit, where the inductive component could remain far away from the capacitor (for example outside of the guidewire inside the detector system) if the capacitance is large enough.

[0161] Due to the proliferation of miniaturized electronics such as cell phones these ceramic structures are becoming available in ever smaller and higher capacitance variants. The goal of the industry is to provide a higher density of capacitance per volume. The number of layers is, therefore, increasing. Aiding this trend is the fact that supply voltages of modern ICs are dropping to lower values, thus requiring less breakdown voltage rating of capacitors. That is advantageous for this invention as it reduces the source impedance of the pressure-induced capacitive change signal and thus increases the chance of only needing this one capacitive element in the guidewire as a sensor.

[0162] The blood pressure monitoring process may be done periodically during interventional procedures or as needed to classify the hemodynamic significance of a lesion, so that the blood pressure about the site of intervention can be accurately measured.

[0163] From the foregoing description, it will be apparent that there have been provided a quasi wireless pressure sensing guide wire and detector. Variations and modifications in the herein described apparatus, method, and system in accordance with the invention will undoubtedly suggest themselves to those skilled in the art.

[0164] FIG. **37** demonstrates the utilization of typical guide wire components as electrical conductors to avoid having to integrate additional electrical wires into the guide wire structure which negatively affects wire handling. The compromised wire handling of the commercially available pressure sensing guide wires represents a significant barrier towards widespread use of pressure sensing guide wires. As FIG. **37** demonstrates the wire handling can be equal to non pressure sensing guide wires by requiring only 2 electrical connections, utilizing the standard wire components, core wire and distal tip.

Patch electrode (**904**) grounding techniques are widely utilized in RF ablation procedures with a typical impedance of about 100 Ohms from RF electrode to ground. The other end of the resonance circuit is connected to the wire body or core wire. The proximal end portion of the wire is not insulated in order to make contact with the contact brush within the sheath as shown in FIG. **39**. This has the advantage that wire handling is not compromised since standard wire components (core wire and distal tip) are utilized as electrical conductors

avoiding the insertion of additional electrical wires. Alternatively a clip contact or wire torquer contact can be employed. Another contacting method could be a conductive sterile liquid or gel type contact sleeve because the allowed contact resistance can easily be 100 Ohms or more.

[0165] Phase detection circuit **908** may typically comprise an electronic signal processing circuit configured for monitoring electrical-current phase changes. The signal processing circuit preferably includes an oscillator, a current sensor, a phase detector, a digitizer and an interface, the interface being operatively connectable to a computer device. The oscillator may be a direct digital synthesis generator.

[0166] Phase detection circuit **908** measures phase of the whole guide wire assembly and determines the capacitance of capacitive sensor **906** at any given time, which indicates the local pressure. Linearization may be required. The oscillator is an RF generator which sends an RF signal of fixed frequency into the guide wire **900** and circuit **908** measures the phase shift between the oscillator output and the current the wire draws. The oscillator/generator can be of any kind that can be controlled via an analog or digital system. Phase-locked loop (PLL) used to be common but due to faster control of the frequency direct digital synthesis (DDS) has become a more contemporary method.

[0167] Phase detection circuit **908** may include a computer or microprocessor that commands the controllable oscillator/generator to move to a certain frequency. The computer or microprocessor then commands the oscillator/generator to increase its frequency incrementally until a desired phase shift between the generator output and the current sense signal has been reached. This phase shift can later be adjusted again to compensate for capacitive drift in the various leakage capacitances from the guide wire **900** to its surroundings.

[0168] It is to be noted that various elements of any one embodiment of the invention may be used to replace functionally analogous components in other embodiments. For instance, any one of capacitive pressure sensors **20**, **207**, **612** and **906** (FIGS. **2**, **20**, **31** and **37**, respectively) may be implemented in a particular case by multilayer ceramic capacitor **224** (FIG. **23**) or electrolyte-containing capacitor **510**, **540**, **550** (FIGS. **28-30**) or MEMS capacitor **702** (FIGS. **43-46**). The circuit components and current paths of any one embodiment for connecting the pressure measuring circuit inside a patient to detection components and ancillary electrical circuitry outside the patient may be replaced by like-purpose components and paths from other embodiments, e.g., the intravascular circuit path of FIG. **31** (as well as the variations thereof shown in FIGS. **32-36**) including core wire **601** and electrodes **603**, **604** may be used with resonator **206** and capacitor **207** of FIG. **20** or the ceramic sensor **210** of FIGS. **21** and **22**. The processing systems **238** and **266** of FIGS. **24** and **25** may be used in any pressure measuring resonant circuit disclosed herein.

1. A system for detection of fluid pressure in an internal organ, comprising: a guide wire; and a resonance circuit provided at least in part at a distal end of said guide wire, said resonance circuit being responsive to changes in pressure of fluid external to said guide wire such that said resonance circuit has a resonance frequency that varies in accordance with changes in pressure of the external fluid.

2-16. (canceled)

17. The system according to claim **1** wherein said resonance circuit is operatively coupled to an electronic signal processing circuit configured for measuring resonance frequency changes of said resonance circuit, said signal processing circuit including a first circuit for compensating for measurement error arising from changes in positioning of said resonance circuit at a fluid-containing site, said signal processing circuit further including a second circuit for detecting changes in pressure of fluid at said site.

18. The system according to claim **17** wherein said resonance circuit includes a capacitor, said first circuit being configured to compensate for changes in leakage capacitances that occur between said guidewire and said fluid-containing site.

19. The system according to claim **17** wherein said first circuit is configured for operating in a first frequency range and said second circuit is configured for operating in a second frequency range, said second frequency range being much lower than said first frequency range, said second circuit being configured to be insensitive to frequencies in said first frequency range.

20. The system according to claim **1** wherein said resonance circuit includes a coil and a capacitor both provided at a distal end of said guide wire and coupled to each other to form said resonance circuit, said capacitor taking the form of a pressure sensitive electrolyte capacitor, said resonance circuit so configured as to vary in its resonance frequency and phase responsive to pressure upon the sensor from fluid external the guide wire, a core wire of said guide wire forming an electrical connection between said resonance circuit and a proximal sheath or clip contact.

21-28. (canceled)

29. The system according to claim **1** wherein said resonance circuit includes a first electrode at or proximate a distal end of said guide wire and a second electrode disposed on or in a guide sheath or catheter, so that said resonance circuit is closed through an ambient fluid carrying current between said first electrode and said second electrode, said second electrode being operatively connectable to a detection circuit, said resonance circuit forming a sensing circuit operatively connectable to said detection circuit and comprising a core wire of said guide wire, said first electrode, a surrounding fluidic electrolyte, and said second electrode, said guide wire including a core wire having a structure taken from the group consisting of (a) a proximal end contacted through a brush contact at a proximal sheath or guide catheter end or hub to close a connection with a detection component, (b) a proximal end contacted through an electrically conducting wire torquer connected to a detection system, (c) a capacitive coupling to a braid or metal layer inside a sheath or guide catheter or to a metalized tube inserted into a sheath or guide catheter.

30-37. (canceled)

38. The system according to claim **29** wherein said second electrode is a conductive cylinder inserted into a sheath or guide hub traversed by a core wire or said guide wire, said conductive cylinder configured to make contact with a fluid column inside the sheath or guide and therewith a patient's bloodstream.

39. The system according to claim **1** wherein said guide wire has a core wire, said distal end and a proximal end, said resonance circuit including a capacitive sensor disposed at said distal end of said guide wire, a ground electrode being provided at said distal end of said guide wire, said capacitive sensor being electrically connectable through said ground electrode of said guide wire with fluid inside a subject, said capacitive sensor being conductively connected to said core

wire of said guide wire, further comprising a sheath or guide catheter contact or a clip at said proximal end of said guide wire, said core wire serving in part to close an electrical circuit through said contact or clip, said electrical circuit including a detector component configured for monitoring a phase shift signal from said capacitive sensor which varies responsive to the amount of pressure from fluid external to said guide wire, said detector component being configured for executing a process taken from the group consisting of (a) a network analysis method to determine capacitance of said capacitive sensor, (b) a complex transform algorithm to determine capacitance of said capacitive sensor, and (c) a continuous impedance measurement to compensate for pressure measurement errors due to changes in impedance.

40. The system according to claim **39** wherein said distal end of said guide wire has a floppy tip, at least a portion of said floppy tip constituting said ground electrode to connect the circuit with the fluid.

41-43. (canceled)

44. The system according to claim **39** wherein a proximal end of said core wire is connected through a brush contact at the proximal sheath or guide catheter end to close the connection with said detector component.

45-49. (canceled)

50. The system according to claim **39** wherein said electrical circuit including said capacitive sensor is a non resonating circuit.

51. The system according to claim **39** wherein said capacitive sensor is the only impedance-varying element of said electrical circuit.

52-54. (canceled)

55. A system for detection of a physiological parameter, comprising: a guide wire having a core wire; a capacitive sensor provided at least in part at a distal end of said guide wire; a guide wire sheath or catheter; a first electrode at or proximate a distal end of said guide wire; a second electrode disposed on or in said guide wire sheath or catheter, said sensor being electrically connectable to a detection circuit through said first electrode, a surrounding ambient fluid, said core wire, and said second electrode.

56. The system according to claim **55** wherein said core wire has a structure taken from the group consisting of (a) a proximal end contacted through a brush contact at a proximal sheath or guide catheter end or hub to close a connection with a detection component, (b) a proximal end contacted through an electrically conducting wire torquer connected to a detection system, and (c) a capacitive coupling to a braid or metal layer inside a sheath or guide catheter or to a metalized tube inserted into a sheath or guide catheter.

57. (canceled)

58. (canceled)

59. The system according to claim **55** wherein said first electrode is a floppy tip of said guide wire or a portion thereof.

60-63. (canceled)

64. The system according to claim **55** wherein said second electrode is a conductive cylinder inserted into a sheath or guide hub traversed by a core wire or said guide wire, said conductive cylinder configured to make contact with a fluid column inside the sheath or guide and therewith a patient's bloodstream.

65-67. (canceled)

68. A system for detection of a physiological parameter comprising:

a guide wire having a core wire and a distal end and a proximal end;

a capacitive sensor disposed at said distal end of said guide wire;

a ground electrode provided at said distal end of said guide wire, said capacitive sensor being electrically connectable through said ground electrode of said guide wire with fluid in a patient, said capacitive sensor being conductively connected to said core wire of said guide wire; and

a sheath or guide catheter contact, a brush, wire torque, or a clip at said proximal end of said guide wire, said core wire serving in part to close an electrical circuit through said contact, brush, or clip.

69. The system according to claim **68** wherein said distal end of said guide wire has a floppy tip, at least a portion of said floppy tip constituting said ground electrode to connect the circuit with the patient's bloodstream.

70. (canceled)

71. (canceled)

72. The system according to claim **68** wherein said electrical circuit includes a detector component configured for monitoring a phase shift signal from said capacitive sensor which varies responsive to the amount of pressure from fluid external to said guide wire, wherein the proximal end of said core wire is connected through said brush at the proximal sheath or guide catheter end (hub) to close the connection with said detector component, said detector component being configured for executing a process taken from the group consisting of (a) a network analysis method to determine capacitance of said capacitive sensor, (b) a complex transform algorithm to determine capacitance of said capacitive sensor, and (c) a continuous impedance measurement to compensate for pressure measurement errors due to changes in impedance.

73-77. (canceled)

78. The system according to claim **68** wherein said electrical circuit including said capacitive sensor is a non resonating circuit and wherein said capacitive sensor is the only impedance-varying element of said electrical circuit.

79-84. (canceled)

* * * * *

专利名称(译)	系统包括用于检测流体压力的导丝		
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申请(专利权)人(译)	引导的介入治疗，INC.		
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摘要(译)

一种用于检测血管中的血压的系统，包括导丝和设置在导丝远端的LC谐振电路。谐振电路可以是响应于导线外部的流体压力变化的非LC谐振电路，使得谐振电路具有根据外部流体的压力变化而变化的谐振频率。