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(54) **SYSTEMS, DEVICES, AND METHODS FOR DETERMINING SEVERITY OF A STENOSIS WITHIN A LUMINAL ORGAN IN THE PRESENCE OF A CATHETER**

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(Continued)

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(Continued)

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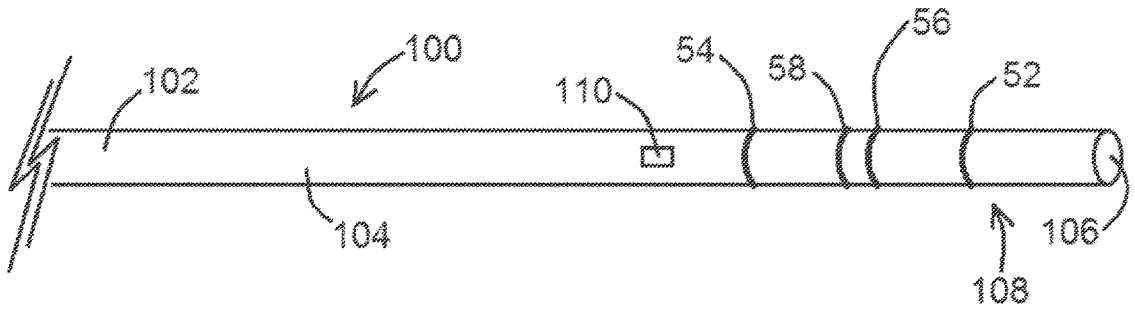
(57) **ABSTRACT**

Systems, devices, and methods for obtaining fractional flow reserve in the presence of a catheter. In a method of determining a fractional flow reserve in the presence of a catheter, the method comprises the steps of obtaining measurements of an inner luminal organ diameter proximal to, at, and distal to a stenosis and a length of the stenosis, obtaining a pressure drop measurement at the stenosis, calculating a volumetric flow of fluid through the inner luminal organ at the stenosis, and determining a stenotic pressure drop at the stenosis corresponding to dimensions of the guidewire as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis.

19 Claims, 4 Drawing Sheets



Related U.S. Application Data

continuation of application No. 13/646,046, filed on Oct. 5, 2012, now Pat. No. 8,696,584.

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A61B 8/12	(2006.01)
A61B 5/00	(2006.01)
A61B 5/053	(2006.01)
A61B 5/026	(2006.01)
A61B 8/06	(2006.01)
A61B 5/02	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 5/02007*** (2013.01); ***A61B 5/0215*** (2013.01); ***A61B 5/0261*** (2013.01); ***A61B 5/02158*** (2013.01); ***A61B 5/0538*** (2013.01); ***A61B 6/481*** (2013.01); ***A61B 6/504*** (2013.01); ***A61B 8/06*** (2013.01); ***A61B 8/12*** (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

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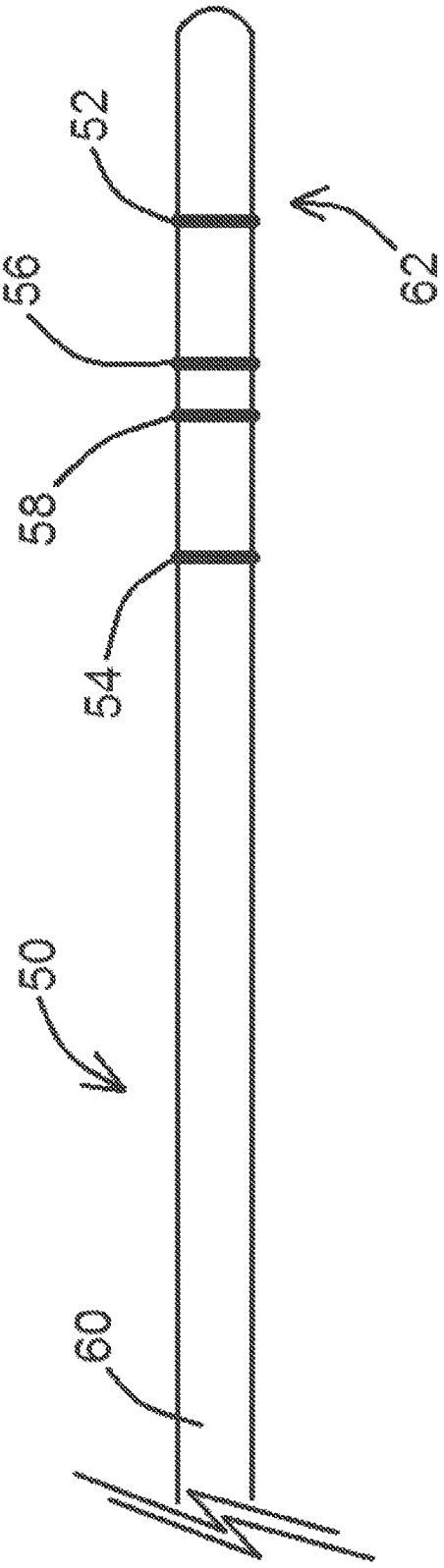

FIG. 1 (PRIOR ART)

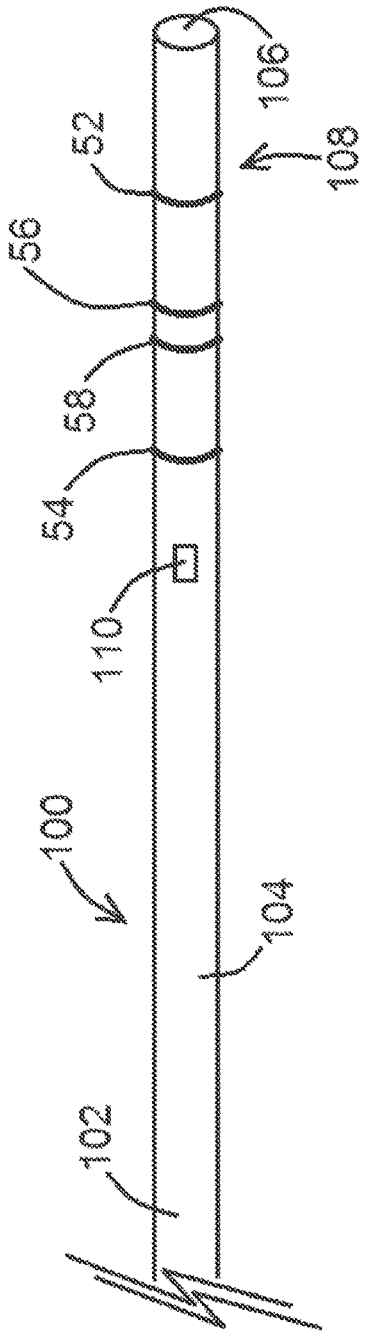

FIG. 2

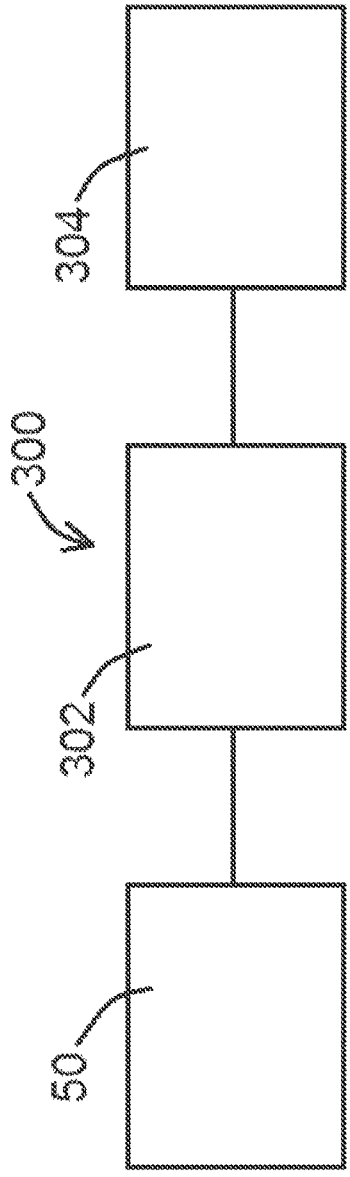

FIG. 3

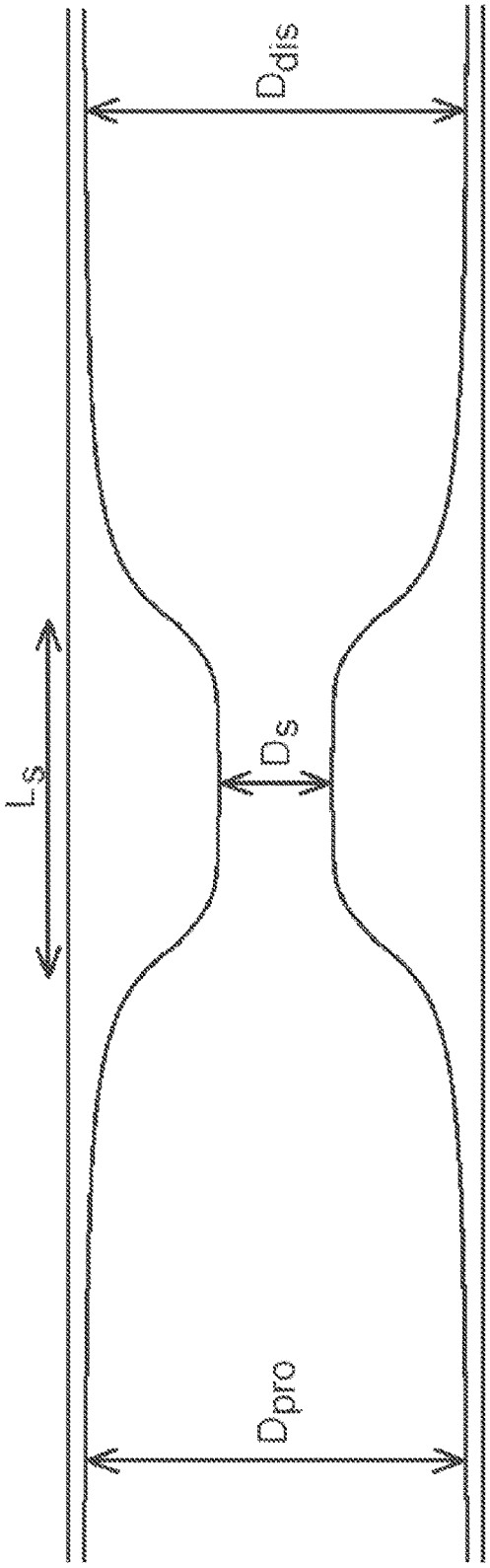

FIG. 4

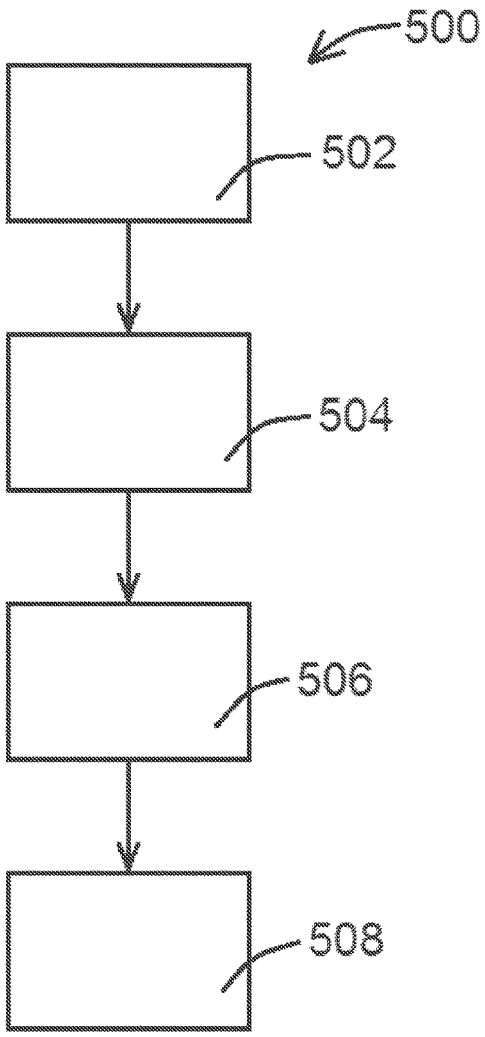

FIG. 5

SYSTEMS, DEVICES, AND METHODS FOR DETERMINING SEVERITY OF A STENOSIS WITHIN A LUMINAL ORGAN IN THE PRESENCE OF A CATHETER

PRIORITY

The present application is related to, claims the priority benefit of, and is a U.S. continuation application of, U.S. patent application Ser. No. 14/253,385, filed Apr. 15, 2014 and issued as U.S. Pat. No. 9,332,916 on May 10, 2016, which is related to, claims the priority benefit of, and is a U.S. continuation application of, U.S. patent application Ser. No. 13/646,046, filed on Oct. 5, 2012 and issued as U.S. Pat. No. 8,696,584 on Apr. 15, 2014, which is related to, and claims the priority benefit of, U.S. Provisional Patent Application Ser. No. 61/543,332, filed Oct. 5, 2011. The contents of each of the aforementioned applications and patent are incorporated by reference in their entirety into this disclosure.

BACKGROUND

Fractional flow reserve (FFR) is a technique for measuring differences in pressure across an arterial stenosis, with the measurement itself being useful to determine the severity of the stenosis. The guidelines for stenotic lesion treatment using FFR have been established based on dimension of a 0.014" outer-diameter pressure wire. It has been shown that this dimension does not significantly affect FFR measurement in the critical range of 0.75-0.8.

By way of example, a patient's luminal organ (such as an artery, for example), may have a 2 mm inner diameter at a location without a lesion, and a 1 mm in diameter at the lesion site. A 0.014" (0.356 mm) diameter wire is approximately half of the diameter of an inner diameter of a vessel at a lesion location if the inner diameter is 1 mm. Advancing a catheter over the pressure wire, such as a 0.02" outer diameter catheter), adds nearly 50% in size to the overall device, which has severe implications with respect to obtaining an accurate FFR measurement.

In view of the foregoing, methods for determining accurate FFR measurements in the view of catheters having dimensions larger than established guideline devices, and devices and systems for facilitating the same, would be appreciated in the marketplace.

BRIEF SUMMARY

In an exemplary embodiment of a method of determining a fractional flow reserve in the presence of a catheter of the present disclosure, the method comprises the steps of obtaining measurements of an inner luminal organ diameter proximal to a stenosis, an inner luminal organ diameter at the stenosis, an inner luminal organ diameter distal to the stenosis, and a length of the stenosis, obtaining a pressure drop measurement at the stenosis using a catheter having a known outer diameter, calculating a volumetric flow of fluid through the inner luminal organ at the stenosis based upon the pressure drop measurement at the stenosis using the catheter, the inner luminal organ diameter proximal to the stenosis, the inner lumen diameter distal to the stenosis, the length of the stenosis, and a difference between the known outer diameter of the catheter and a known outer diameter of a guidewire, and determining a stenotic pressure drop at the stenosis corresponding to dimensions of the guidewire as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis. In another embodiment, the fractional flow reserve is useful to determine a functional assessment of stenosis severity. In an additional embodiment, the method further comprises the step of determining a functional assessment of stenosis severity using the fractional flow reserve. In yet another embodiment, the step of obtaining a pressure drop measurement at the stenosis is performed using a pressure catheter. In an additional embodiment, the step of obtaining a pressure drop measurement at the stenosis is performed using a pressure catheter having a known outer diameter of 0.020" or approximately 0.020".

In an exemplary embodiment of a method of determining a fractional flow reserve in the presence of a catheter of the present disclosure, the step of determining the stenotic pressure drop at the stenosis is further based upon a function of the inner luminal organ diameter proximal to the stenosis, the inner luminal organ diameter at the stenosis, the inner luminal organ diameter distal to the stenosis, and the length of the stenosis. In an additional embodiment, the step of obtaining measurements is performed using the guidewire. In yet an additional embodiment, the step of obtaining measurements is performed using an impedance guidewire having a known outer diameter equivalent to the known outer diameter of the guidewire. In another embodiment, the step of obtaining measurements is performed using an impedance guidewire having two outer excitation electrodes and two inner detection electrodes, wherein the excitation electrodes are operable to generate an electric field within a luminal organ that can be detected by the detection electrodes. In yet another embodiment, the step of obtaining measurements is performed using a procedure selected from the group consisting of (i) angiography and intravascular ultrasound and (ii) angiography and optical coherence tomography.

In an exemplary embodiment of a method of determining a fractional flow reserve in the presence of a catheter of the present disclosure, the step of obtaining a pressure drop measurement is performed using a pressure catheter. In another embodiment, the step of obtaining a pressure drop measurement is performed using the catheter having a pressure sensor. In yet another embodiment, the difference between the known outer diameter of the catheter and the known outer diameter of the guidewire is 0.006" or approximately 0.006".

In an exemplary embodiment of a system for determining a fractional flow reserve of the present disclosure, the system comprises a mechanism configured to obtain measurements of an inner luminal organ diameter proximal to a stenosis within a mammalian body, an inner luminal organ diameter at the stenosis, an inner luminal organ diameter distal to the stenosis, and a length of the stenosis, and a catheter having at least one pressure sensor, the catheter configured to fit around a guidewire and further configured to obtain a pressure drop measurement at the stenosis, and a data acquisition and processing system configured to calculate a volumetric flow of fluid through the inner luminal organ at the stenosis and to determine a stenotic pressure drop at the stenosis as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis. In another embodiment, the mechanism comprises an impedance guidewire. In yet another embodiment, the impedance guidewire comprises two outer excitation electrodes and two inner detection electrodes, wherein the excitation electrodes are operable to

generate an electric field within a luminal organ that can be detected by the detection electrodes. In an additional embodiment, the impedance guidewire has an outer diameter of 0.014" or approximately 0.014". In yet an additional embodiment, the mechanism is elected from the group consisting of an angiography device, an intravascular ultrasound device, and an optical coherence tomography device.

In an exemplary embodiment of a system for determining a fractional flow reserve of the present disclosure, the catheter comprises a pressure catheter. In an additional embodiment, the catheter has a known outer diameter of 0.020" or approximately 0.020". In yet an additional embodiment, the data acquisition and processing system is configured to calculate the volumetric flow of fluid through the inner luminal organ at the stenosis based upon the pressure drop measurement, the inner luminal organ diameter proximal to the stenosis, the inner lumen diameter distal to the stenosis, the length of the stenosis, and a difference between a known outer diameter of the catheter and a known outer diameter of a guidewire. In another embodiment, the known outer diameter of the catheter is 0.020" or approximately 0.020", and wherein the known outer diameter of the guidewire is 0.014" or approximately 0.014". In yet another embodiment, the fractional flow reserve is useful to determine a functional assessment of stenosis severity.

In an exemplary embodiment of a method of determining a fractional flow reserve in the presence of a catheter of the present disclosure, the method comprises the steps of obtaining measurements of an inner luminal organ diameter proximal to a stenosis, an inner luminal organ diameter at the stenosis, an inner luminal organ diameter distal to the stenosis, a length of the stenosis, and a pressure drop measurement at the stenosis using a catheter having a known outer diameter, calculating a volumetric flow of fluid through the inner luminal organ at the stenosis based upon the pressure drop measurement at the stenosis using the catheter, the inner luminal organ diameter proximal to the stenosis, the inner lumen diameter distal to the stenosis, the length of the stenosis, and a difference between the known outer diameter of the catheter and a reference device diameter, and determining a stenotic pressure drop at the stenosis corresponding to a reference device diameter as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis. In another embodiment, the fractional flow reserve is useful to determine a functional assessment of stenosis severity. In yet another embodiment, the step of obtaining measurements is performed using the having a known outer diameter of 0.020" or approximately 0.020".

In an exemplary embodiment of a method of determining a fractional flow reserve in the presence of a catheter of the present disclosure, the step of determining the stenotic pressure drop at the stenosis is further based upon a function of the inner luminal organ diameter proximal to the stenosis, the inner luminal organ diameter at the stenosis, the inner luminal organ diameter distal to the stenosis, and the length of the stenosis. In an additional embodiment, the step of obtaining measurements is performed using the catheter having a pressure sensor, two outer excitation electrodes, and two inner detection electrodes, wherein the excitation electrodes are operable to generate an electric field within a luminal organ that can be detected by the detection electrodes, and wherein the pressure sensor can obtain the pressure drop measurement. In yet an additional embodiment, the difference between the known outer diameter of the catheter and the reference device diameter is 0.006" or approximately 0.006".

In an exemplary embodiment of a system for determining a fractional flow reserve of the present disclosure, the system comprises a catheter configured to obtain measurements of an inner luminal organ diameter proximal to a stenosis within a mammalian body, an inner luminal organ diameter at the stenosis, an inner luminal organ diameter distal to the stenosis, a length of the stenosis, and a pressure drop measurement at the stenosis. In another embodiment, the system further comprises a data acquisition and processing system configured to calculate a volumetric flow of fluid through the inner luminal organ at the stenosis and to determine a stenotic pressure drop at the stenosis as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis. In yet another embodiment, the catheter comprises two outer excitation electrodes and two inner detection electrodes, wherein the excitation electrodes are operable to generate an electric field within a luminal organ that can be detected by the detection electrodes. In an additional embodiment, the catheter further comprises a pressure sensor configured to can obtain the pressure drop measurement.

In an exemplary embodiment of a system for determining a fractional flow reserve of the present disclosure, the data acquisition and processing system is configured to calculate the volumetric flow of fluid through the inner luminal organ at the stenosis based upon the pressure drop measurement, the inner luminal organ diameter proximal to the stenosis, the inner lumen diameter distal to the stenosis, the length of the stenosis, and a difference between the known outer diameter of the catheter and a reference device diameter. In an additional embodiment, the reference device diameter is 0.014" or approximately 0.014". In yet an additional embodiment, the catheter has a known outer diameter of 0.020" or approximately 0.020". In another embodiment, the fractional flow reserve is useful to determine a functional assessment of stenosis severity. In yet another embodiment, the catheter is configured to fit around a guidewire and further configured to obtain a pressure drop measurement at the stenosis.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed embodiments and other features, advantages, and disclosures contained herein, and the matter of attaining them, will become apparent and the present disclosure will be better understood by reference to the following description of various exemplary embodiments of the present disclosure taken in conjunction with the accompanying drawings, wherein:

FIG. **1** shows a device useful for obtaining impedance measurements;

FIG. **2** shows a device useful for obtaining at least one FFR measurement, according to an exemplary embodiment of the present disclosure;

FIG. **3** shows a block diagram of a system useful for obtaining at least one FFR measurement, according to an exemplary embodiment of the present disclosure;

FIG. **4** shows a cross-sectional side view of an exemplary luminal organ having a stenosis therein; and

FIG. **5** shows steps of an exemplary method for determining fractional flow reserve in the presence of a catheter, according to an exemplary embodiment of the present disclosure.

An overview of the features, functions and/or configurations of the components depicted in the various figures will now be presented. It should be appreciated that not all of the features of the components of the figures are necessarily described. Some of these non-discussed features, such as various couplers, etc., as well as discussed features are inherent from the figures themselves. Other non-discussed features may be inherent in component geometry and/or configuration.

DETAILED DESCRIPTION

For the purposes of promoting an understanding of the principles of the present disclosure, reference will now be made to the embodiments illustrated in the drawings, and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of this disclosure is thereby intended.

Advantages exist to measuring FFR using a catheter over a standard workhorse guidewire or an impedance wire. Naturally the catheter must have an outer diameter greater than the wire (such as a 0.014" guidewire or impedance wire) since it is advanced over the wire.

The guidelines for lesion treatment using FFR have been established based on a dimension of 0.014" (such as a 0.014" pressure wire). It has been shown that this dimension does not significantly affect FFR measurement in the critical range of 0.75-0.8. In theory, a larger diameter than 0.014" will increase the pressure drop and hence decrease FFR (i.e., overestimate the severity of the lesion). Hence, it is important to provide a physics-based correction of FFR due to a measurement device that exceeds 0.014" dimension. The foregoing analysis provides a solution.

An exemplary wire useful to obtain one or more FFR measurements is shown in FIG. **1**. Such a wire, for example, may be a wire disclosed within U.S. Patent Application Publication Nos. 20110178383 and 20110178417 of Kassab, having an outer diameter of 0.014" and a series of impedance electrodes positioned thereon. As shown in FIG. **1**, an exemplary prior art device **50** may have an impedance portion comprising two outer excitation electrodes **52**, **54** and two inner detection electrodes **56**, **58** positioned along a body **60** of device **50** at or near the distal end **62** of body **50**. The two excitation electrodes **56**, **58** are operable to generate an electric field that can be detected by the two inner detection electrodes **56**, **58**. This combination of electrodes is useful to obtain a series of impedance measurements within a patient's luminal organ in the presence of injected fluid(s) having known conductances and/or a fluid native to the luminal organ, such as the patient's blood, with said impedance measurements useful to obtain luminal cross-sectional areas, fluid velocity through the luminal organ, and the like.

At least another device useful to obtain one or more FFR measurements of the present application is shown in FIG. **2**. As shown in FIG. **2**, device **100** comprises a catheter **102** having a body **104** and a lumen **106** defined therethrough. Device **100**, as shown in FIG. **2**, comprises two outer excitation electrodes **52**, **54** and two inner detection electrodes **56**, **58** positioned along body **104** of device **100** at or near the distal end **108** of body **100**. In addition, and as shown in FIG. **2**, device **100** has a pressure sensor **110** thereon, whereby one or more pressure measurements, as referenced in further detail herein, can be obtained. Devices **100**, in various embodiments, are configured to fit around a guidewire and further configured to allow one or more therapeutics, fluids, and/or the like to be delivered through lumen **106** into a patient's body.

In at least another embodiment, an exemplary device **100** comprises a catheter **102** having a pressure sensor **110** thereon, whereby catheter has no outer excitation electrodes **52**, **54** or inner detection electrodes **56**, **58**. Such an embodiment of device **100**, useful to obtain one or more FFR measurements as referenced herein, would be used in connection with a device **50** or another procedure, such as angiography, intravascular ultrasound (IVUS), or optical coherence tomography (OCT), for example.

FIG. **3** shows a block diagram of components of an exemplary system of the present disclosure. As shown in FIG. **3**, system **300** comprises an exemplary device **50** of the present disclosure, a catheter **302** configured to fit around device **50**, and an optional data acquisition and processing system **304** configured to receive and/or process data from device **50** and/or catheter **302**.

By way of background, myocardial FFR is known as functional parameter of stenosis severity. FFR during hyperemic flow is expressed as:

$$FFR = \frac{P_{distal} - P_v}{P_a - P_v} \quad [1]$$

wherein P_a is the mean aortic pressure ($P_a \approx P_{proximal}$ assuming no diffuse coronary artery disease), P_v is the central venous pressure, and $P_{proximal}$ and P_{distal} are the hyperemic coronary pressure proximal and distal to stenosis, respectively. If the central venous pressure is assumed to be negligible, Equation [1] is generally approximated as:

$$FFR = \frac{P_{distal}}{P_a} = \frac{P_a - \Delta P}{P_a} \quad [2]$$

where ΔP is the pressure gradient along the axis of vessel segment from proximal to distal position of stenosis.

In at least one embodiment of a method of the present disclosure, the method is useful to determine an accurate FFR measurement using any number of catheters having an outer diameter larger than the workhorse impedance wire (i.e., larger than 0.014"). FIG. **4** shows a cross-sectional side view of an exemplary luminal organ having a stenosis therein. Various dimensions are shown in FIG. **4**, including an inner diameter proximal to the stenosis (identified as D_{pro}), an inner diameter at the stenosis (D_s), an inner diameter distal to the stenosis (D_{dis}), and the length of the stenosis itself (L_s). Such dimensions may be measured using the device shown in FIG. **1**, as angiography alone would not be sufficient to provide the required accuracy (either IVUS or OCT would also be required).

In at least one embodiment of a method **100** of the present disclosure, ΔP is equal to a function of the inner diameter proximal to the stenosis (D_{pro}), the inner diameter at the stenosis (D_s), the inner diameter distal to the stenosis (D_{dis}), the length of the stenosis itself (L_s), and the volumetric flow of a fluid (such as blood) through the stenosis (Qs), identified as follows:

$$\Delta P = f(D_{dis}, D_{pro}, D_s, L_s, Q_s) \quad [3]$$

The form of this analytic equation involves various energy dissipation terms in form of integrals as referenced in, for example, U.S. Patent Application Publication Nos. 20110178383 and 20110178417 of Kassab.

As referenced herein, an exemplary standard workhorse impedance wire has an outer diameter of 0.014". The calculations herein are based on such a configuration, which are consistent with current guidelines for lesion treatment using FFR as referenced above. Any catheter that would then be advanced over the wire would be larger than 0.014", and for the purposes of the present exemplary method, the outer diameter of the catheter (D_{out}) would be calculated as follows:

$$D_{out}=0.014"+\delta \quad [4]$$

wherein δ is the difference D_{out} between and 0.014".

If a catheter of dimension D_{out} is positioned across the stenosis, a pressure gradient change at the stenosis (ΔP_{cath}) can be measured. After the measurements of ΔP_{cath}, D_{dis}, D_{pro}, D_s, L_s are obtained, Q_s can be calculated as the positive root of the following equation

$$\Delta P_{cath}=f(D_{dis}+\delta, D_{pro}+\delta, L_s, Q_s) \quad [5]$$

whereby the relation is quadratic in terms of Q_s and hence will yield two solutions, namely $\pm Q_s$. Once Q_s is determined, the following relation will provide the desired solution for pressure drop corresponding to 0.014" device:

$$\Delta P_{0.014"}=f(D_{dis}, D_{pro}, D_s, L_s, Q_s) \quad [6]$$

Clearly, $\Delta P_{0.014"}<\Delta P_{cath}$, which provides the corrected estimate of pressured drop and hence FFR for functional assessment of lesion severity that conforms with established clinical guidelines. The only assumption here is that flow is less sensitive to stenosis than pressure, i.e., flow changes less in the presence of a catheter than pressure. This assumption is well accepted and forms the rationale for the use of pressure measurement as a surrogate for FFR which is fundamentally a flow index.

As for the form of Equation [3] referenced above, the law of conservation of mass (the general Bernoulli equation) can be written as:

$$\Delta P=\Delta P_{convective}+\Delta P_{constriction}+\Delta P_{diffusive}+\Delta P_{expansion} \quad [7]$$

wherein $\Delta P_{convective}$, $\Delta P_{constriction}$, $\Delta P_{diffusive}$, and $\Delta P_{expansion}$ are energy losses due to flow convection, sudden constriction in CSA from proximal normal vessel to stenosis, flow diffusion, and sudden expansion in CSA from stenosis to distal normal vessel, respectively. In addition,

$$\Delta P_{convective}=\frac{\rho Q^2}{2}\left(\frac{1}{CSA_{outlet}^2}-\frac{1}{CSA_{inlet}^2}\right) \quad [8]$$

where CSA_{inlet} and CSA_{outlet} are the inlet and outlet cross-sectional areas, respectively, Q is the hyperemic flow rate in a vessel segment, and p is the density of blood. If the flow transition, from proximal normal vessel to stenosis, is well-bound and follows the streamlines, the energy loss due to sudden constriction is relatively small (loss coefficient <<0.1 generally) and negligible such that $\Delta P_{constriction}=0$.

Although $\Delta P_{diffusive}$ is generally caused by the viscosity in the fully-developed region (i.e., viscous energy loss as referenced herein), the pressure drop serves both to accelerate the flow and to overcome viscous drag in the entrance region of a stenosis, which contributes to the diffusive energy loss. For the entrance region of stenosis, a dimensionless radius of the inviscid core (α) can be defined, in which the flow velocity is uniform such as α=r at the inlet, 0<α<r from the inlet to the fully-developed region, and α=0 at the fully-developed region. The dimensionless radius of inviscid core (α) can then be calculated from:

$$\frac{\pi\mu L_{stenosis}}{4\rho Q}=\frac{1}{4}\int_a^1\frac{(1-\alpha)(6+\alpha)(1+4\alpha+9\alpha^2+4\alpha^3)}{5\alpha(3+2\alpha)(3+2\alpha+\alpha^2)^2}\,d\alpha \quad [9]$$

where $L_{stenosis}$ is the length of stenosis, and L_{vessel} is the length of vessel, which is comprised of both normal vessel and stenosis. If α≥0.05 (as shorter lesions <3 cm, which is most typical for coronary arteries), $\Delta P_{diffusive}$ and $\Delta P_{expansion}$ are expressed as:

$$\Delta P_{diffusive}^{\alpha\geq 0.05}=\frac{\rho Q^2}{2\cdot CSA_{stensosis}^2}\frac{96}{5}\int_a^1\frac{(1+4\alpha+9\alpha^2+4\alpha^3)}{\alpha(3+2\alpha)(3+2\alpha+\alpha^2)^2}\,d\alpha+\int_0^{L_{vessel}-L_{stenosis}}\frac{8\pi\mu}{CSA^2}Q\,dx \text{ and} \quad [10]$$

$$\Delta P_{expansion}^{\alpha\geq 0.05}=\frac{\rho Q^2}{2}\cdot\left\{\left(\frac{1}{CSA_{stenosis}}-\frac{1}{CSA_{distal}}\right)^2+\left[2\cdot\left(\frac{1}{CSA_{stenosis}}-\frac{1}{CSA_{distal}}\right)\cdot\left(\frac{1}{CSA_{stenosis}}-\frac{1}{3}\cdot\frac{1}{CSA_{distal}}\right)-\left(\frac{1}{CSA_{stenosis}}-\frac{1}{CSA_{distal}}\right)^2\right]\cdot(1-\alpha)^2\right\} \quad [11]$$

If α<0.05 (longer lesions, >3 cm, less typical), the entire stenosis is divided into entrance and fully-developed regions and the entrance length ($L_{entrance}$) is obtained from

$$\frac{\pi\mu L_{entrance}}{4\rho Q}=\frac{1}{4}\int_{0.05}^1\frac{(1-\alpha)(6+\alpha)(1+4\alpha+9\alpha^2+4\alpha^3)}{5\alpha(3+2\alpha)(3+2\alpha+\alpha^2)^2}\,d\alpha \quad [12]$$

such that:

$$\Delta P_{diffusive}^{\alpha<0.05}=\frac{\rho Q^2}{2\cdot CSA_{stenosis}^2}\frac{96}{5}\int_{0.05}^1\frac{(1+4\alpha+9\alpha^2+4\alpha^3)}{\alpha(3+2\alpha)(3+2\alpha+\alpha^2)^2}\,d\alpha+\int_0^{L_{vessel}-L_{entrance}}\frac{8\pi\mu}{CSA^2}Q\,dx \text{ and} \quad [13]$$

$$\Delta P_{expansion}^{\alpha<0.05}=\rho Q^2\cdot\left(\frac{1}{CSA_{stenosis}}-\frac{1}{CSA_{distal}}\right)\cdot\left(\frac{1}{CSA_{stenosis}}-\frac{1}{3}\cdot\frac{1}{CSA_{distal}}\right) \quad [14]$$

In accordance with the foregoing, the entrance effect plus the viscosity (Poiseuille's formula in the fully-developed region) leads to the diffusive energy loss. The energy loss due to sudden expansion in CSA is also taken into account, based on the outlet flow pattern that represents the growth of boundary layer from the inlet of stenosis to the outlet.

As referenced above, one can assume that the flow regime falls in the $\alpha>0.05$ since most coronary lesions are <2 cm in length and use various equations herein along with the terms for convective and constriction terms (minor in magnitude). Once the flow is determined as outlined above, the α can be recalculated to determine if $\alpha>0.05$ or <0.05 and to iterate the calculation.

In view of the foregoing, steps of an exemplary method of determining FFR of the present disclosure are shown in FIG. **5**. As shown in FIG. **5**, an exemplary method **500** comprises the steps of obtaining measurements of an inner luminal organ diameter proximal to a stenosis, an inner luminal organ diameter at the stenosis, an inner luminal organ diameter distal to the stenosis, and a length of the stenosis (an exemplary geometry measurement step **502**), and the step of obtaining a pressure drop measurement at the stenosis (an exemplary pressure drop measurement step **504**). Geometry measurement step **502** may be performed using a device **50** as shown in FIG. **1** or a device **100** as shown in FIG. **2**. In other embodiments, geometry measurement step **502** may be performed using angiography, intravascular ultrasound, and optical coherence tomography. Pressure drop measurement step **504** may be performed using a device **100** of the present disclosure, such as a pressure catheter having a known outer diameter of 0.020" or approximately 0.020". Such an exemplary device **100** may comprise, for example, a catheter **102** having a pressure sensor **110**, two outer excitation electrodes **52**, **54**, and two inner detection electrodes **56**, **58**, wherein the excitation electrodes **52**, **54** are operable to generate an electric field within a luminal organ that can be detected by the detection electrodes **56**, **58**, and wherein the pressure sensor **100** can obtain the pressure drop measurement.

An exemplary method **500** of the present disclosure may further comprise the step of calculating a volumetric flow of fluid through the inner luminal organ at the stenosis based upon the pressure drop measurement at the stenosis using the catheter, the inner luminal organ diameter proximal to the stenosis, the inner lumen diameter distal to the stenosis, the length of the stenosis, and a difference between the known outer diameter of the catheter and a reference device diameter (such as a known outer diameter of a guidewire) (an exemplary volumetric flow calculating step **506**). Method **500**, in various embodiments, further comprises the step of determining a stenotic pressure drop at the stenosis corresponding to the reference device diameter (such as the dimensions of the guidewire, for example), as a function of the calculated volumetric flow of fluid through the inner luminal organ at the stenosis, wherein the stenotic pressure drop is indicative of a fractional flow reserve at or near the stenosis (an exemplary FFR determination step **508**). FFR determination step **508** may be performed, in various embodiments, to determine a functional assessment of stenosis severity. In at least one embodiment, the step of determining a stenotic pressure drop within FFR determination step **508** is further based upon a function of the inner luminal organ diameter proximal to the stenosis, the inner luminal organ diameter at the stenosis, the inner luminal organ diameter distal to the stenosis, and the length of the stenosis. An exemplary difference between the reference device diameter (the outer dimensions of the guidewire, for example) and the outer diameter of the catheter may be 0.006" or approximately 0.006", for example. In such an embodiment, the reference diameter may be 0.014", and the catheter outer diameter may be 0.020".

While various embodiments of devices and systems for obtaining fractional flow reserve in the presence of a catheter and methods of using the same have been described in considerable detail herein, the embodiments are merely offered as non-limiting examples of the disclosure described herein. It will therefore be understood that various changes and modifications may be made, and equivalents may be substituted for elements thereof, without departing from the scope of the present disclosure. The present disclosure is not intended to be exhaustive or limiting with respect to the content thereof.

Further, in describing representative embodiments, the present disclosure may have presented a method and/or a process as a particular sequence of steps. However, to the extent that the method or process does not rely on the particular order of steps set forth therein, the method or process should not be limited to the particular sequence of steps described, as other sequences of steps may be possible. Therefore, the particular order of the steps disclosed herein should not be construed as limitations of the present disclosure. In addition, disclosure directed to a method and/or process should not be limited to the performance of their steps in the order written. Such sequences may be varied and still remain within the scope of the present disclosure.

The invention claimed is:

1. A method of determining severity of a stenosis within a luminal organ in the presence of a catheter, comprising the steps of:

obtaining a measurement of a pressure gradient change within the luminal organ at the stenosis using a catheter having a known size;

obtaining luminal organ size measurements determined based upon conductance measurements obtained prior to, at, and distal to the stenosis using an impedance wire; and

determining the severity of the stenosis based upon the measurement of the pressure gradient change, the luminal organ size measurements, and a size difference between the catheter and the impedance wire.

2. The method of claim **1**, wherein the catheter has an outer diameter greater than 0.014".

3. The method of claim **1**, wherein the pressure gradient change is measured using the catheter selected from the group consisting of a pressure catheter and the catheter having a pressure sensor.

4. The method of claim **1**, wherein the conductance measurements are obtained using the impedance wire at least partially positioned within a lumen of the catheter.

5. The method of claim **1**, wherein the severity of the stenosis is based upon a flow reserve calculation.

6. The method of claim **1**, wherein the severity of the stenosis is further determined using a mean aortic pressure within the luminal organ.

7. The method of claim **6**, wherein the mean aortic pressure is measured using the catheter selected from the group consisting of a pressure catheter and the catheter having a pressure sensor.

8. The method of claim **6**, wherein the mean aortic pressure is measured using the catheter.

9. The method of claim **1**, wherein the severity of the stenosis is further determined using a calculated volumetric flow of fluid through the luminal organ at the stenosis.

10. A method of determining severity of a stenosis within a luminal organ in the presence of a catheter, comprising the steps of:

obtaining a measurement of a pressure gradient change within the luminal organ at the stenosis using a catheter having a known size;

obtaining luminal organ size measurements determined based upon conductance measurements obtained using an impedance wire positioned at least partially within a lumen of the catheter and

determining the severity of the stenosis based upon the measurement of the pressure gradient change, the luminal organ size measurements, and a size difference between the catheter and the impedance wire.

11. The method of claim **10**, wherein the luminal organ size measurements comprise a luminal organ size measurement proximal to the stenosis and a luminal organ size measurement distal to the stenosis.

12. The method of claim **10**, wherein the severity of the stenosis is further determined using an identified length of the stenosis.

13. The method of claim **10**, wherein the pressure gradient change is measured using the catheter selected from the group consisting of a pressure catheter and the catheter having a pressure sensor.

14. The method of claim **10**, wherein the catheter has an outer diameter greater than 0.014".

15. The method of claim **10**, wherein the severity of the stenosis is further determined using a flow reserve calculation.

16. A system for determining severity of a stenosis within a luminal organ in the presence of a catheter, comprising:

an impedance wire configured to obtain conductance measurements;

a catheter having at least one pressure sensor, the catheter configured to fit around the impedance wire and further configured to measure a pressure gradient change at the stenosis within the luminal organ; and

a processor configured to determine the severity of the stenosis using luminal organ size measurements calculated based upon the conductance measurements obtained using the impedance wire when positioned at least partially within a lumen of the catheter and a calculated flow reserve at or near the stenosis based upon the pressure gradient change, the calculated luminal organ size measurements, and a size difference between the catheter and the impedance wire.

17. The system of claim **16**, wherein the catheter has an outer diameter greater than 0.014".

18. The system of claim **16**, wherein the catheter further comprises two outer excitation electrodes and two inner detection electrodes, wherein the two outer excitation electrodes are operable to generate an electric field within the luminal organ that can be detected by the detection electrodes.

19. The system of claim **16**, wherein the impedance wire comprises a detector configured to generate an electric field within the luminal organ and detect the electric field to obtain the conductance measurements.

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