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(54) **SYSTEM, CATHETER, AND METHOD FOR CALCULATING CORRECTED FRACTIONAL FLOW RESERVE**

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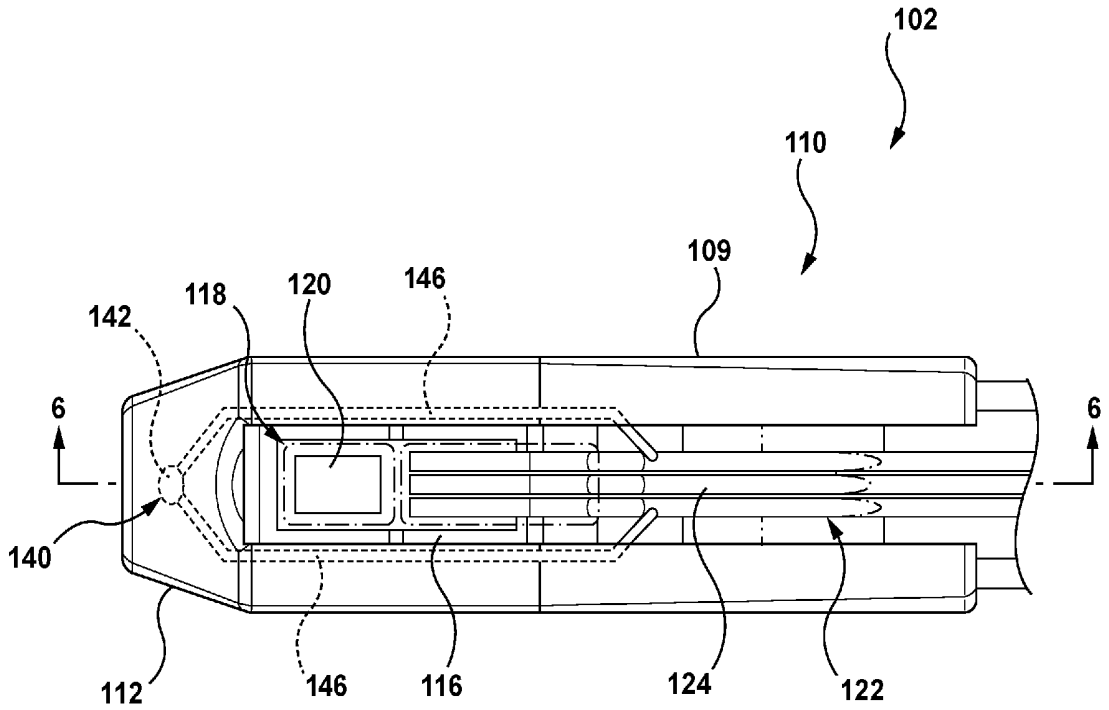
CPC ***A61B 5/026*** (2013.01); ***A61B 5/6852*** (2013.01); ***A61B 5/01*** (2013.01); ***A61B 5/02158*** (2013.01)

(57) **ABSTRACT**

A catheter includes an elongate shaft, a pressure sensor, and a thermistor. The elongate shaft defines a guidewire lumen. The pressure sensor is coupled to a distal portion of the elongated shaft such that the pressure sensor senses a blood pressure distal of a stenosis. The thermistor is coupled to the distal portion of the elongate shaft such that the thermistor measures blood flow velocity distal of the stenosis. The pressure sensor and thermistor are in communication with a processor. The processor calculates a corrected Fractional Flow Reserve including a correction based on blood flow velocity.



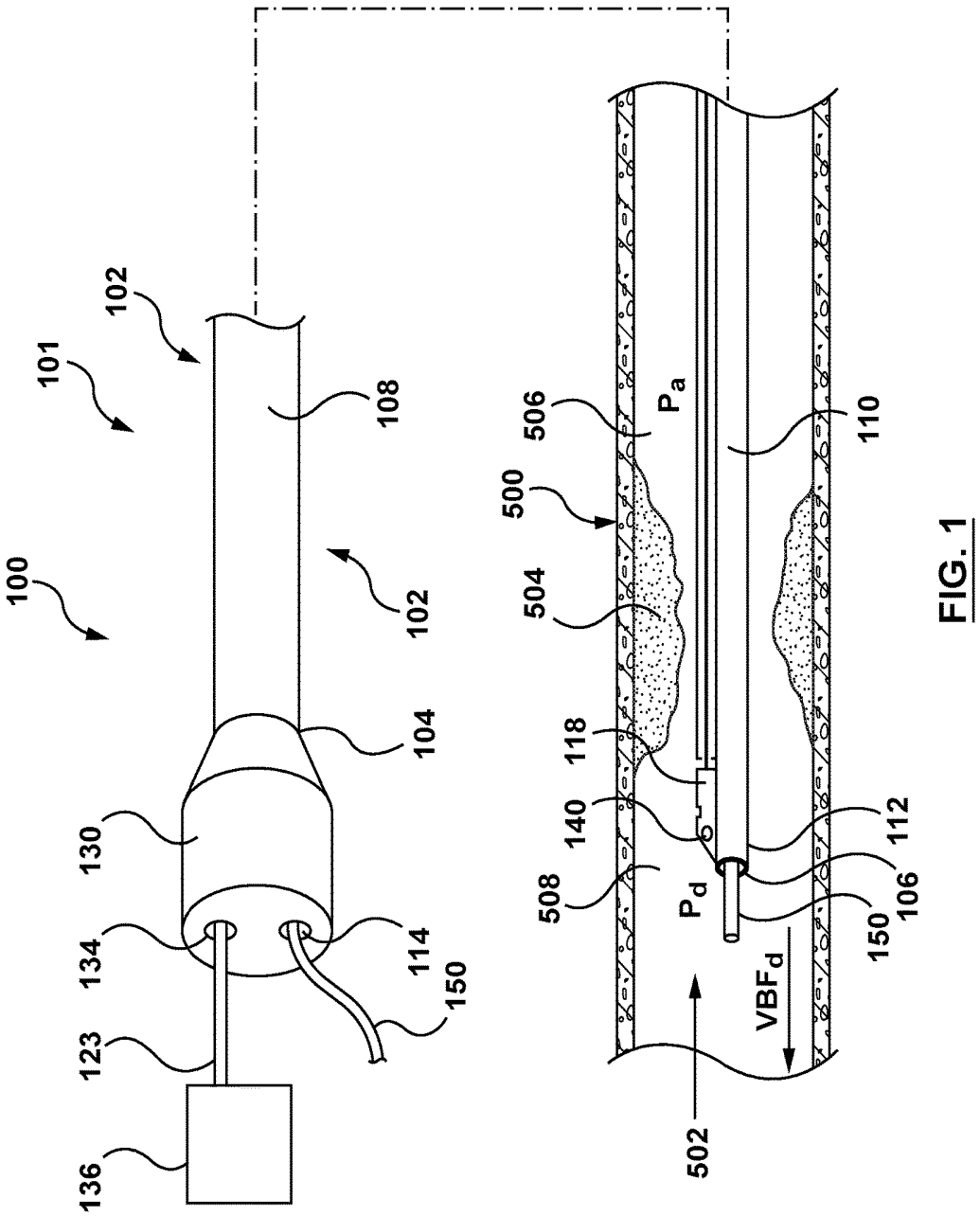

100
101
102
102
104
108
110
114
118
123
130
134
136
140
150
150
500
502
504
506
508
106
112
P_a
P_d
VBF_d

FIG. 1

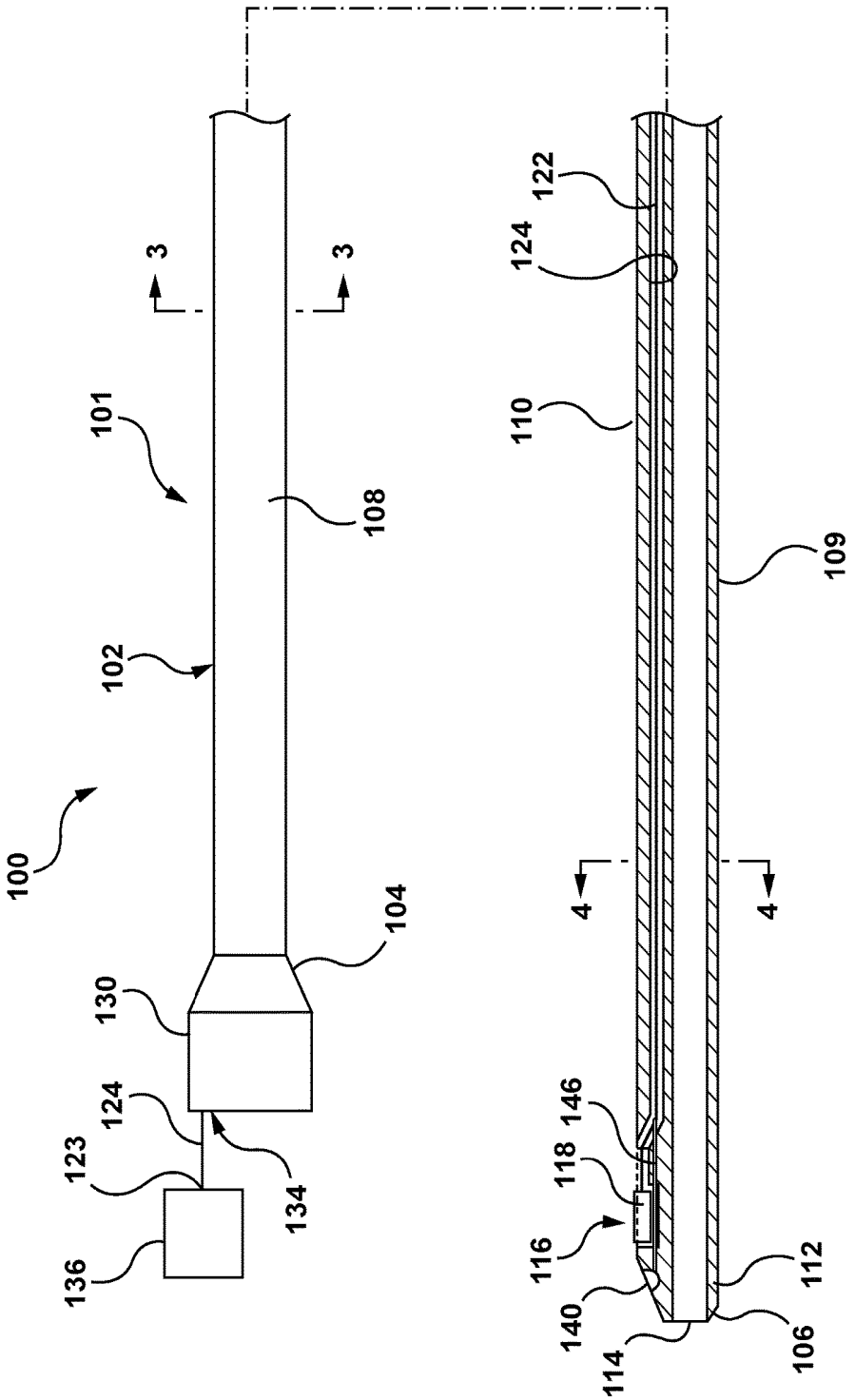

3
3
101
108
102
100
104
130
124
123
134
136
122
124
110
109
4
4
146
118
116
140
114
112
106

FIG. 2

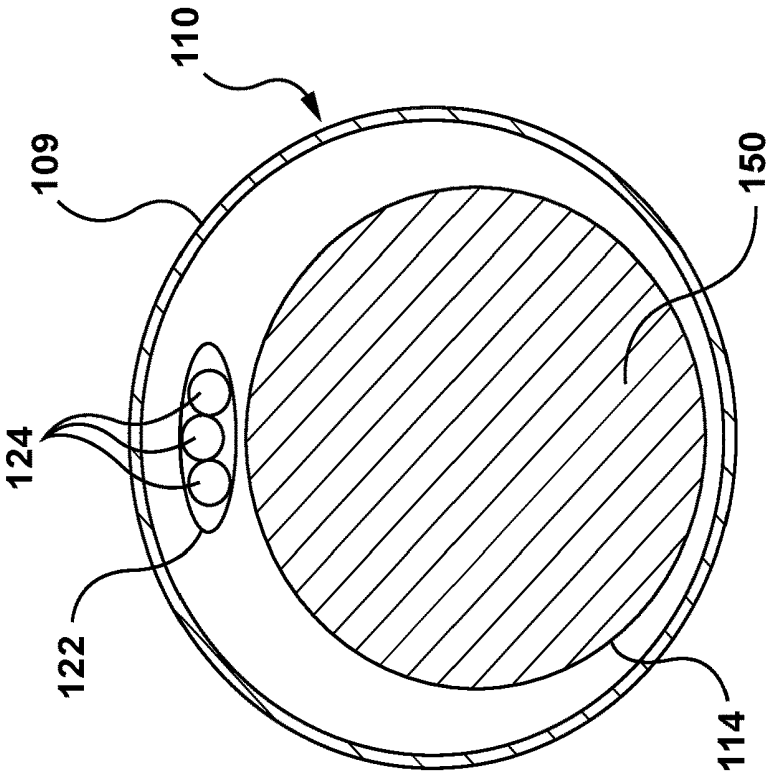


FIG. 4

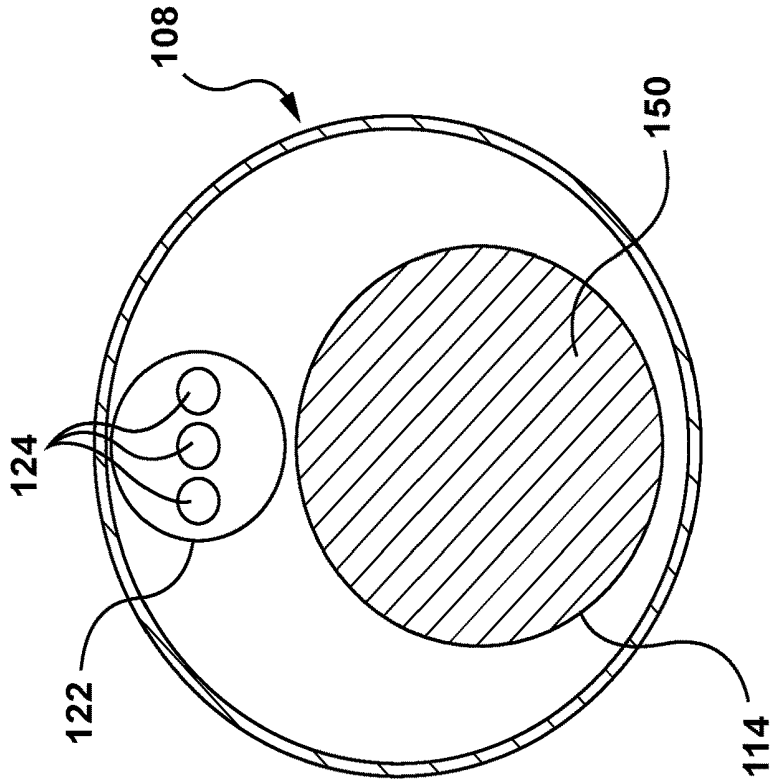


FIG. 3

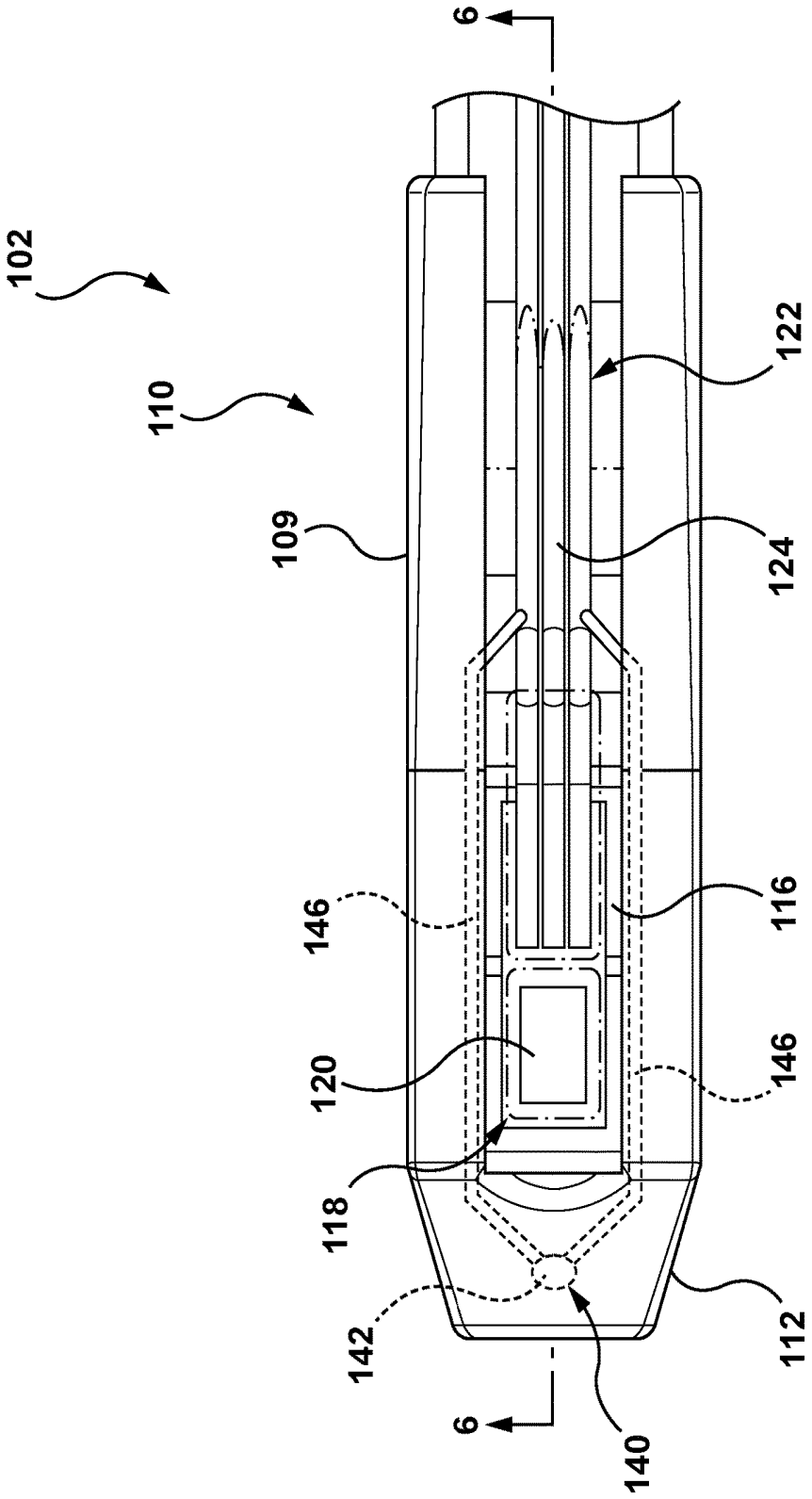


FIG. 5

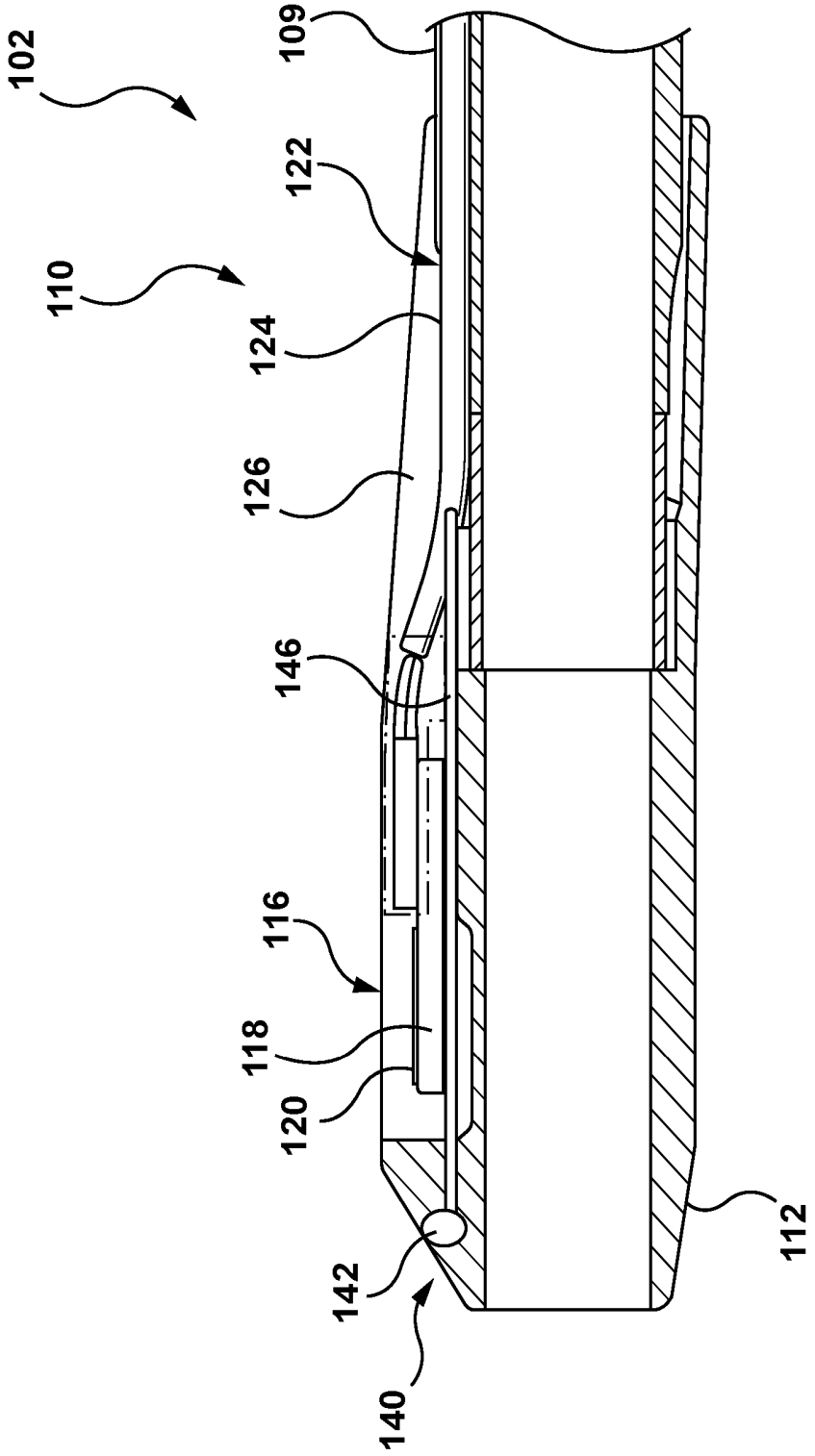


FIG. 6

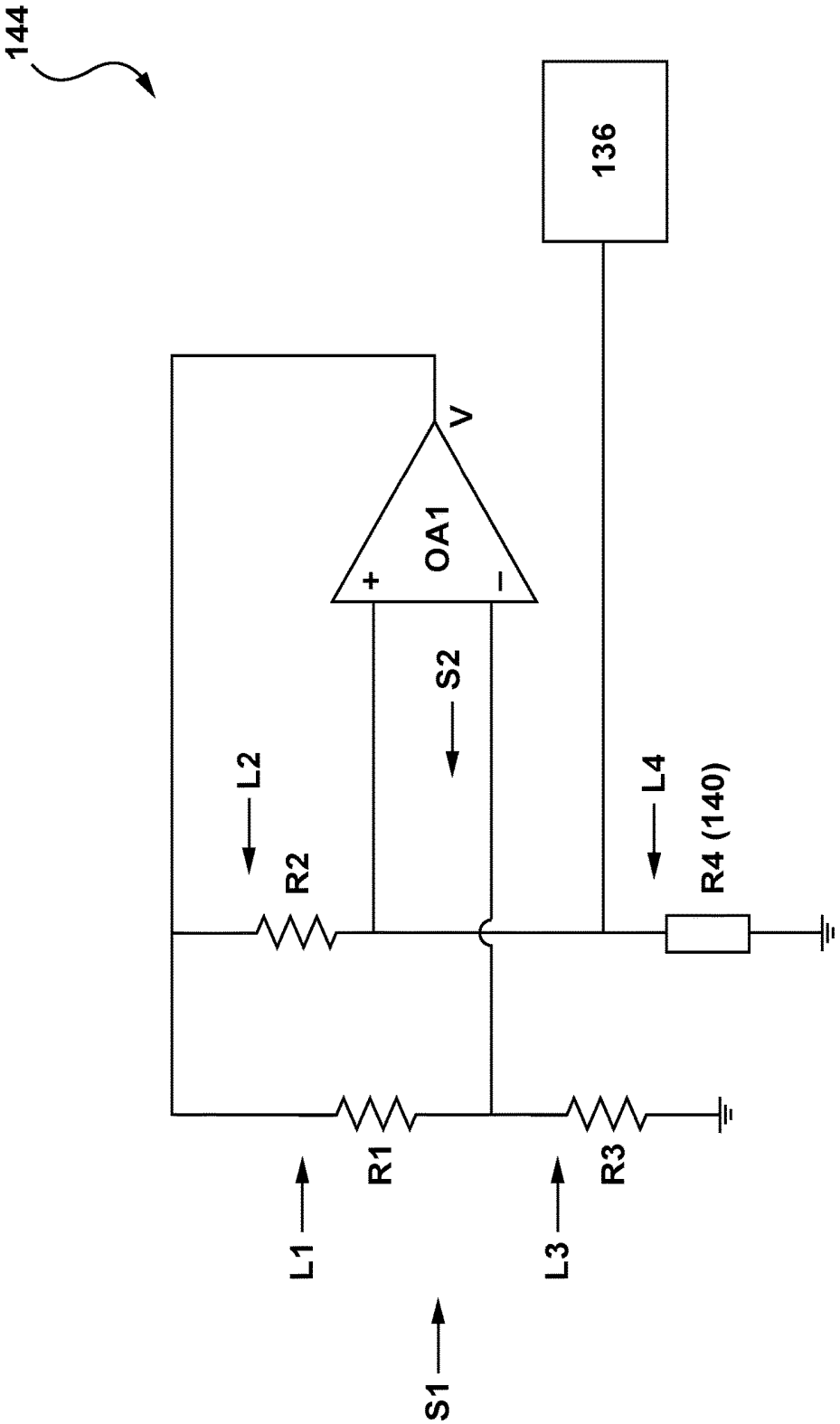


FIG. 7

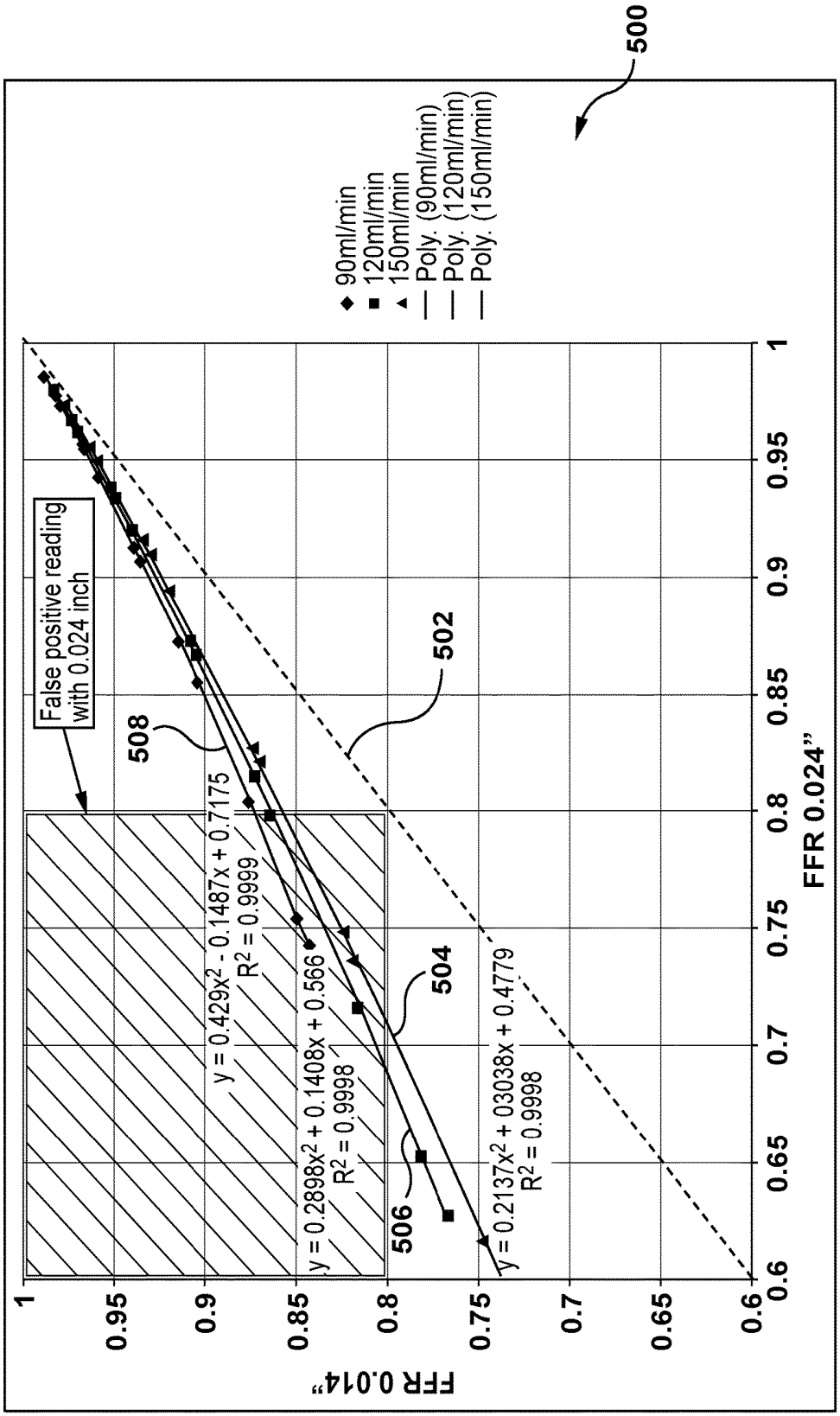

500
90ml/min
120ml/min
150ml/min
Poly. (90ml/min)
Poly. (120ml/min)
Poly. (150ml/min)
False positive reading with 0.024 inch
508
502
504
506
y = 0.429x² - 0.1487x + 0.7175
R² = 0.9999
y = 0.2898x² + 0.1408x + 0.566
R² = 0.9998
y = 0.2137x² + 03038x + 0.4779
R² = 0.9998
FFR 0.014"
FFR 0.024"
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6

FIG. 8

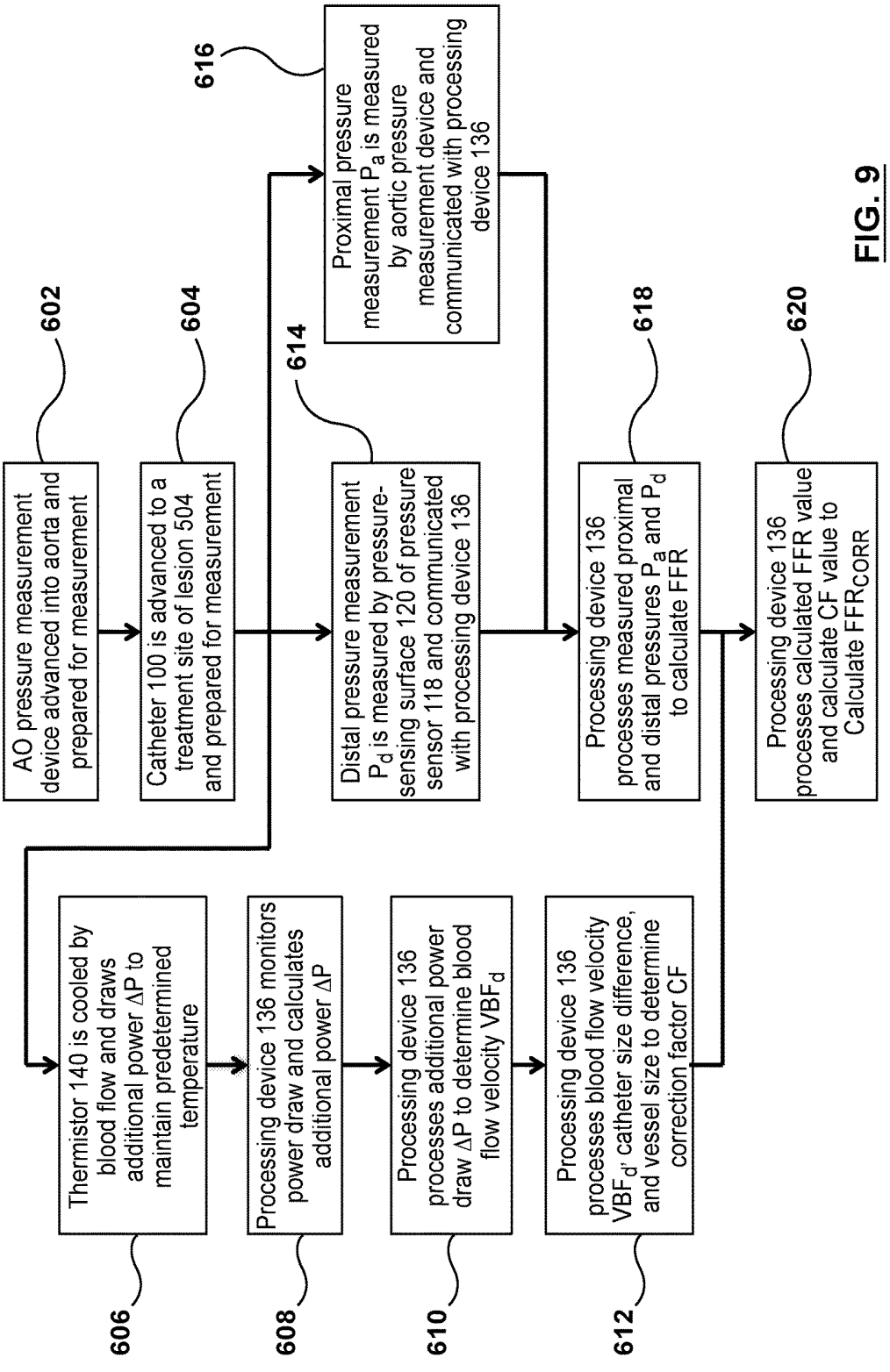

602
AO pressure measurement device advanced into aorta and prepared for measurement
604
Catheter 100 is advanced to a treatment site of lesion 504 and prepared for measurement
614
Distal pressure measurement P_d is measured by pressure-sensing surface 120 of pressure sensor 118 and communicated with processing device 136
616
Proximal pressure measurement P_a is measured by aortic pressure measurement device and communicated with processing device 136
618
Processing device 136 processes measured proximal and distal pressures P_a and P_d to calculate FFR
620
Processing device 136 processes calculated FFR value and calculate CF value to Calculate FFR_{CORR}
606
Thermistor 140 is cooled by blood flow and draws additional power ΔP to maintain predetermined temperature
608
Processing device 136 monitors power draw and calculates additional power ΔP
610
Processing device 136 processes additional power draw ΔP to determine blood flow velocity VBF_d
612
Processing device 136 processes blood flow velocity VBF_d, catheter size difference, and vessel size to determine correction factor CF

FIG. 9

SYSTEM, CATHETER, AND METHOD FOR CALCULATING CORRECTED FRACTIONAL FLOW RESERVE

FIELD OF THE INVENTION

[0001] The present invention relates to systems and methods for calculating a Fractional Flow Reserve. More particularly, the present invention relates to calculating a corrected Fractional Flow Reserve with a catheter, wherein the corrected Fractional Flow Reserve accounts for blood flow velocity.

BACKGROUND OF THE INVENTION

[0002] The severity of a stenosis or lesion in a blood vessel may be assessed by obtaining proximal and distal pressure measurements relative to the given stenosis and using those measurements for calculating a value of a Fractional Flow Reserve (FFR). FFR is defined as the ratio of a first or distal pressure P_d measured on the distal side of the lesion to a second or proximal pressure P_a measure on the proximal side of the lesion, usually within the aorta. Conventionally, a sensor is placed on a distal portion of a guidewire or FFR wire to obtain the distal pressure P_d, while an external pressure transducer is fluidly connected via tubing to a guide catheter for obtaining the proximal, or aortic (AO) pressure P_a. Calculation of the FFR value provides a lesion specific index of the functional severity of the stenosis in order to determine whether the blockage limits blood flow within the vessel to an extent that treatment is needed. An optimal or normal value of FFR in a healthy vessel is 1.00, while values less than about 0.80 are generally deemed significant and in need of an interventional treatment. Common interventional treatment options include balloon angioplasty and/or stent implantation.

[0003] If an interventional treatment is required, the interventional device, such as a balloon catheter, is tracked over a guide wire to the site of the lesion. Conventional FFR wires generally are not desired by clinicians to be used as guide wires for such interventional devices. Accordingly, if an intervention treatment is required, the clinician generally removes the FFR wire, inserts a conventional guide wire, and tracks the interventional device to the treatment site over the conventional guide wire.

[0004] To address this concern, efforts have been made to utilize catheters to take pressure measurements for calculating FFR. Using a catheter, a clinician may use a preferred guidewire for tracking the FFR catheter to the site of the lesion. If an interventional treatment is required, the guidewire used with the catheter may remain in situ and the interventional device may be tracked over the existing guidewire to the site of the lesion.

[0005] However, some deviation from FFR values calculated using an FFR guidewire may be introduced into the distal blood pressure P_d measured distal of the lesion if a cross-sectional size of the portion of the measurement device (catheter) that crosses the lesion is larger than a conventional FFR guidewire. Further, the distal blood pressure P_d, and hence FFR value, is affected by blood flow rate or velocity. In other words, for the same stenosis, different FFR values may be obtained depending on the blood flow velocity distal of the stenosis. Because decisions regarding intervention have been based on FFR values taken using FFR guidewires, there is a need to correlate or correct FFR values calculated using catheters to FFR values taken using guidewires. Accordingly, correction factors for correlating FFR values taken using a catheter have been developed to account for size differences between FFR catheters and FFR guidewires. However, there remains a need to accurately account for blood flow velocity.

BRIEF SUMMARY OF THE INVENTION

[0006] Embodiments hereof relate to a catheter including an elongate shaft, a pressure sensor, and a thermistor. The elongate shaft defines a guidewire lumen. The pressure sensor is coupled to a distal portion of the elongate shaft such that a pressure-sensing surface of the pressure sensor faces outside an outer surface of the distal portion of the elongate shaft. The thermistor is coupled to the distal portion of the elongate shaft such that a surface of the thermistor faces outside the outer surface of the distal portion of the elongate shaft. The pressure sensor senses a pressure of blood distal of a stenosis in a blood vessel. The pressure sensor and thermistor are in communication with a processor. The thermistor measures blood flow velocity distal of the stenosis such that the processor may calculate a corrected Fractional Flow Reserve including a correction based on blood flow velocity.

[0007] Embodiments hereof also relate to a system for calculating a corrected Fractional Flow Reserve associated with a stenosis in a blood vessel. The system includes a pressure sensor, a pressure-sensing device, a thermistor, and a processing device. The pressure sensor is placed within a blood vessel to measure a distal pressure distal of the stenosis. The pressure-sensing device measures a proximal pressure proximal of the stenosis. The thermistor is placed within the blood vessel to measure blood flow velocity distal of the stenosis. The processing device is in communication with the pressure sensor, the pressure-sensing device, and the thermistor. The processing device calculates a Fractional Flow Reserve based on the distal pressure relative to the proximal pressure. The processing device calculates or selects a transfer function including a flow velocity correction based on the measured blood flow velocity.

[0008] Embodiments hereof also relate to a method for calculating a corrected Fractional Flow Reserve in a vessel. A catheter is delivered to a distal side of a stenosis of the vessel. The catheter includes a distal pressure sensor and a thermistor. The blood flow velocity within the vessel is measured utilizing the thermistor. A transfer function including a blood flow velocity correction based on the measured blood flow velocity is calculated or selected. A pressure distal of the stenosis is measured. A pressure proximal of the stenosis is measured. The corrected Fractional Flow Reserve is calculated using the measured proximal and distal pressures and application of the transfer function.

BRIEF DESCRIPTION OF DRAWINGS

[0009] FIG. **1** is an illustration of a system for calculating a corrected Fractional Flow Reserve (FFR_{CORR}) with a catheter thereof shown within a vessel including a lesion, in accordance with an embodiment hereof.

[0010] FIG. **2** is a partial longitudinal cross-section illustration of the system and catheter of FIG. **1**.

[0011] FIG. **3** is a cross-sectional illustration of an embodiment of a proximal portion of the catheter, taken along line **3-3** of FIG. **2**.

[0012] FIG. **4** is a cross-sectional illustration of an embodiment of a distal portion of the catheter, taken along line **4-4** of FIG. **2**.

[0013] FIG. **5** is a close-up top cutaway illustration of an embodiment of the distal portion of the catheter of FIG. **2**.

[0014] FIG. **6** is a close-up side cutaway illustration of the distal portion of the catheter of FIG. **2**.

[0015] FIG. **7** is a schematic diagram of an embodiment of a Wheatstone bridge with a thermistor as a leg of the Wheatstone bridge.

[0016] FIG. **8** is a graph illustrating FFR measured using a 0.024 inch FFR catheter compared to FFR measured using a 0.014 inch FFR wire for different flow rates and different lesions.

[0017] FIG. **9** is a block diagram of an embodiment of a method for calculating corrected Fractional Flow Reserve (FFR_{CORR}) using the system of FIG. **1**.

DETAILED DESCRIPTION OF THE INVENTION

[0018] Specific embodiments of the present invention are now described with reference to the figures, wherein like reference numbers indicate identical or functionally similar elements. The terms "distal" and "proximal", when used in the following description to refer to a catheter or delivery system are with respect to a position or direction relative to the treating clinician. Thus, "distal" and "distally" refer to positions distant from, or in a direction away from the treating clinician, and the terms "proximal" and "proximally" refer to positions near, or in a direction toward the clinician. The terms "distal" and "proximal" used in the following description to refer to a vessel or a lesion are used with reference to the direction of blood flow. Thus, "distal" and "distally" refer to positions in a downstream direction with respect to the direction of blood flow, and the terms "proximal" and "proximally" refer to positions in an upstream direction with respect to the direction of blood flow.

[0019] The following detailed description is merely exemplary in nature and is not intended to limit the invention or the application and uses of the invention. Although the description of the invention is in the context of treatment of blood vessels such as the coronary arteries, the invention may also be used in any other body passageways where it is deemed useful such as but not limited to peripheral arteries, carotid arteries, renal arteries, and/or venous applications. Furthermore, there is no intention to be bound by any expressed or implied theory presented in the preceding technical field, background, brief summary or the following detailed description.

[0020] A system **100** for calculating a corrected Fractional Flow Reserve (FFR_{CORR}) according to an embodiment of the present disclosure is shown in FIG. **1** and in greater detail in FIGS. **2-7**. System **100** includes a catheter **101**, a proximal pressure-sensing device (not shown in FIGS. **1-7**), and a processing device **136**, as shown in FIG. **1**. Catheter **101** includes a pressure sensor **118** and a thermistor **140** coupled thereto, as described in greater detail below. System **100** is configured to calculate a Fractional Flow Reserve (FFR) of a lesion **504** based on a distal pressure P_d relative to a proximal pressure P_a, as explained in greater detail below. System **100** is further configured to calculate or select a transfer function, including a flow velocity correction based on a measured blood flow velocity VBF_d distal of lesion **504**. The transfer function is used to calculate the corrected FFR (FFR_{CORR}). Various features of the components of system **100** reflected in FIGS. **1-7** and described below can be modified or replaced with different structures and/or mechanisms. System **100** is merely an exemplary embodiment of a system for measuring and calculating FFR and FFR_{CORR} according to an embodiment hereof and modifications can be made to the embodiments described herein without departing from the spirit and scope of the present disclosure. The present disclosure is in not limited to the components described herein, and the components of system **100** may assume different forms and construction based upon application. Therefore, the following detailed description is not meant to be limiting.

[0021] Catheter **101** of system **100** may be a catheter or micro-catheter, and may include an elongate shaft **102** having a proximal end **104** coupled to a handle or luer **130**, and a distal end **106**, as shown in FIG. **1**. Catheter **101** is configured to be disposed with a proximal portion **108** of elongate shaft **102** extending outside of a patient and a distal portion **110** of elongate shaft **102** positioned in situ within a lumen **502** of a vessel **500** having stenosis or lesion **504**. In an embodiment, vessel **500** is a blood vessel such as, but not limited to, a coronary artery. Lesion **504** is generally representative of any blockage or other structural arrangement that results in a restriction to the flow of fluid through lumen **502** of vessel **500**. Lesion **504** may be a result of plaque buildup, including without limitation plaque components such as fibrous, fibro-lipidic (fibro fatty), necrotic core, calcified (dense calcium), blood, fresh thrombus, and mature thrombus. Generally, the composition of lesion **504** will depend on the type of vessel being evaluated. In that regard, it is understood that embodiments hereof are applicable to various types of blockages or other narrowing of a vessel that results in decreased fluid flow.

[0022] Elongate shaft **102** includes proximal end **104**, distal end **106**, proximal portion **108**, and distal portion **110**, and defines a guidewire lumen **114** therein, as shown in FIG. **2**. Elongate shaft **102** may be formed of a polymeric material, non-exhaustive examples of which include polyethylene, PEBA, polyamide and/or combinations thereof, either blended or co-extruded. Optionally, elongate shaft **102** or some portion thereof may be formed as a composite having a reinforcement material incorporated within a polymeric body in order to enhance strength and/or flexibility. Suitable reinforcement layers include braiding, wire mesh layers, embedded axial wires, embedded helical or circumferential wires, and the like. In one embodiment, for example, at least the proximal portion **108** of elongate shaft **102** may be formed from a reinforced polymeric tube. In other embodiments of an elongate tubular shaft or component in accordance herewith, a proximal segment thereof may be a hypotube of a medical grade stainless steel with outer and inner tubes of a distal segment thereof being formed from any of the polymeric materials listed above. Further, although proximal portion **108** and distal portion **110** of elongate shaft **102** are described separately, they are described in such a manner for convenience and elongate shaft **102** may be constructed unitarily such that the portions described are part of a unitary shaft. However, different portions of elongate shaft **102** may also be constructed separately and joined together.

[0023] While FIGS. **1-7** show elongate shaft **102** of catheter **101** with guidewire lumen **114** extending therethrough

in an over-the-wire configuration, this is not meant to limit the design and other configurations may be utilized, including, but not limited to, a rapid exchange configuration, or other configurations suitable for the purposes described herein.

[0024] In an embodiment, proximal portion **108** of elongate shaft **102** is disposed proximal of distal portion **110** and extends proximally thereof to proximal end **104** of elongate shaft **102**, as shown in FIG. **2**. In an embodiment, proximal portion **108** defines two lumens, a proximal portion of guidewire lumen **114** (FIG. **3**) and a proximal portion of a sensor wire lumen **122** (FIG. **3**). In an embodiment, guidewire lumen **114** and sensor wire lumen **122** may be disposed parallel or side-by-side to each other along proximal portion **108**, as shown in FIG. **3**, taken along line **3-3** of FIG. **2**.

[0025] Guidewire lumen **114** is configured to retain a guidewire **150** therein, as shown in FIGS. **3-4**. In an embodiment, guidewire lumen **114** may be disposed from proximal end **104** of elongate shaft **102** to distal end **106** of elongate shaft **102**, as shown in FIG. **2**. Stated another way, guidewire lumen **114** may extend the length of elongate shaft **102**, including proximal portion **108** and distal portion **110**. Guidewire lumen **114** is sized to accept guidewire **150** therein. However, as explained above, guidewire lumen **114** may extend only along a portion of elongate shaft **102** in a rapid-exchange configuration. For example, and not by way of limitation, guidewire lumen **114** may be eliminated in proximal portion **108** of elongate shaft **102** such that the guidewire extends alongside a modified proximal portion of elongate shaft **102** that includes only sensor wire lumen **122**. Further, while proximal portion **108** of elongated shaft **102** is shown with two lumens therein, this is not meant to limit the design and, and more or fewer lumens may be utilized.

[0026] Sensor wire lumen **122** is configured to retain a wire bundle **124** therein, as shown in FIGS. **3-4**. In an embodiment, sensor wire lumen **122** is in communication with pocket **116** of distal portion **110**, as shown in FIGS. **2**, **5**, and **6** and described in greater detail below. In an embodiment, sensor wire lumen **122** extends from pocket **116** to proximal end **104** of elongate shaft **102**.

[0027] While sensor wire lumen **122** is depicted in FIG. **3** as circular in cross-section, this is not meant to limit the design, and other configurations may be utilized, including but not limited to elliptical, crescent-shaped, or other configurations suitable for the purposes described herein.

[0028] While FIGS. **1-6** include sensor wire lumen **122**, this is not meant to limit the design, and other configurations may be utilized. For example, wire bundle **124** may extend from pressure sensor **118** and thermistor **140** other than in a sensor wire lumen. For example, and not by way of limitation, sensor wire lumen **122** may be eliminated and signals from pressure sensor **118** and thermistor **140** may be sent to processing device **136** via wireless transmission. In another non-limiting example, wire bundle **124** may be integrated into the wall of distal portion **110** and proximal portion **108** of elongate shaft **102**.

[0029] Distal portion **110** of elongate shaft **102** is disposed distal of proximal portion **108** extending distally thereof to distal end **106** of elongate shaft **102**, as shown in FIG. **2**. In an embodiment, distal portion **110** includes a shaft wall **109** defining a portion of guidewire lumen **114** extending therethrough, as shown in FIG. **2** and FIG. **4**, taken along line **4-4** of FIG. **2**. Distal portion **110** further includes pressure sensor **118** disposed within pocket **116**, thermistor **140**, a distal tip **112**, and a distal portion of sensor wire lumen **122**, as shown in FIG. **2** and described in greater detail below. Distal portion **110** is configured to receive guidewire **150** in the distal portion of guidewire lumen **114**, as shown in FIG. **4**. Distal portion **110** is further configured, as shown in FIG. **1**, to extend from a proximal side **506** of lesion **504**, crossing (or extending past) lesion **504**, to a distal side **508** of lesion **504** such that distal tip **112** is disposed on distal side **508** of lesion **504**.

[0030] Pressure sensor **118** of distal portion **110** of elongate shaft **102** includes a pressure-sensing surface **120**, as shown in FIGS. **5-6**. Pressure sensor **118** may be a piezo-resistive pressure sensor, a piezo-electric pressure sensor, a capacitive pressure sensor, an electromagnetic pressure sensor, an optical pressure sensor, and/or combinations thereof suitable for the purposes described herein. Pressure sensor **118** is configured with pressure-sensing surface **120** facing outwardly from an outer surface of shaft wall **109** of distal portion **110** of elongate shaft **102** such that pressure-sensing surface **120** measures pressure P_d of a fluid outside distal portion **110** of elongate shaft **102**. Pressure sensor **118** is further configured to communicate measured pressure P_d with processing device **136** (FIG. **1**) through wire bundle **124**, as shown in FIG. **2**. In an embodiment, pressure sensor **118** is disposed within distal portion **110** of elongate shaft **102** and proximal of distal tip **112** such that pressure sensor **118** is disposed on distal side **508** of lesion **504**, as shown in FIG. **1**.

[0031] In an embodiment shown in FIGS. **5-6**, pressure sensor **118** is disposed in and coupled to pocket **116** of elongate shaft **102**. Pressure sensor **118** is further coupled to wire bundle **124**. Pressure sensor **118** may be coupled to pocket **114**, for example, and not by way of limitation, by adhesives, fusing, welding, or any other method suitable for the purposes of the present disclosure. Pressure sensor **118** may be coupled to wire bundle **124** for example, and not by way of limitation, by soldering, fusing, welding, for any other method suitable for the purposes of the present disclosure.

[0032] While pocket **114** is shown with a generally cubic shape, this is not meant to limit the design and other configurations of pocket **114** may be utilized, including, but not limited to spheroid, arched, or other configurations suitable for the purposes described herein. Further, pocket **114** and pressure sensor **118** may be configured with tabs, arms, slots, or other configurations suitable to enhance coupling of pressure sensor **118** with pocket **114**. Further, other configurations for mounting pressure sensor **118** to distal portion **110** may be utilized. For example, and not by way of limitation, pressure sensor **118** may be coupled to distal portion **110** described in U.S. Patent Application Publication Nos. 2015/0305633 A1; 2015/0359438 A1; 2016/0081564 A1; and 2016/0199003 A1, each of which is incorporated by reference herein in its entirety.

[0033] Thermistor **140** coupled to distal portion **110** of elongate shaft **102** may be any thermistor suitable for the purposes described herein. In an embodiment shown in FIGS. **5-6**, thermistor **140** is a bead-type thermistor. However thermistor **140** may be other thermistor types including, but not limited to rod, plate, disc, chip, or other configurations suitable for the purposes described herein. Thermistor **140** is coupled to distal portion **110** of elongate shaft **102** such that a surface **142** faces outside an outer surface of distal portion **110**. Thus, when catheter **101** is disposed at the

treatment site, as shown in FIG. **1**, surface **142** of thermistor **140** is exposed to blood flow on distal side **508** of lesion **504**. In one non-limiting example thermistor **140** is about 0.15 mm to 0.5 mm in diameter. However, other sized thermistors with other shapes may be utilized. Thermistor **140** may be coupled to distal portion **110**, for example, and not by way of limitation, by adhesives, fusing, welding, for any other method suitable for the purposes of the present disclosure. Thermistor **140** is further coupled to wire bundle **124**. Thermistor **140** may be coupled to wire bundle **124** for example, and not by way of limitation, by soldering, fusing, welding, for any other method suitable for the purposes of the present disclosure.

[0034] Thermistor **140** forms a leg of a Wheatstone bridge **144**, an embodiment of which is shown in FIG. **7**. Wheatstone bridge **144** is also known as a null comparator. Wheatstone bridge **144** may be any Wheatstone bridge design suitable for the purposes described herein. In the embodiment shown, Wheatstone bridge **144** includes two (2) sides S**1** and S**2** and an operational amplifier OA**1**, as shown in FIG. **7**. Side S**1** includes two (2) legs L**1** and L**3**. Side S**2** includes two (2) legs L**2** and L**4**. Each leg L**1**, L**2**, L**3**, and L**4** includes a corresponding resistor R**1**, R**2**, R**3**, and R**4**. Wheatstone bridge **144** is configured with thermistor **140** as resistor R**4** of leg L**4**. Thermistor **140** includes a resistive value R**4** that changes based on temperature. At a predetermined temperature, such as 1-2° C. above body temperature, the resistive value R**4** of thermistor **140** balances Wheatstone bridge **144**. The function of Wheatstone bridge **144** is described in greater detail below.

[0035] In an embodiment, thermistor **140** of Wheatstone bridge **144** is disposed at distal portion **110** of catheter **101**, and the remainder of Wheatstone bridge **144** is disposed at processing device **136**. However, other configurations may be utilized. For example, and not by way of limitation, all of Wheatstone bridge **144** may be disposed at distal portion **110**. In another non-limiting example, thermistor **140** may be disposed at distal portion **110**, with the remainder of Wheatstone bridge **144** as a stand-alone device in communication with processing device **136**. Other configurations suitable for the purposes described herein may also be utilized.

[0036] Processing device **136**, as shown in FIGS. **1-2**, may be any processing device suitable for the purposes described herein. Processing device **136** may include such components as a CPU, a display device, an amplification and filtering device, an analog-to-digital converter, portions of Wheatstone bridge **144**, and various other components. Processing device **136** is configured to receive a proximal pressure P_a and a distal pressure P_d. Processing device **136** is further configured to monitor power draw of thermistor **140** of Wheatstone bridge **144**, as explained in more detail below. Processing device **136** is further configured to process P_a, P_d, and thermistor power measurements as described in greater detail below, and provide a continuous display of FFR_{corr}. Processing device **136** is coupled to wire bundle **124** such that processing device **136** is in communication with pressure sensor **118**. Processing device **136** is further in communication with Wheatstone bridge **144**. A proximal end **123** of wire bundle **124** and Wheatstone bridge **144** may be coupled to processing device **136** via various communication pathways, including but not limited to one or more physical connections including electrical, optical, and/or fluid connections, a wireless connection, and/or combinations thereof. Accordingly, it is understood that additional components (e.g., cables, connectors, antennas, routers, switches, etc.) not illustrated in FIG. **1** and FIG. **7** may be included to facilitate communication between proximal end **123** of wire bundle **124** and processing device **136**, and between Wheatstone bridge **144** and processing device **136**. In other embodiments, instead of a dedicated sensor wire lumen **122**, communication between pressure sensor **118** and processing device **136** may be accomplished wirelessly, or wire bundle **124** may be incorporated into the wall of elongate shaft **102**.

[0037] In an embodiment, as shown in FIG. **2**, pocket **116** is in communication with sensor wire lumen **122** such that wire bundle **124** from pressure sensor **118** may extend from pocket **116** proximally through sensor wire lumen **122**, through a corresponding lumen or luer **130** exiting through a proximal port **134** to processing device **136** coupled to proximal end **123** of wire bundle **124**. Additionally, thermistor **140** is in communication with sensor wire lumen **122** such as through wires **146** (FIG. **5**). Wires **146** may connect thermistor **140** to wire bundle **124**, which extends proximally through sensor wire lumen **122**, through a corresponding lumen (not shown) in luer **130** exiting through proximal port **134** to the remainder of Wheatstone bridge **144** coupled to proximal end **123** of wire bundle **124**. In the embodiment of FIGS. **5-6**, wire bundle **124** is utilized to connect both pressure sensor **118** and thermistor **140** utilizing a multiplexed signal over wire bundle **124** to processing device **136** and Wheatstone bridge **144**.

[0038] With an understanding of the components of system **100** above, the interactions of the various components, inputs, and calculations of system **100** will be described. System **100** is configured to determine FFR_{CORR} of a vessel. Distal portion **110** of elongate shaft **102** is configured to cross lesion **504** such that pressure sensor **118** and thermistor **140** are disposed on distal side **508** of lesion **504**, as shown in FIG. **1**.

[0039] As explained above, thermistor **140** is disposed on distal portion of elongate shaft **102** such that thermistor **140** is exposed to blood flow on distal side **508** of lesion **504**. Thermistor **140** is configured to measure blood flow on distal side **508** of lesion **504**. Thus, as explained above, thermistor **140** is configured such that Wheatstone bridge **144** is in a balanced configuration when thermistor **140** is at a predetermined temperature over body temperature. Therefore, when balanced, the following relationships apply.

$$\text{Balanced configuration: } R1/R3=R2/R4 \quad (1)$$

$$\textit{Ohm's Law: } V=IR \text{ or } V/R=I \quad (2)$$

(wherein V is voltage, I is current, and R is resistive value)

$$\text{Power: } P=VI \quad (3)$$

[0040] Therefore, power P is directly proportional to voltage V and current I. Substituting equation 2 into equation 3:

$$P=V^2/R \quad (4)$$

[0041] Therefore, power P is inversely proportional to resistance R. Stated another way, as resistance R decreases, power P increases.

$$P\propto 1/R \quad (5)$$

[0042] Thermistor **140** is further configured such that as blood flow BF_d of distal side **508** of lesion **504** (FIG. **1**) contacts surface **142** (FIG. **5**) of thermistor **140**, resistance

R4 of thermistor **140** decreases. With resistance R4 decreased, Wheatstone bridge **144** transitions to an unbalanced configuration. To balance Wheatstone bridge **144**, side S2 (with thermistor **140**) will draw additional current ΔI as defined by Ohm's Law. As current I is directly proportional to power P, side S2 will draw additional power ΔP. Therefore, when Wheatstone bridge **144** is in the unbalanced configuration, the following relationships apply:

$$\text{Unbalanced configuration: } R1/R3 \neq R2/R4 \quad (6)$$

$$\text{Power: } P=V^2/R \quad (7)$$

[0043] Therefore, with voltage V constant, as resistance R4 (thermistor **140**) decreases, power P increases. Accordingly, processing device **136** is configured to measure ΔP of Wheatstone bridge based on the change in resistance R4 of thermistor **140**.

$$\text{Additional power(Side 2): } \Delta P=P_{unbalanced}-P_{balanced} \quad (8)$$

[0044] Processing device **136** is further configured to calculate blood flow velocity VBF_d from ΔP. In particular, the ability of a medium (such as blood) to dissipate heat may be defined as:

$$P/dT=\text{ability of medium to dissipate heat} \quad (9)$$

(where P is power and dT is the temperature difference across thermistor **140** and blood flow BF). Heat dissipation is proportional to blood temperature, thermal properties, and blood flow velocity V_{BFd}.

[0045] Power P, specifically ΔP, is measured by processor **136**, as described above. Temperature difference dT is assumed to be constant. Blood temperature is assumed to be constant. Thermal properties of blood flow BF are assumed to be constant. Therefore, power P, or additional power ΔP, is proportional to blood flow velocity V_{BFd}:

$$\Delta P \propto V_{BFd} \quad (10)$$

[0046] Thus, by measuring ΔP of Wheatstone bridge **144** caused by blood flow across thermistor **140**, processing device **136** can calculate blood flow velocity. In particular, empirical data may be used to correlate ΔP to blood flow velocity. For example, and not by way of limitation, various blood flow velocities may be measured using conventional techniques when not performing an FFR measurement procedure. For example, and not by way of limitation, blood flow velocities may be measured using videocapillary microscoping with frame-to-frame analysis, or other techniques known to those skilled in the art. Simultaneously, a thermistor and a Wheatstone bridge, as described above, are used to obtain ΔP. Using the data comparing measured blood flow velocities to measured ΔP, a table may be created to correlate ΔP to blood flow velocity. Thus, blood flow velocities may be calculated from the table which correlates ΔP to blood flow velocity. Alternatively, an established look-up table correlating ΔP to blood flow velocities may be used. Thus, by obtaining ΔP from as described above, processing device **136** may utilize the established look-up table to obtain the blood flow velocity corresponding to ΔP.

[0047] Processing device **136** is further configured to utilize blood flow velocity VBF_d, difference in catheter diameter (catheter diameter versus diameter of a standard FFR guidewire), and vessel diameter to determine transfer function coefficients to calculate a corrected FFR. Processing device **136** may take other information into account, such as, but not limited to, the length of the lesion, length of the blood vessel, etc. to calculate a corrected FFR. FIG. **8** shows a particular example of using a look up table in which the blood flow velocity VBF_d and difference in catheter diameter are used to establish a formula for correcting FFR.

[0048] Thus, referring to a graph **500** in FIG. **8**, the horizontal axis represents FFR values for 0.024 inch FFR catheter. The vertical axis represents FFR values for a 0.014 inch FFR wire. If no difference existed between measuring FFR with a 0.024 in FFR catheter and a 0.014 inch FFR wire, measured date would fall generally on line **502**. In other words, there would be a 1:1 correlation between measuring FFR with a 0.024 inch FFR catheter and a 0.014 inch FFR wire. However, the measurements do differ. Thus, in FIG. **8**, experimental data is used to compare FFR measurements with a 0.024 inch catheter to FFR measurements with a 0.014 inch catheter. Further, the experimental data varies the blood flow rate. Thus, referring to FIG. **8**, the diamond shaped data points are measured FFR for a 0.024 inch FFR catheter and a 0.014 inch FFR wire at a blood flow rate of 90 ml/minute. The square shaped dated points are measured FFR for a 0.024 inch FFR catheter and a 0.014 inch FFR wire at a flow rate of 120 ml/minute. The triangular shaped data points are measured FFR for a 0.024 inch FFR catheter and a 0.014 inch FFR wire at a flow rate of 150 ml/minute. Thus, for example, there is a square data point at 0.8 on the X-axis and just above 0.85 on the Y-axis. This data point represents that for a particular simulated lesion and a blood flow rate of 120 ml/minute, an FFR value of 0.8 measured using a 0.024 inch FFR catheter correlates to an FFR value of just above 0.85 if the FFR value had been measured with a 0.014 inch FFR wire.

[0049] As noted above, it is important to correlate to an FFR value measured with a 0.014 inch FFR wire because historical data on whether to perform an interventional treatment on a patient based on FFR value has been based on FFR value using an FFR wire. For example, historically, FFR values taken with a 0.014 inch FFR wire that are less than about 0.80 are generally deemed significant and in need of an interventional treatment. Thus, in the chart of FIG. **8**, there is a shaded portion that is a "false positive" area. This is based on the 0.80 FFR value. Thus, the shaded area represents an area that a 0.024 inch FFR catheter measures an FFR value of less than or equal to 0.80, thereby indicating intervention, but that the measured FFR value using a 0.014 inch FFR wire would have been above 0.80, thereby not indicating intervention.

[0050] The different data points for each flow rate are for different lesions, which is why there are several data points for each flow rate. FIG. **8** is only an example, and other flow rates may be included, such as in 10 ml/minute increments. Further, while FIG. **8** correlates FFR taken with a 0.024 inch FFR catheter with FFR taken with a 0.014 in FFR wire, this is not meant to be limiting. Thus, similar charts and formulas (discussed below) for other sizes of FFR catheters, such as but not limited to a 0.020 inch FFR catheter, may be used. With the data points, line **504** is a best fit line through the data for the 150 ml/minute flow rate, line **506** is the best fit line through the data for the 120 ml/minute data points, and line **508** is the best fit line through the data for the 90 ml/minute line. Above each line is a formula or transfer function for correlating the FFR measured using a 0.024 inch FFR catheter to the FFR value of the same lesion at the same flow rate measured using a 0.014 inch FFR wire. This formula or transfer function is how the FFR measured using

a 0.024 inch FFR catheter is corrected or correlated to FFR measured using a 0.014 inch FFR wire. The formulas take the form of:

$$Y=aX^2+bX+c \quad (11)$$

where Y is the corrected FFR, X is the measured FFR using a 0.024 inch FFR catheter at the given flow rate, and "a", "b", and "c" are transfer function coefficients that are determined by finding the best fit through the data points. Thus, for example, for 120 ml/minute flow rate, the formula to correct FFR is as follows:

$$FFR_{Corr}=0.2898(FFR)^2+0.1408(FFR)+0.566 \quad (12)$$

[0051] Thus, in an example, if the thermistor results in a measured blood flow rate of 120 ml/minute, and the FFR measured with the 0.024 in FFR catheter is 0.80, the corrected FFR is as follows:

$$FFR_{Corr}=0.2898(0.80)^2+0.1408(0.80)+0.566=0.864 \quad (13)$$

[0052] With the above equations in mind, FFR and corrected FFR may be calculated. In particular, a distal pressure P_d of blood on distal side **508** of lesion **504** is sensed by pressure sensor **118** and is communicated with processing device **136**. Simultaneously, an aortic or proximal pressure P_a of blood on proximal side **506** of lesion **504** is sensed and communicated with processing device **136**. Aortic pressure P_a may be sensed by an aortic or proximal pressure measurement device (not shown). The aortic pressure measurement device may be part of catheter **101** or may be a separate device. Generally, the aortic pressure measurement device is part of a guide catheter inserted into the aorta with an external AO pressure transducer. However, other devices can be used to for measuring the aortic or proximal pressure.

[0053] Processing device **136** calculates FFR using the measured proximal and distal pressures P_a and P_d, as shown in equation 13 below. Processing device **136** also calculates the blood flow rate as discussed above. Based on the blood flow rate, processing device **136** determines the appropriate formula/transfer function to calculate the corrected FFR. Processing device **136** then uses the calculated FFR and the transfer function to calculate FFR_{Corr}. In particular, the following calculations are used to obtain the FFR_{Corr} value.

$$FFR=P_d/P_a \quad (14)$$

$$FFR_{Corr}=a(FFR)^2+b(FFR)+c \quad (15)$$

[0054] The coefficients "a", "b", and "c" are based on empirical data using the catheter size and blood flow rate. Other factors, such as lesion length, vessel diameter, etc. may also be taken into account using empirical data as outlined above with respect to FIG. **8**.

[0055] FIG. **9** shows an embodiment of a method of calculating a corrected Fractional Flow Reserve (FFR_{Corr}). Steps **602-620** of FIG. **9** reference components and the vasculature shown in FIG. **1**.

[0056] In step **602**, an aortic pressure measurement device (not shown) is advanced within the vasculature. In a non-limiting example, the aortic pressure measurement device may be a guide catheter (not shown) with an external pressure transducer (not shown), as known in the art. However, this is not meant to be limiting, and other proximal pressure measurement devices may be utilized. The proximal pressure measure measurement device is configured to measure proximal pressure P_a.

[0057] In step **604** of the embodiment of the method of FIG. **9**, catheter **101** is advanced into a patient's vasculature, and positioned such that pressure sensor **118** and thermistor **140** are positioned on distal side **508** of lesion **504**. Radiopaque markers may be utilized to determine when distal portion **110** of catheter **101** is in the proper position. In an embodiment, catheter **101** is advanced through a guide catheter (not shown).

[0058] In step **606** of the embodiment of the method of FIG. **8**, with catheter **101** in position, surface **142** of thermistor **140** is cooled by blood flow BF_d on distal side **508** of lesion **504**. As thermistor **140** cools from a predetermined temperature above body temperature, thermistor **140** draws additional power to balance the Wheatstone bridge **144**.

[0059] In step **608** of the embodiment of the method of FIG. **9**, processing device **136** monitors power draw and calculates additional power draw ΔP required to maintain Wheatstone bridge **144** balanced. In step **610** of the embodiment of FIG. **9**, processing device **136** processes the additional power draw ΔP to calculate blood-flow velocity VBF_d (VBF_d is proportional to additional power draw ΔP of thermistor **140**), as explained above.

[0060] In step **612** of the embodiment of FIG. **9**, processing device **136** processes blood flow velocity VBF_d, catheter size difference (catheter to FFR guidewire), and vessel size to determine transfer function coefficients, and uses the transfer function coefficients to calculate corrected FFR, as explained above.

[0061] Simultaneous with step **608**, in step **614** of the embodiment of FIG. **9**, distal pressure P_d is measured by pressure-sensing surface **120** of pressure sensor **118** on distal side **508** of lesion **504**. Distal pressure P_d is communicated to processing device **136**.

[0062] Simultaneous with steps **608** and **614**, in step **616** of the embodiment of the method of FIG. **9**, proximal pressure P_a of blood on proximal side **506** of lesion **504** is measured by the aortic pressure measurement device (not shown), such as an external AO pressure transducer. Measured proximal pressure P_a is communicated to processing device **136**.

[0063] In step **618** of the embodiment of the method of FIG. **9**, processing device **136** processes measured proximal and distal pressures P_a and P_d to calculate FFR. In step **620**, processing device **136** processes the calculated FFR value and calculated transfer function coefficients to calculate FFR_{CORR}.

[0064] While the method of FIG. **9** shows proximal pressure P_a as measured by an external AO pressure transducer, this is not meant to limit the method, and other methods of obtaining proximal pressure P_a may be utilized, including replacing the step of measuring proximal pressure P_a with external AO pressure transducer of step **616** with a step of measuring proximal pressure P_a with a pressure-sensing device coupled to catheter **101**, measuring proximal pressure P_a with pressure sensor **118** either before or after the step of measuring distal pressure P_d with pressure sensor **118**, or measuring proximal pressure P_a by any other method suitable for the purposes described in step **616**.

[0065] Although the method of FIG. **9** is described with respect to system **100** of FIG. **1** in coronary artery **510**, those skilled in the art will understand that the method described herein may utilize a system according to any embodiment described herein, and may be used in other bodily vessels where a FFR_{CORR} measurement is useful.

[0066] While the embodiments and methodology of FIGS. **1-9** describe a thermistor coupled to a catheter to calculate FFR_{CORR}, this is not meant to limit the design and method, a thermistor disposed on a guidewire-based FFR system may be utilized with a similar methodology to FIG. **9** to calculate FFR_{CORR} for blood flow velocity.

[0067] While only some embodiments according to the present invention have been described herein, it should be understood that they have been presented by way of illustration and example only, and not limitation. Various changes in form and detail can be made therein without departing from the spirit and scope of the invention. Further, each feature of each embodiment discussed herein, and of each reference cited herein, can be used in combination with the features of any other embodiment. All patents and publications discussed herein are incorporated by reference herein in their entirety.

What is claimed is:

1. A catheter comprising:

an elongate shaft defining a guidewire lumen;

a pressure sensor coupled to a distal portion of the elongate shaft such that a pressure-sensing surface of the pressure sensor faces outside of an outer surface of the distal portion of the elongate shaft; and

a thermistor coupled to the distal portion of the elongate shaft such that a surface of the thermistor faces the outside of the outer surface of the distal portion;

wherein the pressure sensor is configured to sense a pressure of blood distal of a stenosis in a blood vessel, and wherein the pressure sensor is in communication with a processor;

wherein the thermistor is configured to measure a blood flow velocity distal of the stenosis such that the processor may calculate a corrected Fractional Flow Reserve including a correction based on the blood flow velocity.

2. The catheter of claim **1**, wherein the thermistor is one arm of a Wheatstone bridge.

3. The catheter of claim **2**, wherein the blood flow velocity is proportional to power required to maintain balance of the Wheatstone bridge, wherein the thermistor changes resistance based on exposure to blood flow, and wherein the change in resistance unbalances the Wheatstone bridge.

4. A system for calculating a corrected Fractional Flow Reserve associated with a stenosis in a blood vessel comprising:

a pressure sensor configured for placement within a blood vessel to measure a distal pressure distal to the stenosis;

a pressure-sensing device configured to measure a proximal pressure proximal of the stenosis;

a thermistor configured for placement within the blood vessel to measure blood flow velocity distal of the stenosis; and

a processing device in communication the pressure sensor, the pressure-sensing device, and the thermistor;

wherein the processing device is configured to calculate a Fractional Flow Reserve based on the distal pressure relative to the proximal pressure; and

wherein the processing device is configured to calculate or select a transfer function including a flow velocity correction based on the measured blood flow velocity, wherein the processing device is configured to apply the transfer function to the calculate Fractional Flow Reserve to calculate a corrected Fractional Flow Reserve.

5. The system of claim **4**,

wherein the thermistor is one arm of a Wheatstone bridge,

wherein power to maintain the thermistor at a predetermined temperature is proportional to blood flow velocity, and

wherein the processor is configured to calculate blood flow velocity based on the power to maintain the thermistor at the predetermined temperature.

6. The system of claim **4**,

wherein the pressure sensor is coupled to a catheter having a catheter cross-sectional area in a portion of the catheter configured to cross the stenosis to measure the distal pressure, and

wherein the transfer function selected or calculated by the includes a size correction based on the catheter cross-sectional area as compared to a cross-sectional area of a wire-based pressure-sensing device.

7. The system of claim **6**,

wherein the transfer function selected or calculate by the processor includes a vessel size correction based on a size of the blood vessel at the stenosis.

8. A method for calculating a corrected Fractional Flow Reserve in a vessel, the method comprising the steps of:

delivering a catheter to a distal side of a stenosis of the vessel, the catheter including a distal pressure sensor and a thermistor;

measuring the blood flow velocity within the vessel using the thermistor;

calculating or selecting a transfer function including a blood flow velocity correction based on the measured blood flow velocity;

measuring a pressure distal of the stenosis;

measuring a pressure proximal of the stenosis; and

calculating the corrected Fractional Flow Reserve using the measured proximal and distal pressures and application of the transfer function.

9. The method of claim **8**, wherein the blood vessel is a coronary artery.

10. The method of claim **8**, wherein the thermistor is one arm of a Wheatstone bridge, and wherein blood flow velocity is measured based on power to maintain the thermistor at a predetermined temperature.

11. The method of claim **8**, wherein the transfer function also includes a catheter-size correction, wherein the catheter-size correction is selected or calculated based on a cross-sectional area of the catheter in a portion of the catheter configured to cross the lesion.

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专利名称(译)	系统，导管和计算校正的分流量储备的方法		
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[标]申请(专利权)人(译)	美敦力瓦斯科尔勒公司		
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摘要(译)

导管包括细长轴，压力传感器和热敏电阻。细长轴限定导丝管腔。压力传感器联接到细长轴的远侧部分，使得压力传感器感测狭窄远端的血压。热敏电阻耦合到细长轴的远端部分，使得热敏电阻测量狭窄远端的血流速度。压力传感器和热敏电阻与处理器通信。处理器计算校正的分数流量储备，包括基于血流速度的校正。