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Inventor(s)	Sturm; Bernhard

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### **Computed tomography-based pathway for co-registration of intravascular data and blood vessel metrics with computed tomography-based three-dimensional model**

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#### **Abstract**

A co-registration system includes a processor circuit that receives x-ray fluoroscopy images of a blood vessel while an intravascular catheter moves through the blood vessel. The processor circuit also receives intravascular data from the intravascular catheter as the catheter moves through the blood vessel. The processor circuit generates a 2D pathway based on the fluoroscopy images. The processor circuit generates an additional 2D pathway from a 3D CT model. The processor circuit performs a co-registration between the intravascular data and the CT-based 2D pathway based on a mapping between corresponding locations of the fluoroscopy-based 2D pathway and the CT-based 2D pathway. The processor circuit performs an additional co-registration between the intravascular data and the 3D CT model based on the first co-registration and outputs the 3D model with a graphical representation of the intravascular data to a display.

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## Background/Summary

### TECHNICAL FIELD

(1) The present disclosure relates generally to co-registering data from different medical diagnostic modalities. In particular, intravascular data and blood vessel metrics from angiography images may be co-registered to a three-dimensional computed tomography-based model by co-registering the intravascular data with a computed tomography-based two-dimensional pathway and projecting the intravascular data to the three-dimensional computed tomography-based model.

### BACKGROUND

(2) Physicians use many different medical diagnostic systems and tools to monitor a patient's health and diagnose and treat medical conditions. Different modalities of medical diagnostic systems may provide a physician with different images, models, and/or data relating to internal structures within a patient. These modalities include invasive devices and systems, such as intravascular systems, and non-invasive devices and systems, such as x-ray systems, and computed tomography (CT) systems. Using multiple diagnostic systems to examine a patient's anatomy provides a physician with added insight into the condition of the patient.

(3) In the field of intravascular imaging and physiology measurement, co-registration of data from invasive devices (e.g. intravascular ultrasound (IVUS) devices or instantaneous wave-free ratio (iFR) devices) with images collected non-invasively (e.g. via x-ray angiography) is a powerful technique for improving the efficiency and accuracy of vascular catheterization procedures. Co-registration identifies the locations of intravascular data measurements along a blood vessel by mapping the data to an angiography image of the vessel. A physician may then know exactly where in the vessel a measurement was made, rather than estimate the location.

(4) Currently, no method of co-registering intravascular data with a three-dimensional CT model is commercially available. There is also currently no method of co-registering data from an x-ray angiography image (e.g. QCA) with a three-dimensional CT model. If a physician obtains intravascular data or x-ray angiography data of a patient's anatomy as well as a three-dimensional CT model, the physician must estimate the locations of intravascular and angiography data within the CT model which may lead to decreased accuracy in treatment recommendations or procedures.

### SUMMARY

(5) Embodiments of the present disclosure are systems, devices, and methods for co-registering intravascular data and angiography data such as blood vessel metrics to a three-dimensional CT-based model. This advantageously provides guidance to the physician concerning locations of features of interest, such as occlusions, within a blood vessel. It also provides exact locations of measurements, such as vessel or lumen diameter, pressure ratio, and blood flow, in a three-dimensional CT-based model giving the physician more accurate and more detailed views of a patient's anatomy. A system configured to perform the co-registration may include an intravascular

device, an x-ray imaging device, and a CT device, all in communication with a co-registration system.

(6) In one aspect, the co-registration system receives x-ray fluoroscopy images of a patient vasculature at a given angle while an intravascular device moves through the vasculature collecting data. The intravascular data is mapped to the fluoroscopy images associating the intravascular data with locations along a two-dimensional pathway. The system also receives CT imaging data of the same vasculature which is used to construct a three-dimensional model. The three-dimensional CT-based model is used to create multiple CT-based two-dimensional pathways at different angles. The multiple CT-based pathways are compared to the fluoroscopy-based pathway. The system identifies the CT-based pathway that is most similar to the fluoroscopy-based pathway. The locations along the fluoroscopy-based pathway are mapped to the same locations along the selected CT-based pathway and the intravascular data is associated with corresponding locations of the CT-based pathway. The two-dimensional CT-based pathway and its associated intravascular data is then projected back to the three-dimensional CT-based model. The intravascular data may then be displayed at the correct locations within the three-dimensional CT-based model.

(7) In another aspect, the system may receive an angiography image at any angle and calculate angiography-based data using the image (e.g. QCA data). The angiography-based data may similarly be mapped to corresponding locations along a CT-based two-dimensional pathway created by projecting the three-dimensional CT-based model to a two-dimensional plane. The CT-based two-dimensional pathway and its associated angiography-based data may then be projected back to the three-dimensional CT-based model and displayed at the correct locations within the three-dimensional CT-based model.

(8) In an exemplary aspect of the present disclosure, a co-registration system is provided. The co-registration comprises a processor circuit configured for communication with a display, an x-ray fluoroscopy device, and an intravascular catheter or guidewire, wherein the processor circuit is configured to: receive, from the x-ray fluoroscopy device, a plurality of x-ray fluoroscopy images of the blood vessel while the intravascular catheter or guidewire moves through the blood vessel; receive, from the intravascular catheter or guidewire, intravascular data representative of the blood vessel while the intravascular catheter or guidewire moves through the blood vessel; generate, using the plurality of x-ray fluoroscopy images, a first two-dimensional (2D) pathway of the blood vessel based on the intravascular catheter or guidewire moving through the blood vessel; generate a second 2D pathway of the blood vessel using a three-dimensional (3D) model of the blood vessel based on computed tomography (CT) imaging data; perform a first co-registration between the intravascular data and the second 2D pathway based on a mapping between corresponding locations of the first 2D pathway and the second 2D pathway; perform a second co-registration between the intravascular data and the 3D model based on the first co-registration; and output, to the display, the 3D model and a graphical representation of the intravascular data at a co-registered location of the 3D model.

(9) In some aspects, the processor circuit is configured to: determine if the first 2D pathway and the second 2D pathway are comparable; and perform the first co-registration only in response to determining that the first 2D pathway and the second 2D pathway are comparable. In some aspects, the processor circuit is configured to: compute a similarity measure representative of if the first 2D pathway and the second 2D pathway are comparable; determine that the first 2D pathway and the second 2D pathway are comparable when the similarity measure satisfies a threshold. In some aspects, the processor circuit is configured to: generate a plurality of 2D pathways of the blood vessel using the 3D model of the blood vessel based on CT imaging data; and select a given 2D pathway of the plurality of 2D pathways as the second 2D pathway when the given 2D pathway and the first 2D pathway are comparable. In some aspects, the plurality of 2D pathways correspond to a plurality of angles for projecting the 3D model to a 2D plane. In some aspects, the processor circuit is configured to use an angle at which the plurality of x-ray fluoroscopy images were

obtained to generate the second 2D pathway. In some aspects, the processor circuit is configured to compute a first projection of the 3D model to a 2D plane to generate the second 2D pathway. In some aspects, the processor circuit is configured to compute a second projection from the second 2D pathway to the 3D model to perform the second co-registration, wherein second projection is an inverse of the first projection. In some aspects, the intravascular data comprises at least one of pressure data, flow data, or imaging data. In some aspects, the co-registration system comprises the intravascular catheter or guidewire. In some aspects, the first 2D pathway and the second 2D pathway are representative of a same portion of the blood vessel.

(10) In an exemplary aspect of the present disclosure, a co-registration system is provided. The co-registration system comprises a processor circuit configured for communication with a display and an x-ray angiography device, wherein the processor circuit is configured to: receive, from the x-ray angiography device, an x-ray angiography image of the blood vessel while the intravascular catheter or guidewire moves through the blood vessel; determine a metric representative of the blood vessel based on the x-ray angiography image; determine, using the x-ray angiography image, a first two-dimensional (2D) pathway of the blood vessel; generate a second 2D pathway of the blood vessel using a three-dimensional (3D) model of the blood vessel based on computed tomography (CT) imaging data; perform a first co-registration between the metric and the second 2D pathway based on a mapping between corresponding locations of the first 2D pathway and the second 2D pathway; perform a second co-registration between the metric and the 3D model based on the first co-registration; and output, to the display, the 3D model and a graphical representation of the metric at a co-registered location of the 3D model.

(11) In some aspects, the processor circuit is configured to: determine if the first 2D pathway and the second 2D pathway are comparable; and perform the first co-registration only in response to determining that the first 2D pathway and the second 2D pathway are comparable. In some aspects, the processor circuit is configured to: compute a similarity measure representative of if the first 2D pathway and the second 2D pathway are comparable; determine that the first 2D pathway and the second 2D pathway are comparable when the similarity measure satisfies a threshold. In some aspects, the processor circuit is configured to: generate a plurality of 2D pathways of the blood vessel using the 3D model of the blood vessel based on CT imaging data; and select a given 2D pathway of the plurality of 2D pathways as the second 2D pathway when the given 2D pathway and the first 2D pathway are comparable. In some aspects, the plurality of 2D pathways correspond to a plurality of angles for projecting the 3D model to a 2D plane. In some aspects, the processor circuit is configured to use an angle at which the plurality of x-ray fluoroscopy images were obtained to generate the second 2D pathway. In some aspects, the processor circuit is configured to compute a first projection of the 3D model to a 2D plane to generate the second 2D pathway. In some aspects, the processor circuit is configured to compute a second projection from the second 2D pathway to the 3D model to perform the second co-registration, wherein second projection is an inverse of the first projection. In some aspects, the co-registration system comprises the x-ray angiography device. In some aspects, the first 2D pathway and the second 2D pathway are representative of a same portion of the blood vessel.

(12) Additional aspects, features, and advantages of the present disclosure will become apparent from the following detailed description.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) Illustrative embodiments of the present disclosure will be described with reference to the accompanying drawings, of which:

(2) FIG. 1 is a schematic diagram of a medical diagnostic system, according to aspects of the

present disclosure.

(3) FIG. 2 is a diagrammatic view of an intravascular device, according to aspects of the present disclosure.

(4) FIG. 3 is a diagrammatic view of an x-ray imaging device, according to aspects of the present disclosure.

(5) FIG. 4 is a diagrammatic view of a computed tomography (CT) imaging device, according to aspects of the present disclosure.

(6) FIG. 5 is a schematic diagram of a processor circuit, according to aspects of the present disclosure.

(7) FIG. 6 is a flow diagram of a method of co-registering intravascular data with a CT-based 3D model, according to aspects of the present disclosure.

(8) FIG. 7 is a flow diagram of a method of co-registering intravascular data with a CT-based 3D model, according to aspects of the present disclosure.

(9) FIG. 8 is a diagrammatic view of a coronary CT-based 3D model, according to aspects of the present disclosure.

(10) FIG. 9 is a diagrammatic view of a CT-based 3D model used to generate a CT-based 2D pathway, according to aspects of the disclosure.

(11) FIG. 10 is a diagrammatic view of a relationship between x-ray fluoroscopy images, intravascular data, a fluoroscopy-based 2D pathway defined by the motion of an intravascular device, a CT-based 2D pathway, and a CT-based 3D model, according to aspects of the present disclosure.

(12) FIG. 11 is a diagrammatic view of the fluoroscopy-based 2D pathway overlaid on a CT-based 2D pathway, according to aspects of the present disclosure.

(13) FIG. 12 is a diagrammatic view of the fluoroscopy-based 2D pathway overlaid on a CT-based 2D pathway, according to aspects of the present disclosure.

(14) FIG. 13 is a diagrammatic view of a graphical user interface displaying intravascular data co-registered to a CT-based 3D model, according to aspects of the present disclosure.

(15) FIG. 14 is a diagrammatic view of a graphical user interface displaying intravascular data co-registered to a CT-based 3D model, according to aspects of the present disclosure.

(16) FIG. 15 is a flow diagram of a method of co-registering angiography-based data with a CT-based 3D model, according to aspects of the present disclosure.

(17) FIG. 16 is a flow diagram of a method of co-registering angiography-based data with a CT-based 3D model, according to aspects of the present disclosure.

(18) FIG. 17 is a diagrammatic view of an x-ray angiography image and an enlarged view of the x-ray angiography image with angiography-based data, according to aspects of the present disclosure.

(19) FIG. 18 is a diagrammatic view of a relationship between an x-ray angiography image, angiography-based data, a CT-based 2D pathway, and a CT-based 3D model, according to aspects of the present disclosure.

(20) FIG. 19 is a diagrammatic view of a graphical user interface displaying angiography-based data co-registered to a CT-based 3D model, according to aspects of the present disclosure.

(21) FIG. 20 is a diagrammatic view of a graphical user interface displaying angiography-based data co-registered to a CT-based 3D model, according to aspects of the present disclosure.

#### DETAILED DESCRIPTION

(22) 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 is nevertheless understood that no limitation to the scope of the disclosure is intended. Any alterations and further modifications to the described devices, systems, and methods, and any further application of the principles of the present disclosure are fully contemplated and included within the present disclosure as would normally occur to one skilled in the art to which the disclosure relates. In particular, it is fully contemplated that the features,

components, and/or steps described with respect to one embodiment may be combined with the features, components, and/or steps described with respect to other embodiments of the present disclosure. For the sake of brevity, however, the numerous iterations of these combinations will not be described separately.

(23) FIG. 1 is a schematic diagram of a medical diagnostic system **100**, according to aspects of the present disclosure. The diagnostic system **100** may include an intravascular device **146** in communication with an intravascular data processing system **144**, an x-ray angiography imaging device **156** in communication with an x-ray angiography processing system **154**, an x-ray fluoroscopy imaging device **166** in communication with an x-ray fluoroscopy processing system **164**, and a computed tomography (CT) imaging device **176** in communication with a CT processing system **174**. In addition, the diagnostic system **100** may include a co-registration processing system **134** in communication with the intravascular data processing system **144**, the x-ray angiography processing system **154**, the x-ray fluoroscopy processing system **164**, and the CT processing system **174**. The co-registration processing system **134** may additionally be in communication with a display **132** as well as any other suitable components, processors, systems, or devices. The diagnostic system **100** may be used for many different medical procedures, such as but not limited to diagnostic procedures, planning treatment, guiding treatment (e.g., during deployment of a treatment device), and evaluating the efficacy of treatment after it has been performed.

(24) The co-registration processing system **134** shown in FIG. 1 may include any suitable hardware components, software components, or combinations of hardware and software components. For example, the processing system **134** may include any suitable circuitry, communication interfaces, processors, or processor circuits, among other components. In some embodiments, the processing system **134** may include one or more processor circuits substantially similar to the processor circuit **510** described with reference to FIG. 5. Any of the systems **144**, **154**, **164**, and/or **174** may also include one or more processor circuits substantially similar to the processor circuit **510** described with reference to FIG. 5. Any of the systems **144**, **154**, **164**, and/or **174** may also include similar features, components, hardware components, software components, or combinations thereof as that of the co-registration processing system **134** described.

(25) The intravascular data processing system **144** may be configured to receive intravascular data collected with the intravascular device **146**. The intravascular data processing system **144** may receive intravascular data via a connecting cable and/or a communication interface as will be discussed in more detail with reference to FIG. 2. In some embodiments, the processing system **144** may process the received intravascular data to reconstruct an image of the tissue structures in the medium surrounding the intravascular device **146**. In other embodiments, the system **144** may process received intravascular data to calculate metrics relating to the medium surrounding the device **146** such as but not limited to the diameter of a body lumen, fluid pressure or flow within a body lumen, or other physiological data or metrics. The system **144** may also perform any other suitable calculations or measurements depending on the type of device **146** and the type of data received. The intravascular data processing system **144** may be in communication with the display **132** or another display. The intravascular data processing system **144** may display images, graphical representations, metrics, or other data relating to the body lumen imaged or measured via this display.

(26) The x-ray angiography processing system **154** may be configured to receive angiography data collected with the x-ray angiography imaging device **156**. The x-ray angiography processing system **154** may receive x-ray angiography data via a connecting cable and/or a communication interface. The angiography data can be used to generate angiographic images frames depicting the patient's anatomy. The angiography data obtained with the x-ray angiography imaging device **156** may correspond to an anatomy with a contrast agent introduced. The contrast agent may be used to enhance the visibility of internal fluids or structures within a patient's anatomy. In some

embodiments, the contrast agent absorbs external x-rays from an x-ray source, resulting in decreased exposure on an x-ray detector in conjunction with the x-ray source. The contrast agent may be of any suitable material, chemical, or compound and may be a liquid, powder, paste, tablet, or of any other suitable form. For example, the contrast agent may include iodine-based compounds, barium sulfate compounds, gadolinium-based compounds, or any other suitable compounds. The contrast agent may additionally be referred to as a radiocontrast agent, a contrast dye, a radiocontrast dye, a contrast material, a radiocontrast material, a contrast media, or a radiocontrast media, among other terms.

(27) In some embodiments, the processing system **154** may process the received angiography data to reconstruct an image of the patient anatomy and/or calculate metrics relating to the anatomy based on the angiography data. In some applications, the x-ray angiography processing system **154** may determine metrics associated with the patient anatomy using various image processing techniques or machine learning techniques as will be discussed in more detail hereafter with reference to FIG. **16**. The x-ray angiography processing system **154** may be in communication with the display **132** or another display. The x-ray angiography processing system **154** may display images, graphical representations, metrics, or data to a user of the imaging system **100** via this display.

(28) The x-ray fluoroscopy processing system **164** may be configured to receive fluoroscopy data collected with the x-ray fluoroscopy imaging device **166**. In some embodiments, the x-ray fluoroscopy processing system **164** may be the same system as the x-ray angiography system **154** and the x-ray fluoroscopy imaging device **166** may be the same device as the x-ray angiography imaging device **156**. However, the fluoroscopy imaging device **166** may obtain x-ray images of an anatomy without a contrast agent introduced to a patient's vasculature. In other embodiments, the x-ray fluoroscopy processing system **164** and the x-ray angiography processing system **154** are separate systems and the x-ray fluoroscopy imaging device **166** and the x-ray angiography imaging device **156** are separate devices. In either embodiment, the x-ray fluoroscopy processing system **164** may include any or all of the same features or characteristics of the x-ray angiography processing system **154** and the x-ray fluoroscopy imaging device **166** may include any or all of the same features or characteristics of the x-ray angiography imaging device **156**. The fluoroscopy data can be used to generate fluoroscopic images frame depicting the patient's anatomy. In some instances, the fluoroscopic image frames can collectively form a video sequence of x-ray images.

(29) The CT processing system **174** may be configured to receive CT data collected with the CT imaging device **176**. The CT processing system **174** may receive CT data via a connecting cable and/or a communication interface. The CT data obtained with the CT imaging device **176** may correspond to an anatomy with contrast agent introduced or without contrast agent introduced. The contrast agent introduced to a patient's anatomy during a CT imaging procedure may be substantially similar to the contrast agent previously described in relation to the x-ray angiography imaging device **156** and processing system **154**. In some embodiments, the processing system **174** may process the received CT data to reconstruct an image of the patient's anatomy or may reconstruct a three-dimensional model of the anatomy. In some applications, the CT processing system **174** may additionally determine metrics associated with the patient's anatomy using various image processing techniques or machine learning techniques. The CT processing system **174** may be in communication with the display **132** or another display. The CT processing system **174** may display images, 3D models, graphical representations, metrics, or data to a user via this display.

(30) In some embodiments, the systems **134**, **144**, **154**, **164**, and/or **174** may each be a part of a combined system **100**. For example, in some embodiments, the processing systems **134**, **144**, **154**, **164**, and/or **174** may all be positioned within the same enclosure or housing. In addition, the processing systems **134**, **144**, **154**, **164**, and/or **174** may share one or more software or hardware components. In other embodiments, the processing systems **134**, **144**, **154**, **164**, and/or **174** may be separate systems but may be in communication with one another. The processing systems may be



in continuous communication with one another or may be in intermittent communication with one another. The processing systems may be in communication with one another or with the devices **145, 156, 166, 176**, and/or the display **132** via one or more wired connecting cables including any suitable conductors, such as single conductors, twisted pairs, universal serial bus (USB) cables, or any other suitable connecting cables. The processing systems **134, 144, 154, 164**, and/or **174** may additionally or alternatively be in communication or with the devices **145, 156, 166, 176**, and/or the display **132** via a wireless connection, an optical connection, or may be in connection via any suitable type of movable memory or storage media, or via any other suitable means of communication. In some embodiments, the co-registration processing system **134** may receive data, including raw data and/or processed data, images, models, graphical representations, metrics, or any other information from any of the processing systems **144, 154, 164**, and/or **174**. The co-registration processing system **134** may receive such data from the other processing systems **144, 154, 164**, and/or **174** simultaneously or separately. Any and/or all of the processing systems **134, 144, 154, 164**, and/or **174** may include or be a part of any suitable system or device such as, but not limited to, a mobile console, a desktop computer, laptop computer, tablet, smartphone, or any other suitable computing device.

(31) It is understood that aspects of the present disclosure may include any combination of extraluminal or extravascular imaging modalities such with x-ray angiography, x-ray fluoroscopy, computed tomography (CT), magnetic resonance imaging (MM), ultrasound, etc. For example, the CT processing system **174** and the CT imaging device **176** may be an Mill processing system and MM imaging device, or an ultrasound processing system and an ultrasound imaging device. In that regard, extraluminal or extravascular imaging be any suitable modality or modalities that can be used to generate 3D paths of anatomy (e.g., coronary vasculature).

(32) FIG. 2 is a diagrammatic view of an intravascular device **146**, according to aspects of the present disclosure. The intravascular device **146** may be any type of invasive intravascular device used to acquire data from within the body of a patient. For example, the intravascular device **146** could be a catheter, a guide wire, or a guide catheter. In general, the device **146** can be an intraluminal device that obtains data from within any suitable lumen, chamber, or anatomy within the patient's body. An intraluminal device can also be referred to as an intra-body probe or an endo-cavity probe. The device **146** can be a sensing device that obtains information about the patient's body while positioned inside the patient's body. In some instances, the device **146** is an imaging device, such as an intravascular ultrasound (IVUS) device, including a rotational IVUS device or a solid-state IVUS device, an optical coherence tomography (OCT) device, an intravascular photoacoustic (IVPA) device, an intracardiac echocardiography device, or a transesophageal echocardiography (TEE) device. In some instances, the device **146** is a physiological-sensing device, such as a pressure-sensing device, a flow-sensing device, or a temperature-sensing device. The device **146** may include a flexible elongate member **221**, a sensor assembly **210**, a sensor **224**, a transmission line bundle or cable **212**, and a patient interface module (PIM) connector **214**, among other components.

(33) At a high level, the intravascular device **146** may acquire data relating to the region of anatomy surrounding the intravascular device **146**. In that regard, the device **146** can be sized, shaped, or otherwise configured to be positioned within the body lumen **220** of a patient. In some embodiments, the system **100** may include a patient interface module (PIM) communicatively disposed between the intravascular device **146** and the intravascular data processing system **144** that receives and transfers the data obtained by the sensor **224** to the intravascular data processing system **144**. The intravascular data processing system **144** can execute computer readable instructions stored on a non-transitory tangible computer readable medium.

(34) The flexible elongate member **221** may be sized and shaped, structurally arranged, and/or otherwise configured to be positioned within a body lumen **220** of a patient. The flexible elongate member **221** may be a part of guidewire and/or a catheter (e.g. an inner member and/or an outer

member). The flexible elongate member **221** may be constructed of any suitable flexible material. For example, the flexible elongate member **221** may be constructed of a polymer material including polyethylene, polypropylene, polystyrene, or other suitable materials that offer flexibility, resistance to corrosion, and lack of conductivity. In some embodiments, the flexible elongate member **221** may define a lumen for other components to pass through. The flexible elongate member **221** may be sufficiently flexible to successfully maneuver various turns or geometries within the vasculature of a patient. The flexible elongate member **221** may be of any suitable length or shape and may have any suitable characteristics or properties.

(35) The sensor assembly **210** may be coupled to the flexible elongate member **221** and positioned at a distal portion or a distal end of the flexible elongate member **221**. The sensor assembly **210** may house various circuitry, sensors, transducers, or any other suitable components used to acquire intravascular data. For example, the sensor assembly may include a support member, unibody, sensor housing, sensor mount, pressure sensor, flow sensor, temperature sensor, transducer array, control logic dies, various circuits, flexible substrates, various adhesives, or backing material, among other components. The sensor assembly **210** may provide structural support to components within the intravascular imaging device **146**. The sensor assembly **210** may be constructed of any suitable material, including flexible or inflexible materials. The sensor assembly **210** may be of any suitable shape, including a tubular or circular shape, as well as any other geometric or non-geometric shape.

(36) The sensor assembly **210** can acquire data relating to the lumen in which the device **146** is positioned. The sensor assembly **210** may acquire this data via any suitable number or type of sensors or other measurement tools. The data obtained by the intravascular device **146** and/or the sensor **224** data may be of any suitable form. In some embodiments, the sensor **224** is an ultrasound transducer or ultrasound transducer array. The sensor **224** can include one or more ultrasound transducer elements that emit ultrasonic energy and receive echoes that can be used to generate an ultrasound image (e.g., an IVUS image). In another embodiment, the sensor **224** is a pressure sensor that acquires pressure data at one or more locations along the body lumen of the patient as the device **146** moves through the body lumen. Pressure data can be used by the processing system **144** to calculate fractional flow reserve (FFR), instantaneous wave-free ratio (iFR), Pd/Pa, and/or any other suitable pressure ratio. In another embodiment, the sensor **224** is a flow sensor that obtains data related to velocity and/or volume of blood flow within a blood vessel. Flow data can be used by the processing system **144** to calculate coronary flow reserve (CFR), and/or any other suitable flow metric. For example, the flow sensor **224** can be a Doppler ultrasound transducer element. In another embodiment, the sensor **224** is a temperature sensor that obtains temperature data within the body lumen. In other embodiments, the sensor **224** may acquire OCT imaging data, IVPA imaging data, or any other suitable data.

(37) The sensor **224** shown in FIG. 2 may be any suitable type of sensor depending on the specific application or type of intravascular device **146** including any of the components for intravascular data acquisition previously listed. In addition, the sensor **224** may represent more than one sensor. For example, in some embodiments, the sensor **224** may include multiple sensor devices including 2, 4, 6, 8, 16, 32, 64, 128, or more sensors, or any suitable number therebetween. In some embodiments, the sensor **224** may include a transducer array. The sensor **224** may additionally be a single rotating transducer. In some embodiments, the sensor **224** may be one or more pressure sensors and one or more flow sensors. The sensor **224**, although positioned at a distal region of the sensor assembly **210** and the flexible elongate member **221**, may be positioned at any suitable location on or within the sensor assembly **210** or the flexible elongate member **221**.

(38) The flexible elongate member **221** and/or the cable **212** include one, two, three, four, five, six, seven, or more conductors, optical fibers, or other signal communication lines. The signal communication lines are communicatively coupled to the connector **214** and the sensor **224**. The signal communication lines carry electrical signals, optical signals, and/or any suitable type of

signal from the sensor **224** to the processing system **144** (e.g., data obtained by the sensor **224**) and/or from the processing system **114** to the sensor **224** (e.g., command/control signals). The cable **212** may facilitate communication between the intravascular device **146** and the intravascular data processing system **144** or any other control system or host system.

(39) The cable **212** may be coupled to the patient interface module (PIM) connector **214** at a proximal portion or proximal end of the intravascular device **146**. The PIM connector **214** may communicatively couple the signal communication lines to the PIM or other interface in communication with the intravascular data processing system **144**. The PIM connector **214** may also physically couple the intravascular device **146** to the PIM.

(40) In some embodiments, the intravascular device **146** and/or the PIM may perform preliminary processing of the intravascular data prior to relaying the data to the processing system. In examples of such embodiments, the intravascular device **146** and/or the PIM may perform amplification, filtering, and/or aggregating of the data. In an embodiment, the intravascular data processing system **144** may also supply high- and low-voltage DC power to support operation of the device **146** and/or the PIM including circuitry within the device.

(41) FIG. **3** is a diagrammatic view of an x-ray imaging device **300**, according to aspects of the present disclosure. The x-ray imaging device **300** may be the x-ray angiography imaging device **156** (FIG. **1**) or may be the x-ray fluoroscopy imaging device **166** (FIG. **1**) or may be a different device. In some embodiments, the x-ray imaging device **300** shown in FIG. **3**, the x-ray angiography imaging device **156**, and the x-ray fluoroscopy imaging device **166** may be the same device. The x-ray imaging device **300** may be of any suitable type, for example, it may be a stationary x-ray system such as a fixed c-arm x-ray device, a straight arm x-ray device, or a w-arm device. The x-ray imaging device **300** may additionally be any suitable mobile device such as a mobile c-arm x-ray device. The x-ray imaging device **300** may also be in communication with the x-ray angiography imaging processing system **154** and/or the x-ray fluoroscopy processing system **164**. In some embodiments, the x-ray device **300** may include a digital radiography device or any other suitable device.

(42) The x-ray imaging device **300** as shown in FIG. **3** includes an x-ray source **360**, a detector **370** including an x-ray input screen **374**. The x-ray source **360** and the input screen **374** may be mounted at a mutual distance and mounted on a movable arm **352**. Positioned between the x-ray source **360** and the x-ray detector **370** may be an anatomy of a patient or object **380**. The x-ray imaging device **300** may be used to image any suitable location or region of a patient's anatomy, including tissues, organs, malignancies, or any other structures or features. For example, the x-ray imaging device **300** may image without limitation the liver, heart, kidneys, gall bladder, pancreas, lungs; ducts; intestines; nervous system structures including the brain, dural sac, spinal cord and peripheral nerves; the urinary tract; as well as valves within the blood vessels, blood, chambers or other parts of the heart, abdominal organs, and/or other systems of the body. The imaging device **300** may additionally image tumors, cysts, lesions, hemorrhages, or blood pools, muscle, blood, blood plasma, interstitial fluid, lymph plasma, cerebrospinal fluid, intraocular fluid, serous fluid, synovial fluid, digestive fluid, urinary fluid, amniotic fluid, or any other type of suitable fluid, or any other region, structure, fluid, or gas within a patient anatomy.

(43) The x-ray source **360** may include an x-ray tube adapted to generate x-rays. Some aspects of the x-ray source **360** may include one or more vacuum tubes including a cathode in connection with the negative lead of a high-voltage power source and an anode in connection with the positive lead of the same power source. The cathode of the x-ray source **360** may additionally include a filament. The filament may be of any suitable type or constructed of any suitable material, including tungsten or rhenium tungsten, and may be positioned within a recessed region of the cathode. One function of the cathode may be to expel electrons from the high voltage power source and focus them into a well-defined beam aimed at the anode. The anode may also be constructed of any suitable material and may be configured to create x-radiation from the emitted electrons of the

cathode. In addition, the anode may dissipate heat created in the process of generating x-radiation. The anode may be shaped as a beveled disk and, in some embodiments, may be rotated via an electric motor. The cathode and anode of the x-ray source **360** may be housed in an airtight enclosure, sometimes referred to as an envelope.

(44) In some embodiments, the x-ray source **360** may include a radiation object focus which influences the visibility of an image. The radiation object focus may be selected by a user of the system **100** or by a manufacturer of the system **100** based on characteristics such as blurring, visibility, heat-dissipating capacity, or other characteristics. In some embodiments, an operator or user of the system **100** may switch between different provided radiation object foci in a point-of-care setting.

(45) The detector **370** may be configured to acquire x-ray images and may include the input screen **374**. The input screen **374** may include one or more intensifying screens configured to absorb x-ray energy and convert the energy to light. The light may in turn expose a film. The input screen **374** may be used to convert x-ray energy to light in embodiments in which the film may be more sensitive to light than x-radiation. Different types of intensifying screens within the image intensifier may be selected depending on the region of a patient to be imaged, requirements for image detail and/or patient exposure, or any other factors. Intensifying screens may be constructed of any suitable materials, including barium lead sulfate, barium strontium sulfate, barium fluorochloride, yttrium oxysulfide, or any other suitable material. The input screen **374** may be a fluorescent screen or a film positioned directly adjacent to a fluorescent screen. In some embodiments, the input screen **374** may also include a protective screen to shield circuitry or components within the detector **370** from the surrounding environment. The x-ray detector **370** may additionally be referred to as an x-ray sensor.

(46) The object **380** may be any suitable object to be imaged. In an exemplary embodiment, the object **380** may be the anatomy of a patient including any region of a patient's anatomy previously mentioned. More specifically, the anatomy to be imaged may include the coronary region. In some embodiments, the object **380** may include man-made structures.

(47) In some embodiments, the x-ray source **360** and x-ray detector **370** are mounted to the movable arm **352**. In this configuration, the x-ray source **360** and the x-ray detector **370** may be rotated around the object **380** or patient anatomy to acquire images of the object **380** or patient anatomy at different angles. The movable arm **352** may move the x-ray source **360** and detector **370** to any suitable location around the object **380** or patient anatomy. In some embodiments, the movable arm **352** may receive commands from the system **154** or **164** based on a user input to move the x-ray source **360** and detector **370** to a desired position or angle **390** with respect to the object **380** or patient anatomy to be imaged. The arm **352** may be of any suitable type or shape in addition to the one shown in FIG. 3 and may additionally be referred to as a gantry. In some embodiments, the x-ray imaging device **300** may include more than one set of x-ray sources **360** and detectors **370**. For example, the x-ray imaging device **300** may be a bi-plane x-ray imaging system. In embodiments in which the x-ray imaging device **300** includes multiple sets of x-ray sources **360** and corresponding x-ray detectors **370**, a physician may image the same regions of a patient's anatomy from multiple angles simultaneously or may image different regions of the patient's anatomy simultaneously.

(48) As previously mentioned, the x-ray imaging device **300** may be configured to acquire angiography images. In such embodiments, a contrast agent may be introduced to a patient's anatomy before imaging. The contrast agent may be used to enhance the visibility of internal structures within a patient's anatomy. The contrast agent may absorb external x-rays, resulting in decreased exposure on the x-ray detector **370**. The contrast agent may be of any suitable type previously listed. In other embodiments, in which fluoroscopy images are to be obtained, a contrast agent may not be introduced to the patient anatomy prior to imaging.

(49) When an x-ray processing system, such as the x-ray angiography processing system **154** or the

x-ray fluoroscopy processing system **164** of FIG. **1**, is in communication with the x-ray imaging device **300**, various data may be transmitted. This communication includes x-ray imaging data as well as control commands to the x-ray source **360** and/or x-ray detector **370** of the x-ray device **300**. In some embodiments, the x-ray imaging device **300** may perform preliminary processing of the x-ray data prior to relaying the data to the processing system. In examples of such embodiments, the x-ray imaging device **300** may perform amplification, filtering, and/or aggregating of the data. In an embodiment, the x-ray image processing system may also supply high- and low-voltage DC power to support operation of the device **300** including circuitry within the device.

(50) FIG. **4** is a diagrammatic view of a computed tomography (CT) imaging device **176**, according to aspects of the present disclosure. The CT imaging device **176** may include an x-ray source **460**, an x-ray detector **470**, a CT gantry **450**, a rotary drive **454**, a patient support **480**, a drive **484**, a cardiac monitor **486**, and a respiratory monitor **488**, among other components. The CT imaging device **176** may be of any suitable form or type. For example, the CT imaging device **176** may be a spiral CT scanner, a single slice CT scanner, a multi-slice CT scanner, such as a 2, 4, 6, 8, 16, 32, 40, 64, or 128 slice CT scanner or greater slice numbers or a CT scanner of slice numbers therebetween. The CT imaging device **176** may also be a fixed or mobile device. The CT imaging device **176** may additionally have any suitable rotation time, slice width, or any other characteristics or features.

(51) The x-ray source **460** may be substantially similar to the x-ray source **360** of FIG. **3** in that it may be configured to produce and project x-radiation. Specifically, the x-ray source **460** may include an x-ray tube and may include one or more vacuum tubes including a cathode and an anode in connection with a high-voltage power source. The cathode and anode of the x-ray source **460** may be configured to create x-radiation. The cathode and anode of the x-ray source **460** may be housed in an airtight enclosure and mounted to the CT gantry **450**. The x-ray source **460** may also include a radiation object focus similar to the x-ray source **360**.

(52) The x-ray detector **470** may also be substantially similar to the x-ray detector **370** of FIG. **3**. The detector **470** may be configured to acquire x-ray images and may include an input screen similar to the input screen **374** and/or one or more intensifying screens as previously described with reference to FIG. **3**. Components within the x-ray detector **470** are configured to absorb x-ray energy and convert the energy to form an image. The x-ray detector **470** may include a fluorescent screen or a film positioned directly adjacent to a fluorescent screen.

(53) The x-ray source **460** and the x-ray detector **470**, along with various other components, may be mounted to the CT gantry **450** as shown in FIG. **4**. The CT gantry **450** may be configured to rotate around a patient, an object, or the patient support **480** shown. The CT gantry **450** may rotate in a direction shown by arrow **452** or in another direction. As the CT gantry **450** rotates around a central region, the x-ray source **460** may emit x-radiation toward and/or through a patient anatomy. The x-ray detector **470** may be positioned opposed to and equidistant from the x-ray source **460** with relation to the patient anatomy to be imaged and may receive x-radiation emitted by the x-ray source **460**. The CT imaging device **176** may be configured to image any suitable anatomical regions or locations, including any structures or features within a patient anatomy previously mentioned with regards to the x-ray imaging device **300**. Because different structures within a patient anatomy absorb x-radiation differently, differences in absorption may be detected by the x-ray detector **470** and used to reconstruct an image of the anatomy. The x-ray source **460** and/or the x-ray detector **470** may be configured to obtain x-ray data at any suitable sample rate. X-ray data may be obtained from any suitable location or angle around the central region or patient support **480** and used to reconstruct an image of the patient anatomy.

(54) The CT gantry **450** may rotate at any suitable rate. For example, the CT gantry may rotate at a rate of 60, 120, 200, 400 revolutions per minute (rpm) or more, or any suitable rate of rotation therebetween. In embodiments in which a heart is to be imaged, a greater rate of rotation may be

used. The CT gantry **450** may additionally include other components configured to produce, receive, or process x-radiation data or images. For example, the CT gantry **450** may include an inverter, a collimator, a cooling system of any suitable type, additional sensors or detectors, or a multiplier, among other components.

(55) The CT gantry **450** may be coupled to the rotary drive **454**. The rotary drive **454** may be configured to rotate the CT gantry **450** in the manner previously described. The rotary drive **454** may be in communication with the CT processing system **174** (FIG. 1) or another control system of any suitable type. For example, the rotary drive **454** may receive command signals from a control system. An operator of the CT imaging device **176** may select the rate of rotation of the CT gantry **450** and/or the sample rate of the x-ray source **460** and detector **470**.

(56) The patient support **480** may be positioned along a longitudinal axis **482** in relation to the CT gantry **450**. The patient support **480** may be configured to support a patient to be imaged and move along the longitudinal axis or direction **482** so as to move the patient anatomy to be imaged through the CT gantry **450**. The patient support **480** may be configured to move a specified distance corresponding to the region of the patient to be imaged. The drive **484** may be coupled to the patient support **480** and be configured to move the patient support the specified distance through the center of the CT gantry **450**.

(57) In some embodiments, the patient support **480** may include one or more patient monitors configured to monitor metrics or vital signs of the patient anatomy as the patient anatomy is imaged. For example, the cardiac monitor **486** may monitor and track the cardiac cycle of a patient. The cardiac monitor **486** may be of any suitable type, such as an electrocardiography (EKG) lead system, or other type of monitor. In addition, the patient support **480** may include the respiratory monitor **488**. The respiratory monitor **488** may be configured to monitor and track a patient's respiration state. Additional patient monitors may be included within the patient support **480**.

(58) FIG. 5 is a schematic diagram of a processor circuit **510**, according to aspects of the present disclosure. The processor circuit **510** or a similar processor circuit may be implemented in any suitable device or system previously disclosed. One or more processor circuits **510** can be configured to perform the operations described herein. The processor circuit **510** can include additional circuitry or electronic components, such as those described herein. In an example, one or more processor circuits **510** may be in communication with transducer arrays, sensors, circuitry, or other components within the intravascular device **146** (FIGS. 1, 2), the x-ray source **360**, the input screen **374**, circuitry, or any other components within the x-ray imaging device **300** (FIG. 3) or angiography device **156** or fluoroscopy device **166** (FIG. 1). One or more processor circuits **510** may also be in communication with the x-ray source **460**, the x-ray detector **470**, circuitry, or any other components within the CT imaging device **176** (FIGS. 1, 4) and/or the display **132** (FIG. 1), as well as any other suitable component or circuit within the diagnostic system **100**. As shown, the processor circuit **510** may include a processor **560**, a memory **564**, and a communication module **568**. These elements may be in direct or indirect communication with each other, for example via one or more buses.

(59) The processor **560** may include a CPU, a GPU, a DSP, an application-specific integrated circuit (ASIC), a controller, a field programmable gate array (FPGA), another hardware device, a firmware device, or any combination thereof configured to perform the operations described herein. The processor **560** may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

(60) The memory **564** may include a cache memory (e.g., a cache memory of the processor **560**), random access memory (RAM), magnetoresistive RAM (MRAM), read-only memory (ROM), programmable read-only memory (PROM), erasable programmable read only memory (EPROM), electrically erasable programmable read only memory (EEPROM), flash memory, solid state memory device, hard disk drives, other forms of volatile and non-volatile memory, or a

combination of different types of memory. In an embodiment, the memory **564** includes a non-transitory computer-readable medium. The memory **564** may store instructions **566**. The instructions **566** may include instructions that, when executed by the processor **560**, cause the processor **560** to perform the operations described herein with reference to the devices **146**, **156**, **166**, **300**, **176**, and/or the systems **134**, **144**, **154**, **164**, and/or **174**. Instructions **566** may also be referred to as code. The terms “instructions” and “code” should be interpreted broadly to include any type of computer-readable statement(s). For example, the terms “instructions” and “code” may refer to one or more programs, routines, sub-routines, functions, procedures, etc. “Instructions” and “code” may include a single computer-readable statement or many computer-readable statements.

(61) The communication module **568** can include any electronic circuitry and/or logic circuitry to facilitate direct or indirect communication of data between the processor circuit **510**, the previously described devices and systems, and/or the display **132**. In that regard, the communication module **568** can be an input/output (I/O) device. In some instances, the communication module **568** facilitates direct or indirect communication between various elements of the processor circuit **510** and/or the devices and systems of the diagnostic system **100** (FIGS. **1-4**).

(62) FIG. **6** is a flow diagram of a method **600** of co-registering intravascular data with a CT-based 3D model, according to aspects of the present disclosure. One or more steps of the method **600** will be described with reference to FIGS. **8-14**. As illustrated, the method **600** includes a number of enumerated steps, but embodiments of the method **600** may include additional steps before, after, or in between the enumerated steps. In some embodiments, one or more of the enumerated steps may be omitted, performed in a different order, or performed concurrently. The steps of the method **600** can be carried out by any suitable component within the diagnostic system **100** and all steps need not be carried out by the same component. In some embodiments, one or more steps of the method **600** can be performed by, or at the direction of, a processor circuit of the diagnostic system **100**, including, e.g., the processor **560** (FIG. **5**) or any other component.

(63) An advantage of co-registering data from different medical diagnostic modalities includes providing a user of the system **100** with accurate information relating to the position of an intravascular device **146** within the patient anatomy. The method **600** includes providing location information of the intravascular device **146** and measurements or data obtained by the device **146** in conjunction with a three-dimensional CT-based model. A user of the system **100** may then view exact location information corresponding to intravascular measurements relating to a blood vessel as a graphical representation overlaid on or otherwise in conjunction with a CT-based model. In this way, the user of the imaging system **100** need not estimate the location of measurements from an intravascular device **146** based on separate views of an x-ray image and/or measurement display.

(64) At step **605**, the method **600** includes receiving CT imaging data. The CT imaging data may be obtained via the CT imaging device **176** and CT processing system **174** (FIG. **1**) previously described or with any other similar device and processing system. The CT imaging data may correspond to an anatomy of any suitable region or structure of a patient including any of the previously mentioned parts of a patient anatomy. In some embodiments, the CT imaging data may correspond to the vasculature of a heart acquired through a CT scanning procedure or CT scan. In some imaging procedures, a contrast agent may be introduced to the patient vasculature. The anatomy may also be imaged with the CT imaging device **176** without a contrast agent introduced to the vasculature. In procedures in which a heart is to be imaged, a contrast agent may be introduced to the coronary vasculature. As previously described, the CT imaging device **176** may acquire the CT imaging data by rotating the x-ray source **460** and the x-ray detector **470** mounted to the CT gantry **450** (FIG. **4**) around the patient anatomy and acquiring x-ray imaging data at various angles in relation to the patient anatomy and across various regions of the patient anatomy.

(65) At step **610**, the method **600** includes generating a three-dimensional model **800** of the patient's vasculature based on the CT imaging data. Step **610** will be described with reference to FIG. **8**, which is a diagrammatic view of a CT-based 3D model **800** of a heart **820**, according to

aspects of the present disclosure. As shown by the axes **899** adjacent to the model **800**, the model **800** is a three-dimensional object and may be viewed from any suitable angle in three-dimensional space. FIG. **8** depicts an example image of a coronary CT scan of an entire heart of a patient visualized as a three-dimensional model. The CT processing system **174** may use the CT imaging data obtained at step **605** with the CT imaging device **176** (FIG. **1**) to reconstruct multiple two-dimensional images or slices of the patient anatomy. In some embodiments, these two-dimensional images may correspond to locations along the longitudinal axis **482** of the patient anatomy or the patient support **480** (FIG. **4**). For example, one two-dimensional image may correspond to a cross-sectional slice of the patient anatomy at location along the longitudinal axis **482**. These generated two-dimensional images may then be combined to construct a three-dimensional model of the anatomy, similar to the three-dimensional CT-based model **800** shown in FIG. **8**. As shown in FIG. **8**, the heart **820** imaged and displayed includes multiple vessels **830** extending along the surface of the heart. Features may be observed in great detail in the CT-based model **820** as well as viewed from various angles.

(66) At step **615**, the method **600** includes receiving x-ray fluoroscopy images **1010** of the patient vasculature obtained at an imaging angle **1090** while an intravascular device **1020** moves through a blood vessel **830**. Step **615** will be described with reference to FIG. **10**. FIG. **10** is a diagrammatic view of a relationship between x-ray fluoroscopy images **1010**, intravascular data **1030**, a fluoroscopy-based 2D pathway **1040** defined by the motion of an intravascular device **1020**, a CT-based 2D pathway **920**, and a CT-based 3D model **910**, according to aspects of the present disclosure.

(67) At step **615**, the patient anatomy may be imaged with an x-ray device while a physician performs a pullback with an intravascular device **1020** such that the intravascular device **1020** moves through a blood vessel of the anatomy. The x-ray device used to obtain the fluoroscopy images **1010** may be substantially similar to the x-ray device **300** of FIG. **3** or the x-ray fluoroscopy imaging device **166** of FIG. **1**. In some embodiments, the fluoroscopy images **1010** may be obtained while no contrast agent is present within the patient vasculature. Such an embodiment is shown by the fluoroscopy images **1010** in FIG. **10**. The radiopaque portion of the intravascular device **1020** is visible within the displayed fluoroscopy image **1010** as indicated by the circle **1025**. The fluoroscopy images **1010** may correspond to a continuous image stream of fluoroscopy images and may be obtained as the patient anatomy is exposed to a reduced dose of x-radiation. It is noted that the fluoroscopy images **1210** may be acquired with the x-ray source **360** and the x-ray detector **370** positioned at any suitable angle in relation to the patient anatomy. This angle is shown by angle **1090**. In addition, as shown by the axes **1098**, the fluoroscopy images **1010** are two-dimensional.

(68) The intravascular device **1020** may be any suitable intravascular device. The device may be substantially similar to the device **146** of FIGS. **1** and **2**, including any of its described embodiments. As the intravascular device **1020** moves through the patient vasculature, the x-ray imaging system may acquire multiple fluoroscopy images **1010** showing the radiopaque portion of the intravascular device **1020**. In this way, each fluoroscopy image **1010** shown in FIG. **10** may depict the intravascular device **1020** positioned at a different location such that the x-ray system may track the position of the intravascular device **1020** over time.

(69) As the intravascular device **1020** is pulled through the patient vasculature, it may acquire intravascular data **1030**. In an example, the intravascular data **1030** shown in FIG. **10** may be IVUS images. However, the intravascular data may be any suitable data, including IVUS images, FFR data, iFR data, OCT data, or any other measurements or metrics relating to blood pressure, blood flow, lumen diameter, or other physiological data acquired during a pullback of an intravascular device.

(70) As the physician pulls the intravascular device **1020** through the patient vasculature, the system **100** may co-register the intravascular data **1030** to the fluoroscopy images **1010**, as



indicated by the arrow **1061**. In this way, each intravascular measurement acquired by the intravascular device **1020** may be associated with a position within the patient anatomy. For example, the first IVUS image **1030** shown in FIG. **10** may be associated with the first fluoroscopy image **1010**. The first IVUS image **1030** may be an image acquired by the intravascular device **1020** at a position within the vasculature and within the first fluoroscopy image **1010** as shown by the circle **1025**. Similarly, an additional IVUS image **1030** may be associated with an additional fluoroscopy image **1010** showing the intravascular device **1020** at a new location within the image **1010**.

(71) Any suitable number of IVUS images or other intravascular data **1030** may be acquired during an intravascular device pullback and any suitable number of fluoroscopy images **1010** may be obtained. In some embodiments, there may be a one-to-one ratio of fluoroscopy images **1010** and intravascular data **1030**. In other embodiments, there may be differing numbers of fluoroscopy images **1010** and/or intravascular data **1030**. The process of co-registering the intravascular data **1030** with the fluoroscopy images **1010** at step **630** may include some features similar to those described in U.S. Pat. No. 7,930,014, titled, "VASCULAR IMAGE CO-REGISTRATION," and filed Jan. 11, 2006, which is hereby incorporated by reference in its entirety. The co-registration process may also include some features similar to those described in U.S. Pat. Nos. 8,290,228, 8,463,007, 8,670,603, 8,693,756, 8,781,193, 8,855,744, and 10,076,301, all of which are also hereby incorporated by reference in their entirety.

(72) At step **620**, the method **600** includes generating a fluoroscopy-based 2D pathway **1040** defined by the positions of the intravascular device **1020** within the x-ray fluoroscopy images **1010**. Step **620** will also be described with reference to FIG. **10**. In some embodiments, the fluoroscopy-based 2D pathway **1040** may additionally be referred to as a roadmap, a roadmap image, a path, or any other suitable term.

(73) The different positions of the intravascular device **1020** as shown in the fluoroscopy images **1010** may define a fluoroscopy-based two-dimensional pathway **1040**, as shown by the arrow **1060**. The fluoroscopy-based 2D pathway **1040** reflects the path of the intravascular device **1020** as it moved through the patient vasculature. The fluoroscopy-based 2D pathway **1040** defines the path as measured by the x-ray device which acquired the fluoroscopy images **1010**, and therefore shows the path from the same angle **1090** at which the fluoroscopy images were acquired. As shown by the axes **1098**, the pathway **1040** is two-dimensional. Stated differently, the 2D pathway **1040** describes the projection of the 3D path followed by the device onto the imaging plane at the imaging angle **1090**.

(74) As shown by the arrow **1062**, because the two-dimensional path **1040** is generated based on the fluoroscopy images **1010**, each position along the two-dimensional path **1040** may be associated with one or more fluoroscopy images **1010**. As an example, at a location **1041** along the path **1040**, the first fluoroscopy image **1010** may depict the intravascular device **1020** at that same position **1041**. In addition, because a correspondence was also established between the fluoroscopy images **1010** and the intravascular data **1030** as shown by the arrow **1061**, intravascular data **1030**, such as the first IVUS image shown, may also be associated with the location **1041** along the path **1040** as shown by the arrow **1063**.

(75) At step **625**, the method **600** includes generating multiple CT-based 2D pathways **920** by projecting the CT-based 3D model **910** at angles similar to the imaging angle **1090**. Step **625** will be described with reference to FIG. **9** and FIG. **10**. FIG. **9** is a diagrammatic view of a CT-based 3D model **910** used to generate a CT-based 2D pathway **920**, according to aspects of the disclosure. In some embodiments, CT-based 2D pathways may additionally be referred to as a roadmap, a roadmap image, a path, or any other suitable term.

(76) At step **625**, the system **100** may extract a model **910** of the vascular tree from the CT model **800** of FIG. **8**. Specifically, the CT model **800** of FIG. **8** shows the vessels **830** within and around the heart **820** as well as various other tissues, cavities, or other structures within and/or around the

heart **820**. The system **100** may use the model **800** to construct a new model **910** representing only the vessels **830** of the heart **820**. In some embodiments, the step of extracting a model of the coronary tree may be performed after the patient examination or may be completed in post-processing. The CT-based model **910** may be a three-dimensional model as shown by the axes **999**. The vessels **830** may include the region of the patient vasculature imaged by the intravascular device **1020** at step **615**. Constructing a new 3D model **910** including only the vessels **830** of the heart **820** may be accomplished by any suitable method. For example, the system **100** may identify the vascular structures of the heart **820** using a multiscale coronary response (MSCAR) method. The system **100** may additionally or alternatively use segmentation algorithms, multiscale filtering methods, analysis of the eigen values of Hessian matrices, expectation-maximization (EM) estimation segmentation algorithms, artery tracking, or any other suitable method. The system **100** may additionally employ any suitable image processing or machine learning techniques, methods, feedback mechanisms, or algorithms to identify the coronary vascular tree within the CT model **800**. In some embodiments, the method of identifying, segmenting, or extracting the vascular tree **910** from the CT model **800** may include some features similar to those described in the publication entitled, "AUTOMATED CORONARY ARTERY TREE EXTRACTION IN CORONARY CT ANGIOGRAPHY USING A MULTISCALE ENHANCEMENT AND DYNAMIC BALLOON TRACKING (MSCAR-DBT) METHOD," Computerized Medical Imaging and Graphics, vol. 36, no. 1, pp. 1-10, January 2012, by C. Zhou et al. hereby incorporated by reference in its entirety.

(77) As shown by the arrow **930**, the CT-model **910** may be projected from three-dimensional space to two-dimensional space to create a CT-based 2D pathway **920** at an angle **990**. The angle **990** may be any suitable angle. In some embodiments, the angle **990** may be the same as the imaging angle **1090** or the angle at which the fluoroscopy images **1010** were obtained. In some embodiments, the angle **990** may differ from the angle **1090** by one or more degrees as will be discussed in more detail hereafter. As shown by the axes **998**, the CT-based pathway **920** is a two-dimensional image or model. The angle **990** may be referred to as a projection angle or source angle in some instances. It is noted that the pathway **920** is not an image directly acquired by an imaging device or system. Rather, it is a computer generated, two-dimensional projection of the 3D model. In some aspects, however, the CT-based 2D pathway **920** may resemble an angiography image received from an x-ray imaging device.

(78) Any suitable method may be used by the system **100** to project the CT-based 3D model **910** to create the CT-based 2D pathway **920**. For example, the CT-based 3D model may be received by the system **100**. The CT-based 3D model **910** may include multiple three-dimensional coordinates corresponding to the locations of the coronary vessels **830** of the heart **820**. In some embodiments, these three-dimensional coordinates may be organized into any suitable matrix, vector, set, series, or other means of data organization. The three-dimensional coordinates corresponding to the CT-based 3D model **910** may define centerlines along each vessel **830** shown in the model **910**. The coordinates may also correspond to any other suitable location along the vessels **830**. In an embodiment, the coordinates corresponding to the CT-based 3D model **910** may be combined into a matrix, M. A transformation matrix, K, may additionally be determined. The transformation matrix K may be any suitable matrix configured to transform or project the coordinates corresponding to the locations of the blood vessels **830** in three-dimensional space to a two-dimensional plane. For example, in an embodiment, the transformation matrix, K, may be a 3×3 matrix which may preserve the first and second values of a three-dimensional coordinate, while setting the third value to a constant. In some embodiments, the matrix K may additionally perform other matrix transformation functions, such as scaling, rotation, translation, reflection, skewing, shearing, or any other suitable transformation. The matrix K may additionally be correlated to the angle **990** at which the three-dimensional coordinates are projected onto a two-dimensional plane. In other embodiments, this angle may be applied separate from the matrix K. An equation may then be formed to project the three-dimensional coordinates of the CT-based 3D model **910** to a CT-based

2D pathway **920**. The equation may be of any suitable form, include any suitable variables, constants, values, or coordinates, or may include one equation or a set of equations. In an embodiment, the equation used to project the three-dimensional coordinates of the CT-based 3D model **910** to the CT-based 2D pathway **920** may be similar to  $A=KM$ , in which A represents a matrix including two dimensional coordinates of a two-dimensional view of the vessels **820** shown at the projection angle **990**. The two-dimensional nature of the CT-based 2D pathway **920** is additionally illustrated by the axes **998** of FIG. **9**. It is additionally noted that the three-dimensional coordinates corresponding to the CT-based 3D model **910** and the two-dimensional coordinates corresponding to the CT-based 2D pathway **920** both shown in FIG. **9** may be of any suitable coordinate system, including a cartesian, rectangular, polar, cylindrical, spherical coordinate systems, or any other suitable coordinate systems.

(79) At step **625**, as stated, the method **600** includes creating multiple CT-based 2D pathways **920**. These multiple CT-based pathways **920** may be created by varying the angle of projection **990** for each pathway **920**. In this way, the two-dimensional pathways **920** may vary due to a difference in perspective between each pathway **920**. For example, the configuration of vessels **830** shown each pathway **920** may be positioned at different locations within the two-dimensional plane. Stated differently, varying the projection angle **990** used to project the CT-based 3D model **910** to create a CT-based 2D pathway **920** may be a virtual equivalent of moving the x-ray source of an x-ray device to acquire a different x-ray image of a different perspective. In some embodiments, the projection angle **990** used to project the CT-based 3D model **910** to create a CT-based 2D pathway **920** may be any arbitrary angle and may be incrementally varied to create any suitable number of pathways **920** from different angles **990**. For example, the pathways **920** may depict the vasculature from angles varying from one another by 1, 2, 3, or more degrees in each direction. The number of CT-based 2D pathways **920** created may therefore also vary. For example, the pathways **920** may include 1, 2, 3, 5, 10, 20, 50, 100, or more different pathways **920** or any suitable number therebetween, each created via a different projection angle **990**. In some embodiments, the system **100** may create the set of CT-based 2D pathways **920** based on angles of projection **990** similar to the imaging angle **1090**, or the angle of the x-ray source and detector when the fluoroscopy images **1010** were acquired. For example, the system **100** may generate one CT-based 2D pathway **920** at a projection angle **990** equal to the imaging angle **1090**. The system may then vary the projection angle **990** by 5 degrees in a given direction, as an illustrative example and generate an additional CT-based 2D pathway **920** from the updated projection angle **990**. The system **100** may determine ranges of projection angles **990** in any suitable direction at which a pathway **920** is created. For example, the system **100** may vary the projection angle **990** by a maximum of 15 degrees in each direction as opposed to generating pathways **920** from all directions to limit the number of CT-based 2D pathways **920** required.

(80) At step **630**, the method **600** includes identifying a CT-based 2D pathway that is similar to the fluoroscopy-based 2D pathway **1040** of FIG. **10**. Step **630** will be described with reference to FIG. **11** and FIG. **12**. FIG. **11** is a diagrammatic view of the fluoroscopy-based 2D pathway **1040** overlaid on a CT-based 2D pathway **1120**, according to aspects of the present disclosure.

(81) Each generated pathway **920** in the set of CT-based 2D pathways **920** may be compared by the system **100** to the fluoroscopy-based 2D pathway **1040** created at step **620** and shown in FIG. **10**. The system **100** may use any appropriate method, algorithm, or process to compare the CT-based 2D pathways **920** with the fluoroscopy-based 2D pathway **1040**. For example, the system **100** may employ any suitable image processing techniques or machine learning techniques listed herein.

(82) In the example shown in FIG. **11**, the fluoroscopy-based 2D pathway **1040** may be overlaid over a CT-based 2D pathway **1120**. The CT-based 2D pathway **1120** shown in FIG. **11** may be one of the set of CT-based 2D pathways **920** generated by the system **100** at step **625**. As shown in FIG. **11**, the fluoroscopy-based 2D pathway **1040** may be acquired at the angle **1090** and may be a two-dimensional depiction, as shown by the axes **1099**. Similarly, the CT-based 2D pathway **1120** may

be a two-dimensional depiction as shown by the axes **1199**. The CT-based 2D pathway **1120** may be created by projecting the CT-based 3D model **910** onto a two-dimensional plane using any of the previously mentioned equations or techniques at an angle **1190**. In some embodiments, the projection angle **1190** may be the same angle as the imaging angle **1090**. The projection angle **1190** may also differ from the imaging angle **1090**. As shown in FIG. **11**, the position and shape of the fluoroscopy-based 2D pathway **1040** does not correlate to the position and shape of any of the vessels of the CT-based 2D pathway **1120**. In some embodiments, although the projection angle **1190** may be the same as the imaging angle **1090**, the CT-based 2D pathway **1120** may not align with the fluoroscopy-based 2D pathway due to differences in the positioning of the patient anatomy during the CT imaging procedure and the fluoroscopy and intravascular procedure. For example, at a region **1152** of the imaged vessel, the pathway **1040** and the pathway **1120** may be similar. In other embodiments, portions of the pathway **1040** and the pathway **1120** may also correspond to one another. However, at a region **1154**, the fluoroscopy-based pathway **1040** and the CT-based pathway **1120** diverge. Specifically, at a point **1042** identified along the fluoroscopy-based pathway **1040** and identified along a potentially corresponding vessel within the CT-based pathway **1120**, a separation **1180** is observed. In some embodiments, this separation **1180** may be quantified and stored in a memory corresponding to the CT-based pathway **1120** and/or the point **1042**. Additional separations between the fluoroscopy-based pathway **1040** and the CT-based pathway **1120** are also shown in and around the region **1154** in FIG. **11**. In some embodiments, the system **100** may generate an overlap score or other metric relating to the similarity of the pathway **1040** and the pathway **1120**. This overlap score may then be incorporated in a feedback mechanism to select the pathway **1040** relating to the projection angle that is most similar to the pathway **1120**. The feedback mechanism may be or include any suitable image processing techniques and/or machine learning techniques or networks, as will be described in more detail hereafter.

(83) FIG. **12** is a diagrammatic view of the fluoroscopy-based 2D pathway **1040** overlaid on a different CT-based 2D pathway **1220**, according to aspects of the present disclosure. Similar to FIG. **11**, the fluoroscopy-based 2D pathway **1040** may be overlaid over a CT-based 2D pathway **1220**. The pathway **1220** may also be one of the set of CT-based 2D pathways **920** previously discussed. The CT-based 2D pathway **1220** shown in FIG. **12** may differ from the pathway **1120** of FIG. **11** in that it may be generated by projecting the CT-based model **910** at a different angle **1290**. As shown by the axes **1299**, the CT-based 2D pathway **1220** is two-dimensional. In some embodiments, the projection angle **1290** may be the same angle as the imaging angle **1090**. The projection angle **1290** may also differ from the imaging angle **1090**. As shown in FIG. **12**, the position and shape of the fluoroscopy-based 2D pathway **1040** correlates to the position and shape of one of the vessels of the CT-based 2D pathway **1220**. For example, at a region **1252** of the imaged vessel, the pathway **1040** and the pathway **1120** are similar or comparable in shape, position, and curvature. Stated differently, the positions of two-dimensional coordinates defining the fluoroscopy-based 2D pathway **1040** are the same or substantially similar to the centerline of the vessels shown in the CT-based 2D pathway **1220**. As shown in FIG. **12**, the correlation of position, shape, and curvature of the fluoroscopy-based pathway **1040** and the CT-based pathway **1220** is maintained at all locations along the fluoroscopy-based 2D pathway **1040**. That is, at a region **1254** distal of the region **1252**, the fluoroscopy-based pathway **1040** and the CT-based pathway **1220** still correlate to one another such that there is no significant distance or separation between the two pathways **1040** and **1220** at any position.

(84) In some embodiments, the system **100** may compare the fluoroscopy-based 2D pathway **1040** with each CT-based 2D pathway **920** in a similar manner as shown in FIGS. **11** and **12**. In some embodiments, the system may identify multiple points along the fluoroscopy-based pathway **1040** and corresponding points along the corresponding vessel in the CT-based pathway **920**, including either of the pathways **1120** and **1220** shown in FIGS. **11** and **12**. Points may be identified by the system **100** or by a user of the system **100**. In embodiments in which points along the pathways

**1040** and **920** are identified by the system **100**, the system **100** may be identified by any suitable method. For example, the system **100** may identify locations along the pathways **1040** and **920** may use such techniques as a global shift algorithm, warping algorithm, path solving algorithm, calibration algorithm, motion compensation algorithm, modified mean shift algorithm, or any other suitable algorithm, technique, or method. The system **100** may also use any suitable machine learning techniques to identify corresponding positions along the pathways **1040** and **920**. For example, the machine learning techniques may include a deep learning network which employs processing algorithms such as convolutional layers, fully convolutional layers, fully connected layers, feature vectors, or other algorithms or techniques. In some embodiments, a deep learning network may be trained to identify anatomical landmarks along the pathways **1040** and **920** based on trained classification outputs and associated confidence scores. These landmarks may then be used to identify multiple points along the pathways **1040** and **920**. It is noted that any of the described feedback mechanisms, image processing techniques, and/or machine learning techniques may be used by the system **100** to identify locations along the pathways **1040** and **920** as discussed, but also the pathways **1120** and **1220** as well as any locations along the vessels of the CT-based 3D model **910** and/or the model **800** previously discussed.

(85) In some embodiments, after various points are identified along the pathways **1040** and **920**, the system may calculate a metrics corresponding to differences in position between points along the pathway **1040** and corresponding points along the pathway **920** being compared. These points may be substantially similar to the point **1042** shown in FIG. **11** but may be at any suitable location along the pathways **1040** and **920**. The points may correspond to anatomical landmarks identified in the pathways **1040** and **920** or may correspond to any other suitable locations. The metrics corresponding to differences in positions of points along the pathways **1040** and **920** may be substantially similar to the separation **1180** shown in FIG. **11**. In some embodiments, the system **100** may store these metrics when comparing the fluoroscopy-based 2D pathway **1040** to various CT-based 2D pathways **920**.

(86) In some embodiments, the system **100** may overlay the fluoroscopy-based 2D pathway **1040** over all vessels shown in each CT-based 2D pathway **920**. In other embodiments, using any of the previously identified feedback mechanisms, image processing techniques, or machine learning techniques previously discussed, the system **100** may identify one vessel that most closely corresponds to the fluoroscopy-based pathway **1040** and perform a comparison of the pathway **1040** with the selected vessel. In some embodiments, any other suitable methods of shape comparison or differentiation may be used to compare the pathways **1040** and **920**. For example, the system **100** may employ an area overlap technique, may compare the curvature or tortuosity of regions of the vasculature, may compare lengths of the vessels in the vasculature, may compare occlusions, bifurcations, or any other anatomical landmarks within the vasculature, or may use any other suitable method. In some embodiments, the system **100** may account for scaling, rotation, translation, or other characteristics when comparing the pathways **1040** and **920**.

(87) As stated in step **630**, the system **100** may identify a pathway **920** that is similar or comparable to the fluoroscopy-based 2D pathway **1040**. In some embodiments, the system **100** or a user of the system **100** may determine a threshold value corresponding to the stored metrics of separation between points along the pathways **1040** and **920**. In some embodiments, the separation between points along the pathways **1040** and **920** may be added, averaged, multiplied or otherwise combined to create a similarity measure corresponding to the comparison between the pathways **1040** and **920**. The similarity measure may also be referred to as a similarity index. The similarity measure may be determined via any suitable method or may be of any suitable type. For example, the similarity measure may be based on distances between points along both pathways **1040** and **920** as stated. The similarity measure may also be based on the curvature or tortuosity of regions of vessels within the pathways **1040** and **920**, the lengths of vessels within the pathways, locations of occlusions of the vessels within the pathways, locations of bifurcations within the vessels, or any

other anatomical landmarks within the vessels shown in the pathways **1040** and **920**. In an embodiment, in order for a CT-based 2D pathway **920** to be sufficiently similar to the fluoroscopy-based pathway **1040**, this combined similarity measure must satisfy (e.g., greater than, less than, equal to) a predetermined threshold value. In another embodiment, in order for a CT-based 2D pathway **920** to be sufficiently similar to the fluoroscopy-based pathway **1040**, each metric of separation between corresponding points along the pathways **1040** and **920** must satisfy (e.g., greater than, less than, equal to) the predetermined threshold. In some embodiments, the CT-based 2D pathway **920** which shows the least differences between corresponding points along pathways **1040** and **920** or the smallest metrics of separation may be selected by the system **100** at step **630**. The system **100** may use any other suitable method of comparing the pathways **1040** and **920**. For example, the system **100** may use any of the previously mentioned feedback mechanisms, image processing techniques, or machine learning techniques or other methods of shape analysis. In an embodiment, the CT-based 2D pathway **920** selected by the system **100** at step **630** may be the CT-based 2D pathway **1220** shown in FIG. **12**.

(88) In an embodiment in which machine learning techniques are employed to compare the pathways **920** with the fluoroscopy-based 2D pathway and select a pathway **920**, aspects of the disclosure may include a deep learning network (e.g., a convolutional neural network, a multi-class classification network, an encoder-decoder type network, or any suitable network). The deep learning network configuration may be trained for identification of the pathway **920** that is most similar to the fluoroscopy-based 2D pathway **1040**. The deep learning network configuration may be or include a feedback mechanism. In some embodiments, the feedback mechanism may indicate a confidence score relating to the similarity of a pathway **920** with the pathway **1040**. Based on the output of the feedback mechanism, the network configuration may search the input pathways **920** to identify a pathway **920** which is most similar to the fluoroscopy-based 2D pathway **1040**. In this way, any suitable machine learning techniques may be used by the system **100** at any step of any method to direct the search and comparison of pathways or other data through a feedback mechanism.

(89) At step **635**, the method **600** includes co-registering the intravascular data **1030** and the CT-based 2D pathway **1220** identified in step **630** by mapping the locations of the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **1220**. The step **635** will be described with reference to FIG. **10**.

(90) At step **635**, the system **100** or a user of the system **100** may associate any suitable anatomical features identified in the fluoroscopy-based pathway **1040** with the same anatomical features in the CT-based 2D pathway **1220** to create a mapping between the two pathways. In some embodiments, the system **100** or a user of the system **100** may identify anatomical features in the fluoroscopy pathway **1040** and in each CT-based pathway **920** prior to comparison of the various pathways or calculation of any metrics relating to the pathways **1040** and/or **920** as described in step **630**. The anatomical features identified may be any suitable features. For example, the anatomical features may include, but are not limited to, occlusions or regions of constrictions of a vessel, tortuosity of a vessel, bifurcations, or lengths of a vessel, among other features. This association of anatomical features in the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **1220** creates a mapping of physical positions or locations along the vasculature on both pathways or models.

(91) In an embodiment in which the system **100** identifies the previously listed anatomical landmarks, the system **100** may identify anatomical landmarks via any suitable method. For example, the system **100** may employ image processing techniques such as any of the previously mentioned algorithms, techniques, or methods. In addition, the system **100** may segment received images or models or perform various other steps to identify anatomical features. In other embodiments, the system **100** may employ artificial intelligence techniques such as a deep learning network to identify anatomical features including any of the previously listed machine learning techniques, algorithms, or methods.

(92) The feature mapping of locations within the vessel defined by the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **1220** may be configured to allow a user to correlate any location along a vessel shown in either pathway to the other model. To achieve this comprehensive one-to-one feature mapping between the pathways, the mapping correspondences between identified anatomical landmarks may be expanded or extrapolated to include the entire pathway **1040** and pathway **1220**. In such a configuration, any location, including locations not associated with an identified landmark, on the fluoroscopy-based pathway **1040** may be identified or otherwise associated with the same location on the CT-based pathway **1220** and vice versa. The system **100** may employ any suitable method or technique to achieve this comprehensive correspondence between all points along the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **1220**.

(93) Referring to FIG. **10**, in some embodiments, an anatomical landmark or feature may be identified in both the fluoroscopy-based pathway **1040** and the CT-based pathway **1220**. In the example shown in FIG. **10**, the pathway **1040** is compared with the pathway **920**, but it is understood that any description of comparing the pathway **1040** with the pathway **920** may equally apply to comparisons with the pathways **1120** and/or **1220**. As an example, an identified landmark or features may correspond to the point **1041** shown along the vessel in both the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **920** shown in FIG. **10**. The system **100** may establish a mapping correspondence between the identified landmark or feature shown by the point **1041** in the pathway **1040** and the same landmark or feature shown by the point **1041** in the pathway **1220**. This mapping correspondence may indicate that position data, or other data including intravascular data, associated with the point **1041** in the pathway **1040** may be associated and presented with the same point **1041** on the pathway **920** and vice versa. The system **100** may additionally establish a correspondence between locations near the identified anatomical landmark or feature shown by the point **1041**. In an embodiment, a point may be selected in a region along the vessel proximal to the point **1041** along the pathway **1040**. The system **100** may calculate, via any of the previously mentioned image processing or artificial intelligence techniques, the distance between the selected proximal point and the point **1041**. The system may then identify the same proximal point in the CT-based pathway **920** based on this determined distance. In some embodiments, the system **100** may additionally determine an angle or vector corresponding to the difference in positions between the proximal point and the point **1041**. Once the proximal point has been identified in both the pathways **1040** and **920**, a mapping correspondence or relationship. The system **100** may apply this same technique to identify any locations proximal or distal to the position of an anatomical landmark or feature similar to that shown by the point **1041**. In this way, the system **100** may establish a one-to-one correlation between any location or position along the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **920**. This mapping correspondence between all locations along the pathway **1040** and the pathway **920** is shown by the arrow **1064** in FIG. **10**.

(94) After a mapping between corresponding locations along the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **920** has been established, the intravascular data **1030** may be co-registered to the CT-based 2D pathway **920**. This co-registration may be represented both by the arrow **1064** and the arrow **1065** shown in FIG. **10**. Specifically, the intravascular data **1030** may be associated with the pathway **920** as shown by the arrow **1065** and the location data corresponding to the intravascular data **1030** may be associated with the pathway **920** as shown by the arrow **1064**. In this way, just as different fluoroscopy images **1010** and intravascular data **1030** may be associated with various locations along the fluoroscopy-based 2D pathway **1040**, the fluoroscopy images **1010** and intravascular data **1030** may be associated with the same locations along the CT-based 2D pathway **920**. For example, the same location **1041** may be identified on the CT-based 2D pathway **920** using any of the techniques previously described. The same fluoroscopy images **1010** associated with the location **1041** on the fluoroscopy-based pathway **1040** may be associated with

the same location **1041** on the CT-based 2D pathway **920**. Similarly, the same intravascular data **1030** associated with the location **1041** on the fluoroscopy-based pathway **1040** may also be associated with the same location **1041** on the CT-based 2D pathway **920**.

(95) At step **640**, the method **600** includes co-registering the intravascular data **1030** with the CT-based 3D model **910** based on the mapping established at step **635**. The step **640** will also be described with reference to FIG. **10**. To co-register the intravascular data **1030** obtained to the CT-based 3D model **910**, the CT-based 2D pathway **920** may be projected back to the CT-based 3D model **910** such that all the intravascular data **1030**, fluoroscopy data **1010**, or any other suitable data co-registered to the CT-based 2D pathway **920** may be similarly co-registered to the CT-based 3D model **910**. For example, the location information corresponding to any received data may be received, or a correspondence between the same locations may be established, as shown by the arrow **1067**. Similarly, the intravascular data **1030** or any other data may be co-registered with the CT-based 3D model **910** as shown by the arrow **1066**. This projection of the CT-based 2D pathway may be performed by calculating an inverse of the transformation matrices and/or equations previously discussed with reference to FIG. **9**. For example, the projection angle **990** pertaining to the selected CT-based 2D pathway **920** may be stored by the system **100** within a memory. This projection angle **990** may be used to project the CT-based 2D pathway **920** to the CT-based 3D model **910** using any of the previously discussed methods or techniques. As shown by the axes **999**, the CT-based model **910** is three-dimensional.

(96) At step **645**, the method **600** includes outputting to a display a CT-based 3D model **1360** and a graphical representation of the intravascular data **1310**. Step **645** will be described with reference to FIGS. **13** and **14**. FIG. **13** is a diagrammatic view of a graphical user interface **1400** displaying intravascular data **1310** coregistered to the CT-based 3D model **700**, according to aspects of the present disclosure. FIG. **13** additionally depicts an indicator **1315**, an image longitudinal display (ILD) **1312**, and an indicator **1305**.

(97) The CT-based model **1360** output to a display may be either the CT-based 3D model **910** shown in FIGS. **9** and **10** or may be the CT-based 3D model **800** shown in FIG. **8**. The co-registered intravascular data **1310** may include the intravascular data **1030** presented in FIG. **10** or any other data. The CT-based model **1360** with co-registered intravascular data **1310** may be displayed to a user in any suitable format. For example, as shown in FIG. **13**, the CT-based model **1360** may be displayed adjacent to the corresponding intravascular data **1310**. The intravascular data **1310** may be an IVUS image. In other embodiments, co-registered intravascular data **1310** may include any other suitable images, metrics, or other data and may be overlaid over the CT-based model **1360** or arranged or displayed in any other suitable configuration.

(98) In the embodiment shown in FIG. **13**, the indicator **1305** is positioned over the CT-based three-dimensional model **1360** at a location along a vessel imaged by the intravascular device **1020** (FIG. **10**). The IVUS image **1310** displayed adjacent to the CT-based model **1360** is an image acquired by the intravascular device at the location identified by the indicator **1305**. For example, the location identified by the indicator **1305** may correspond to the location **1041** previously identified in FIG. **10**. The fluoroscopy image **1010** and IVUS image **1030** shown in FIG. **10** may be associated with the location **1041** fluoroscopy-based 2D pathway **1040** and/or the CT-based 2D pathway **920** in FIG. **10**. This same location **1041** and its associated IVUS image(s) and/or fluoroscopy image(s) may then be co-registered to the CT-based model **1360** as previously described. This allows the IVUS image obtained at the location **1041** to be displayed alongside the three-dimensional CT-based model **1360** indicating the co-registered location **1041** at which the IVUS image was obtained via the indicator **1305**. In some embodiments, a user of the system **100** may also select an additional IVUS image to be displayed in the graphical user interface **1300**. As a different IVUS image is selected, the indicator **1305** would move to a different location along the vessel corresponding to the location at which the selected IVUS image was obtained. In some embodiments, a user of the system **100** may additionally move the indicator **1305** along any vessel



shown in the CT-based model **1360** and an IVUS image corresponding to the selected location would be displayed to the user if an IVUS image is available.

(99) In some embodiments, additional images may be included and displayed to a user of the system **100**, including the image longitudinal display (ILD) **1312**. The ILD **1312** may provide the user with a longitudinal view of the vessel imaged with the intravascular device. Specifically, one end of the ILD **1312** may correspond to the proximal most region of the imaged vessel and the opposing end of the ILD **1312** may correspond to the distal most region of the imaged vessel. The ILD **1312** may provide a graphical representation of relative diameters of the imaged vessel at all positions along the imaged vessel. The ILD **1312** may include an indicator **1315**. The indicator **1315** may correspond to the position of the intravascular device relative to the entire imaged vessel at the location at which the displayed IVUS image was obtained. In this way, as the indicator **1305** is moved by a user to a different location along the vessel, a different IVUS image would be displayed adjacent to the CT-based model **1360** and the indicator **1315** would also move to a different corresponding position within the ILD **1312**. In some embodiments, a user may be able to move the indicator **1315** to a different location within the ILD **1312** as well and cause the system **100** to recall and display an associated IVUS image as well as move the indicator **1305** to a different corresponding position within the CT-based model **1360**.

(100) The system **100** may display additional images or metrics to a user. For example, the system **100** may display any of the previously discussed images such as the fluoroscopy images **1010**, the fluoroscopy-based 2D pathway **1040**, any CT-based 2D pathway **920**, **1120**, and/or **1220**, or the CT-based 3D model **910**. The system **100** may additionally display any suitable indicators or metrics associated with any of these images.

(101) FIG. **14** is a diagrammatic view of a graphical user interface **1400** displaying intravascular data **1410** co-registered to the CT-based 3D model **1360**, according to aspects of the present disclosure. In the example graphical user interface **1400** shown in FIG. **14**, the intravascular data **1410** may correspond to intravascular data other than IVUS data. For example, the intravascular data **1410** may correspond to iFR data, but in other embodiments, the intravascular data may alternatively correspond to FFR data, OCT data, or any other suitable intravascular data. The intravascular data **1410** includes pressure difference indicators **1411**, an indicator **1416**, pressure metrics **1420**, a graph **1425**, a region **1427**, a graphical element **1412**, and metrics **1414**.

(102) As shown in FIG. **14**, graphical representations corresponding to intravascular data **1410** may be overlaid over the CT-based model **1360**. In other embodiments, intravascular data **1410** may be displayed adjacent to the CT-based model **1360** or in any other configuration. In the embodiment shown in FIG. **14**, the intravascular data **1410** includes multiple pressure difference indicators **1411**. The pressure difference indicators **1411** may convey to a user the severity of differences in pressure at various locations along the measured vessel. The number of indicators **1411** may correspond to the severity of pressure difference. For instance, near an occlusion **1460**, the difference in pressure may be the most significant. The greatest number of indicators **1411** may then be positioned by the location of the occlusion **1460**. In the embodiment shown, the indicators **1411** may be positioned extending in a straight line perpendicular to the vessel. However, the pressure difference indicators **1411** may be arranged in any suitable manner. For example, they may not extend in a straight line, but may extend in any angled or curvilinear line. The indicators **1411** may also be arranged according to any suitable arrangement or pattern which may convey to a user any suitable metric associated with the vessel at a particular location. Although the pressure difference indicators **1411** are of a circular shape in FIG. **14**, the indicators **1411** may be of any suitable type. For example, they may be of any suitable geometric or non-geometric shape or size or may be or include any suitable alphanumeric characters.

(103) The graph **1425** adjacent to the CT-based model **1360** may indicate intravascular pressure at all locations along the measured length of the vessel. For example, an x-axis of the graph **1425** may indicate the distance of locations along the vessel from the most distal or most proximal position

within the vessel at which intravascular measurements were obtained. A y-axis of the graph **1425** may indicate the quantity of intravascular measurement, in this case, iFR measurement data. In some embodiments, a user of the system **100** may select a region **1427** within the graph **1425**. The region **1427** corresponds to a length of the measured vessel. The region **1427** may additionally correspond to the indicator **1416** overlaid on the CT-based model **1360**. The indicator **1416** illustrates the same selected length of vessel on the CT-based model **1360**. In some embodiments, the selected length may be selected by the user either on the CT-based model **1360** or on the graph **1425**.

(104) Upon selection of a region **1427** and/or length shown by the indicator **1416**, the system **100** may generate and display one or more metrics associated with the selected length of vessel. For example, the metrics **1420** may include metrics such as iFR or other measurements relating to a drop or change in pressure across the selected region **1427**. Any additional metrics may also be displayed, such as pressure data related to the distal most location within the selected region **1427**, the proximal most location, an average pressure metric, or any other suitable metrics. The metrics **1420** may additionally include pressure or other intravascular data related to the measured vessel such as an iFR measurement at the distal most measured position of the vessel. The metrics **1420** may additionally include any other suitable intravascular data metrics, such as average pressure or iFR measurements along the entire measured portion of the vessel, change in pressure or iFR measurements along the entire measured portion of the vessel, or any other suitable metrics. The metrics **1420** may be displayed in any suitable location within the graphical user interface, including overlaid on the CT-based model **1360**, adjacent to or near the CT-based model **1360**, overlaid on the graph **1425**, or adjacent to or near the graph **1425**, or at any other position suitable and in any other suitable arrangement, orientation, or organization.

(105) Upon selection of a region **1427** and/or length shown by the indicator **1416**, the system **100** may also generate the graphical element **1412**. The graphical element **1412** may display the same, similar, or different metrics associated with the selected region **1427**. The metrics **1414** shown within the graphical element **1412** may indicate the length of the selected region **1427** and the change or drop in pressure or iFR measurements along the selected region **1427**. The metrics **1414** may additionally or alternatively include any other suitable metrics including any of those listed with reference to metrics **1420**. Similar to the metrics **1420**, the metrics **1414** may be displayed in any suitable location within the graphical user interface, including overlaid on the CT-based model **1360**, adjacent to or near the CT-based model **1360**, overlaid on the graph **1425**, or adjacent to or near the graph **1425**, or at any other suitable position and in any other suitable arrangement, orientation, or organization. It is noted that the method **600** described herein, as well as other similar methods described, allow coregistration of 3D models with 2D projections even when the angle of acquired two-dimensional images is not obvious or known providing for increased flexibility to users of the system.

(106) FIG. 7 is a flow diagram of a method **700** of co-registering intravascular data with a CT-based 3D model, according to aspects of the present disclosure. As illustrated, the method **700** includes a number of enumerated steps, but embodiments of the method **700** may include additional steps before, after, or in between the enumerated steps. In some embodiments, one or more of the enumerated steps may be omitted, performed in a different order, or performed concurrently. The steps of the method **700** can be carried out by any suitable component within the diagnostic system **100** and all steps need not be carried out by the same component. In some embodiments, one or more steps of the method **700** can be performed by, or at the direction of, a processor circuit of the diagnostic system **100**, including, e.g., the processor **560** (FIG. 5) or any other component.

(107) The method **700** is an additional embodiment of the present disclosure. Various steps of the method **700** may be substantially similar to steps of the method **600** previously described. Specifically, the steps **705-720** of the method **700** are the same as the steps **605-620** of the method

**600.** No specific description will be given with reference to steps **705-720** because the description of steps **705-720** is the same as the description of the steps **605-620**.

(108) Step **725** of the method **700** includes projecting the CT-based 3D model **910** to a 2D plane at a projection angle **990** to generate a CT-based 2D pathway **920**. Step **725** will be described with reference to FIG. **9**. In some aspects, the step **725** may be similar to the step **625** of the method **600**. In particular, the model **910** may be projected to a 2D plane at the projection angle **990** using any of the previously mentioned transformation matrices or may involve any of the previously mentioned image processing or machine learning techniques previously described.

(109) Step **725** of the method **700** differs from step **625** of the method **600** in that only one CT-based 2D pathway **920** is created at the step **725**. In some embodiments and the first time the step **725** of the method **700** is performed by a processor of the system **100**, the projection angle **990** may equal the imaging angle **1090**.

(110) Step **730** of the method **700** includes comparing the CT-based 2D pathway **920** generated at step **725** to the fluoroscopy-based 2D pathway **1040**. This comparison may be accomplished via any of the previously described methods or techniques with reference to FIGS. **11** and **12**. As previously described with reference to step **630** of the method **600**, in some embodiments, the distance between corresponding points along the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **920** may be calculated by the system **100** and compared to a threshold value. In other embodiments, an overlap measure may be determined and compared to a threshold value. In some embodiments, any of the same comparison techniques previously identified may be used together to form a similarity measure or similarity index. If the similarity index is determined to be within the maximum threshold determined by the system **100** or a user of the system **100**, the CT-based 2D pathway **920** may be selected by the system **100** and the method proceeds to step **740** as illustrated. If however, the system **100** determines that the distance between corresponding points on the pathways **1040** and **920** exceed the predetermined threshold, the system may determine that the pathways **1040** and **920** are not sufficiently similar to successfully perform a co-registration of the data. If this is the case, the system may proceed to step **735**.

(111) Step **735** of the method includes adjusting the projection angle **990**. The projection angle **990** may be adjusted to any suitable angle. In some embodiments, the projection angle **990** may be adjusted by a small increment. For example, the projection angle **990** may be varied by  $\pm 1, 2, 3, 5, 10, 15$  or more degrees, or by any other suitable change of angle, in any suitable direction.

(112) After the projection angle **990** is adjusted, the system may revert back to step **725** and the CT-based 3D model **910** may be projected to form an additional CT-based 2D pathway **920** at the new projection angle **990**. At step **730**, the system **100** may once again compare the newly generated CT-based 2D pathway **920** with the fluoroscopy-based 2D pathway **1040** and determine whether the two pathways **1040** and **920** are sufficiently similar to proceed to co-registration at step **740**. If the differences between the pathway **1040** and the newly created pathway **920** still exceed the predetermined threshold value, the system may again revert to step **735** and adjust the projection angle **990** again. In some embodiments, the projection angle **990** may be varied by the same amount as the projection angle **990** was adjusted at step **735** as previously described. In some embodiments, the projection angle may be adjusted by the same increment each time the system **100** performs step **735**. In other embodiments, the system **100** may vary the amount by which the projection angle **990** is adjusted each time the system performs step **735**. In some embodiments, the amount and direction of variation of the projection angle **990** may be determined by an output of any of the previously mentioned comparison techniques described with reference to step **730**.

(113) In some embodiments, the system **100** will sequentially perform and repeat steps **725**, **730**, and step **735** until the differences between the fluoroscopy-based 2D pathway **1040** and the CT-based 2D pathway **920** are less than a predetermined threshold, at which point the system **100** may proceed to step **740**.

(114) As shown in FIG. **7**, the steps **740-750** of the method **700** are the same as the steps **635-645** of

the method **600**.

(115) FIG. **15** is a flow diagram of a method **1500** of co-registering angiography-based data with a CT-based 3D model, according to aspects of the present disclosure. One or more steps of the method **1500** will be described with reference to FIGS. **17-20**. As illustrated, the method **1500** includes a number of enumerated steps, but embodiments of the method **1500** may include additional steps before, after, or in between the enumerated steps. In some embodiments, one or more of the enumerated steps may be omitted, performed in a different order, or performed concurrently. The steps of the method **1500** can be carried out by any suitable component within the imaging system **100** and all steps need not be carried out by the same component. In some embodiments, one or more steps of the method **1500** can be performed by, or at the direction of, a processor circuit of the imaging system **100**, including, e.g., the processor **560** (FIG. **5**) or any other component. The angiography-based data described with reference to FIG. **15** and the method **1500** may be any suitable form of data that is derived from or mapped to an x-ray angiography image. For example, such angiography-based data could include QCA data, angiography-based pressure ratio data (e.g., angio Pd/Pa, angio FFR, angio iFR, etc.), and angiography-based functional data (e.g., angio pressure and/or angio flow), or any other suitable data. For example, other data types include vascular perfusion data (e.g., myocardial perfusion imaging) with single photon emission computed tomography (SPECT) or positron emission tomography (PET).

(116) Steps **1505** and **1510** may be substantially similar to steps **605** and **610** of the method **600** (FIG. **6**). For example, at step **1505**, the method **1500** includes receiving CT imaging data. The CT imaging data may be the same CT imaging data received at step **605** or may differ according to the patient anatomy imaged.

(117) At step **1510**, the method **1500** includes generating a 3D model **1905** (FIG. **19**) of the patient's vasculature based on the CT imaging data. The CT-based three-dimensional model **1905** may be the same CT-based model **800** (FIG. **8**) or may differ. The CT-based model **1905** may be generated based on CT imaging data corresponding to a different patient anatomy or different imaging procedure.

(118) At step **1515**, the method **1500** includes receiving an x-ray angiography image **1700** of the patient vasculature obtained at an imaging angle **1790**. Step **1515** will be described with reference to FIG. **17**, which is a diagrammatic view of an x-ray angiography image and an enlarged view of the x-ray angiography image with angiography-based data, according to aspects of the present disclosure. The angiography-based data may also be referred to as blood vessel metrics. In some embodiments, the angiography image **1700** may additionally be referred to as a roadmap, a roadmap image, a path, or any other suitable term.

(119) The x-ray angiography image **1700** may be obtained via the x-ray imaging device **300** (FIG. **3**) or the x-ray angiography imaging device **156** in conjunction with the x-ray angiography processing system **154** (FIG. **1**) previously described or with any other similar device and processing system. The x-ray angiography image **1700** may correspond to an anatomy of any suitable region or structure of a patient anatomy including any of the previously mentioned parts of a patient anatomy. The patient anatomy imaged in the x-ray angiography image **1700** may be the same anatomy imaged in the fluoroscopy images used to create the CT-based 3D model **1905** at step **1510**. A contrast agent may be introduced to the patient vasculature prior to obtaining the angiography image **1700**. The x-ray angiography image **1700** may be acquired at any suitable angle **1790** with respect to the patient anatomy. This angle **1790** may be stored within a memory in communication with the system **100** and may be referred to as the imaging angle. As shown by the axes **1798** in FIG. **17**, the x-ray angiography image **1700** is a two-dimensional image.

(120) At step **1520**, the method **1500** includes determining blood vessel metrics **1750** based on the x-ray angiography image **1700**. Step **1520** will also be described with reference to FIG. **17**. FIG. **17** additionally depicts angiography-based data **1750** overlaid on an enlarged portion **1701** of the angiography image **1700**. The enlarged portion **1701** of the image **1700** may be a portion of the

angiography image **1700** as identified by the region **1760**. The region **1760** may be any suitable portion of the angiography image **1700** and the region shown in FIG. **17** is merely exemplary. In some embodiments, the angiograph-based data or blood vessel metrics **1750** may be determined without selecting or identifying an enlarged portion **1701** of the image. The enlarged portion **1701** is shown in FIG. **17** to increase the visibility of various metrics discussed and may therefore be merely pedagogical in nature. As shown by the axes **1799**, the enlarged portion **1701** of the angiography image **1700** is a two-dimensional image.

(121) The angiography-based data **1750** within the enlarged portion **1701** of the angiography image **1700** includes lumen diameters **1705** and **1710**, a minimum lumen diameter (MLD) value **1715**, a length **1720**, a length measurement **1722**, a graphical element **1724**, a scale **1760**, and additional metrics **1730**. The additional metrics **1730** include an additional length measurement **1732**, MLD data **1734**, and an average lumen diameter **1736**. As previously mentioned, the angiography-based data **1750** may include any suitable angiography image-based data, including QCA data or any other suitable type of data.

(122) In some embodiments, a user of the system **100** may select a region or length **1720** along an imaged vessel as shown in FIG. **17**. In some embodiments, the system **100** may select the length **1720** automatically using any of the previously mentioned image processing or artificial intelligence techniques. In some embodiments, the length **1720** may include multiple vessels within the angiography image **1700** including any suitable landmark features previously described including bifurcations, occlusions, regions of tortuosity, lengths, or other landmark features.

(123) Upon the selection of the length **1720**, multiple angiography-based data **1750** may be determined. For example, at a proximal end of the selected length **1720**, the lumen diameter **1705** may be determined. At a distal end of the selected length **1720**, the lumen diameter **1710** may also be determined. The diameters **1705** and/or **1710** may additionally be referred to as reference diameters.

(124) In some embodiments, the selected length **1720** of an imaged vessel may include an occlusion as shown in FIG. **17**. The system **100** may identify the position of the occlusion and determine the MLD value **1715**. The MLD value may correspond to the severity of the identified occlusion. The MLD value may be a percentage, as shown, or may additionally be a length measurement similar to the diameters **1705** and **1710** or may be any other type of metric to illustrate the severity of the occlusion. The MLD **1715** may be a percentage of occlusion. In some embodiments, a percentage value of MLD at the identified occlusion may be calculated based on the lumen diameter at the occlusion divided by an average of the diameters **1705** and **1710**. In some embodiments, an MLD value **1715** may be calculated by the system **100** after any length **1720** is selected whether or not an occlusion is identified. The MLD value **1715** may assist a physician in determining the proper treatment of occlusions within the vasculature. For example, the MLD value **1715** may provide information relating to the type or size of stent to be placed within the patient vasculature.

(125) The system **100** may also determine a length measurement **1722** of the selected length **1720**. In an embodiment in which the angiography-based data **1750** is displayed to a user within the angiography image **1700** as shown in FIG. **17**, the length measurement **1722** may be positioned within a graphical element **1724** near the length **1720** or an indicator of the length **1720**. The length measurement **1722** may also be positioned elsewhere. The graphical element **1724** may be in any suitable position, however. For example, the graphical element **1724** may be positioned above, beneath, beside, or otherwise adjacent to the angiography image **1700**. In addition, the graphical element **1724** may be of any suitable shape, type, color, opacity, or orientation. The graphical element **1724** may be or include any suitable symbol, graphical representation, or alpha-numeric characters. The graphical element **1724** may include any suitable metrics or angiograph-based data **1750** in addition to the length measurement **1722** shown.

(126) The angiography-based data **1750** may additionally include the scale **1760**. The scale **1760**

may be positioned at any suitable location within the angiography image **1700** and may indicate to a user the scale of the image **1700**. For example, the scale **1760** may display an exemplary length measurement in conjunction with a graphical element displaying how a structure of that exemplary length may appear within the angiography image **1700**.

(127) The angiograph-based data **1750** may also include any suitable additional metrics **1730**. The length measurement **1732** may correlate to the length measurement **1722** previously described but may be included at a different location within the image **1700**. In some embodiments, the length measurement **1732** may also correspond to a different length of the vasculature within the image **1700**, such as the total length of vasculature shown, a previously selected length **1720**, or any other suitable length.

(128) The MLD data **1734** may include any information relating to an occlusion shown within the angiography image **1700** or along the selected length **1720** or any other location of minimum lumen diameter. The MLD data **1734** may include the MLD value **1715** previously discussed or may include additional values, percentages, or metrics. The MLD data **1734** may include a measured diameter of the lumen at a location of minimum diameter.

(129) The average lumen diameter **1736** may also be included within the additional metrics **1730**. The average lumen diameter **1736** may correspond to an average of the two lumen diameters **1705** and **1710** previously discussed. The average lumen diameter **1736** may also correspond to an average of all lumen diameters along the selected length **1720**, may correspond to an average of all the diameters of lumens shown in the angiography image **1700**, or may include some other statistical metric relating to the angiography-based data **1750** shown.

(130) Any suitable additional metrics may be measured and determined in addition to or included with the angiography-based data **1750** described with reference to FIG. **17**. The system **100** may also calculate other metrics based on the metrics shown, such as metrics related to blood pressure, blood flow, bifurcations, regions of tortuosity, vessel trauma, scarring, or any other suitable metrics. In some embodiments, any or all of the previously mentioned metrics may be calculated without a user or the system **100** selecting a region of length **1720**. Any of the mentioned angiography-based data **1750** may be determined for vessels observed within the image as a whole or in part. In some embodiments, the metrics discussed may be calculated, but not displayed to a user. In addition, the angiography image **1700** may not be displayed to a user. Rather, the angiography-based data **1750** may be calculated by the system **100** and stored within a memory. The angiography-based data **1750** may also be displayed to a user overlaid on or in conjunction with images or models different from the angiography image **1700**.

(131) Any or all of the previously mentioned angiography-based data **1750** may be calculated through any suitable method. For example, the data may be determined via image processing or artificial intelligence techniques. The data may be determined using edge detection techniques to identify the locations and borders of vessels within the angiography image **1700**. The system **100** may additionally use any suitable optimization, calibration, or validation methods to identify features or structures of interest within the angiography image **1700**.

(132) At step **1525**, the method **1500** includes generating multiple CT-based 2D pathways **1820** by projecting a CT-based 3D model **1810** at angles similar to the imaging angle. Step **1525** will be described with reference to FIG. **18**, which is a diagrammatic view illustrating a relationship between the x-ray angiography image **1700**, angiography-based data **1750**, a CT-based 2D pathway **1820**, and a CT-based 3D model **1810**, according to aspects of the present disclosure. The step **1525** may be similar to, or share features or characteristics with, the step **625** of the method **600** described with reference to FIG. **6**.

(133) Similar to the step **625** of the method **600**, at step **1525**, the system **100** may extract a model **1810** of the vascular tree from the CT model **1905** of FIG. **19**. The 3D CT model **1905** of FIG. **19** shows the vessels within and around the heart imaged as well as various other tissues, cavities, or other structures within and/or around the heart. The system **100** may use the model **1905** to

construct a new model **1810** representing only the vessels of the heart. The CT-based 3D model **1810** may be a three-dimensional model as shown by the axes **1899**. Constructing a new 3D model **1810** based on the 3D model **1905** to include only the vessels of the heart may be accomplished by a similar method as was used by the system **100** at step **625** of the method **600** to construct the CT-based 3D model **910** (FIG. 9) from the model **800** (FIG. 8).

(134) The CT-model **1810** may be projected from three-dimensional space to two-dimensional space to create a CT-based 2D pathway **1820** at an angle **1891**. The angle **1891** may be referred to as the projection angle. The angle **1891** may be any suitable angle. In some embodiments, the angle **1891** may be the same as the imaging angle **1890** or the angle at which the x-ray angiography image **1700** was obtained. In some embodiments, the angle **1891** may differ from the angle **1890** by one or more degrees. As shown by the axes **1898**, the CT-based pathway **1820** is a two-dimensional image or model.

(135) Any suitable method may be used by the system **100** to project the CT-based 3D model **1810** to create the CT-based 2D pathway **1820** including any of the methods, processes, or techniques including the matrix transformations and projection techniques described with reference to projecting the CT-based 3D model **910** to the CT-based 2D model **920** with reference to FIG. 9 and step **625** of the method **600**.

(136) At step **1525** the method **1500** also includes creating multiple CT-based 2D pathways **1820**. Similar to the CT-based pathways **920** previously described, these multiple CT-based pathways **1820** may be created by varying the angle of projection **1891** for each pathway **1820**. The two-dimensional pathways **1820** may vary due to a difference in perspective between each pathway **1820**. The projection angles **1891** used to create the multiple CT-based 2D pathways **1820** may each vary by standard increments similar to the angles **990** described with reference to FIG. 9 and the set of CT-based 2D pathways **1820** may include any suitable number. The projection angles **1891** may be similar to the imaging angle **1890** or may differ. The creation of the pathways **1820** at step **1525** may share any suitable characteristics of the step **625** of the method **600** described previously.

(137) At step **1530**, the method **1500** includes identifying a CT-based pathway **1820** that is similar to the x-ray angiography image **1700**. The step **1530** may be substantially similar to the step **630** of the method **600** and the system **100** may use any of the methods or processes described previously in relation to the step **630** to perform the step **1530**. Specifically, each generated pathway **1820** may be compared to the angiography image **1700**. In some embodiments, the system **100** may identify a set of two-dimensional coordinates corresponding to the vessels shown in the angiography image **1700**. This collection or set of two-dimensional coordinates may be a two-dimensional pathway or path similar to the fluoroscopy-based 2D pathway **1040** previously discussed. This two-dimensional pathway may be compared with the CT-based 2D pathways **1820** in the same way as the fluoroscopy-based pathway **1040** was compared to the CT-based pathways **920** described previously. In other embodiments, the system **100** may compare the CT-based pathways **1820** to the angiography image **1700** itself. The system **100** may use any appropriate method, algorithm, or process to compare the CT-based 2D pathways **1820** with the angiography image **1700** including any of the methods, algorithms, or processes described with reference to FIGS. 11 and 12. At the step **1530**, the system **100** may identify a CT-based 2D pathway **1820** which is sufficiently similar to the vessels of the angiography image **1700**.

(138) At step **1535**, the method **1500** includes co-registering the blood vessel metrics **1750** and the identified CT-based 2D pathway **1820** by mapping locations of the angiography image **1700** and the CT-based 2D pathway. Step **1535** will be described with reference to FIG. 18. Step **1535** may be substantially similar to the step **635** of the method **600** and may include any of the same description of the step **635** previously discussed.

(139) At step **1535**, the system **100** may associate anatomical features identified in the angiography image **1700** with the same anatomical features in the identified CT-based 2D pathway **1820** to

create a mapping. The anatomical features identified may be any suitable features including those listed with reference to step **635** of the method **600**. This association of anatomical features in the angiography image **1700** and the CT-based 2D pathway **1820** creates a mapping of physical positions or locations along the vasculature shown in the image **1700** and pathway **1820**. The system **100** identifies the previously listed anatomical landmarks, the system **100** may identify anatomical landmarks via any suitable method including any previously described with reference to the step **635** of the method **600**. The feature mapping of locations within the vessel defined by the angiography image **1700** and the CT-based 2D pathway **1820** may be expanded to include a one-to-one mapping of all locations along the vessels including locations at anatomical landmarks or not at anatomical landmarks. This mapping may be created with any suitable method including those listed with reference to step **635** of the method **600**.

(140) After a mapping between corresponding locations along the vessels of the angiography image **1700** and the CT-based 2D pathway **1820** has been established, the blood vessel metrics or angiography-based data **1750** may be co-registered to the CT-based 2D pathway **1820**. This co-registration may be represented both by the arrow **1864** and the arrow **1865** shown in FIG. **18**. Specifically, the angiography-based data **1750** may be associated with the CT-based 2D pathway **1820** as shown by the arrow **1865** and the location data corresponding to the angiography-based data **1750** may be associated with the pathway **1820** as shown by the arrow **1864**. The relationship between the angiography-based data **1750** and its location within the angiography image **1700** may be illustrated by the arrow **1861**.

(141) At step **1540**, the method **1500** includes co-registering the blood vessel metrics **1750** and the CT-based 3D model **1810** based on the mapping created at step **1535**. The step **1540** will also be described with reference to FIG. **18**. The step **1540** may be substantially similar to the step **640** of the method **600** and may include any of the same description of the step **640** previously discussed.

(142) To co-register the angiography-based data **1750** to the CT-based 3D model **1810**, the CT-based 2D pathway **1820** may be projected back to the CT-based 3D model **1810** such that all the angiography-based data **1750** or any other suitable data co-registered to the CT-based 2D pathway **1820** may be similarly co-registered to the CT-based 3D model **1810**. For example, the location information corresponding to any received data may be received, or a correspondence between the same locations may be established, as shown by the arrow **1867**. Similarly, the angiography-based data **1750** or any other data may be co-registered with the CT-based 3D model **1810** as shown by the arrow **1866**. This projection of the CT-based 2D pathway **1820** may be performed by calculating an inverse of the transformation matrices and/or equations used to create the 2D pathway **1820**. The equations and/or techniques used may include the projection angle **1891** and may include any of the methods, techniques, or processes described with reference to the step **640** of the method **600**. As shown by the axes **1899**, the CT-based model **1810** is three-dimensional. As shown by the axes **1897**, the angiography image **1700** and the enlarged view **1701** of the angiography image **1700** shown in FIG. **18** are two-dimensional images.

(143) At step **1545**, the method **1500** includes outputting to a display a CT-based 3D model **1905** and graphical representations of the blood vessel metrics **1750**. Step **1550** will be described with reference to FIGS. **19** and **20**. FIG. **19** is a diagrammatic view of a graphical user interface **1900** displaying angiography-based data **1750** co-registered to a CT-based 3D model **1905**, according to aspects of the present disclosure. FIG. **19** additionally depicts the angiography image **1700**, an enlarged view **1915** of the angiography image **1700**, and an indicator **1912**.

(144) The CT-based model **1905** output to a display may be either the CT-based 3D model **1810** shown in FIG. **18** or may be a CT-based 3D model similar to the CT-based model **800** shown in FIG. **8**. In some embodiments, the CT-based model **1905** may be the CT-based model from which the vasculature tree model **1810** was extracted at step **1510**. The CT-based model **1905** with co-registered angiography-based data **1750** may be displayed to a user in any suitable format. For example, as shown in FIG. **19**, the angiography-based data **1750** may be displayed overlaid on the



CT-based model **1905**. The angiography-based data **1750** may be QCA data. In other embodiments, co-registered angiography-based data **1750** may include any other suitable images, metrics, or other data. The co-registered angiography-based data **1750** may also be positioned beside the CT-based model **1905** or arranged or displayed in any other suitable configuration.

(145) In the embodiment shown in FIG. **19**, the angiography-based data **1750** determined at step **1520** and shown in FIG. **17** in more detail is positioned overlaid on the CT-based model **1905**. As shown, the amount, type, or form of display of the data **1750** may differ from FIG. **17**. In some embodiments, a user of the system **100** may specify which data **1750** to view on the graphical user interface **1900**. In some embodiments, all angiography-based data **1750** displayed in FIG. **16** may also be included within the graphical user interface **1900** shown in FIG. **19**.

(146) Adjacent to the CT-based model **1905**, the angiography image **1700** is shown. In some embodiments, the angiography image **1700** may be replaced with any other suitable angiography image. In some embodiments, a physician may obtain additional angiography images during an x-ray angiography procedure. Any of these images may be displayed adjacent to, or otherwise in conjunction with the CT-based model **1905**. The angiography image **1700** may correspond to a view or angle of the CT-based model **1905** as displayed to the user or may differ. In some embodiments, the system **100** may additionally display an enlarged portion **1915** of the angiography image **1700**. The enlarged portion **1915** of the angiography image **1700** may assist a user to observe landmark features or other features of interest within the angiography image **1700**. The indicator **1912** may convey to a user the section of the angiography image **1700** corresponding to the enlarged portion **1915**. In some embodiments, a user of the system **100** may select the section of the angiography image **1910** to be displayed by creating the indicator **1912** within the image **1700** with any suitable command input device, such as a computer mouse, keyboard, touchscreen, or any other suitable device. In some embodiments, the graphical user interface **1900** may additionally or alternatively include an enlarged view of the CT-based model **1905**. In some embodiments, the metrics **1750** may additionally be displayed on the angiography image **1700**, the enlarged portion **1915** of the angiography image **1700**, or the enlarged portion of the CT-based model **1905**.

(147) FIG. **20** is a diagrammatic view of a graphical user interface **2000** displaying angiography-based data **1750** co-registered to the CT-based 3D model **1905**, according to aspects of the present disclosure. FIG. **20** includes the angiography image **1700**, angiography-based data **1750**, the CT-based model **1905**, a region **2020**, and an enlarged portion **2015** of the angiography image **1700**.

(148) An additional exemplary graphical user interface **2000** may display the angiograph-based data **1750** overlaid on the original angiography image **1700** used to calculate the angiography-based data **1750** at step **1520**. In other embodiments, the angiography image **1700** may be a different angiography image including any previously listed. In some embodiments, a user of the system **100** may select any angiography image to be displayed within the graphical user interface **2000** and the system **100** may overlay the angiography-based data **1750** on the selected angiography image. The angiography data **1750** may be arranged on or beside the angiography image **1700** in any suitable configuration or arrangement and may be of any suitable form or type as described with reference to FIG. **17**.

(149) The CT-based model **1905** may be displayed in conjunction with the angiography image **1700**. For example, as shown in FIG. **20**, it may be positioned adjacent to the angiography image **1700**. In some embodiments, the angiography-based data **1750** may additionally be overlaid on the CT-based model **1905**. In other embodiments, the region **2020** may be overlaid over the CT-based model **1905**. The region **2020** may indicate the location within the CT-based model **1905** of the selected length **1720** discussed with reference to FIG. **17**. In some embodiments, the region **2020** may instead correlate to the region shown by the angiography image **1700** as a whole within the CT-based model **1905**.

(150) The system **100** may additionally display an enlarged portion **2015** of the angiography image

**1700**. The enlarged portion **2015** of the angiography image **1700** may assist a user to observe landmark features or other features of interest within the angiography image **1700** in more detail. In some embodiments, an indicator may be included within the angiography image **1700** to convey to a user the section of the angiography image **1700** corresponding to the enlarged portion **2015**. In some embodiments, a user of the system **100** may select the section of the angiography image **1700** to be displayed by creating the indicator within the image **1700**. In some embodiments, the graphical user interface **2000** may additionally or alternatively include an enlarged view of the CT-based model **1905**. In some embodiments, the metrics **1750** may additionally be displayed on the enlarged portion **2015** of the angiography image **1700**, or the enlarged portion of the CT-based model **1905**.

(151) It is understood that the data, metrics, features, graphical elements, graphical representations, images, or any other aspects of the graphical user interfaces **1900** (FIG. **19**) and/or **2000** are merely exemplary and any other additional data, metrics, features, graphical elements, graphical representations, images, or any other aspects are fully contemplated. In addition, the arrangement of the elements listed above is also exemplary. Any suitable configuration, arrangement, or organization is also fully contemplated.

(152) FIG. **16** is a flow diagram of a method of co-registering angiography-based data with a CT-based 3D model, according to aspects of the present disclosure. As illustrated, the method **1600** includes a number of enumerated steps, but embodiments of the method **1600** may include additional steps before, after, or in between the enumerated steps. In some embodiments, one or more of the enumerated steps may be omitted, performed in a different order, or performed concurrently. The steps of the method **1600** can be carried out by any suitable component within the diagnostic system **100** and all steps need not be carried out by the same component. In some embodiments, one or more steps of the method **1600** can be performed by, or at the direction of, a processor circuit of the diagnostic system **100**, including, e.g., the processor **560** (FIG. **5**) or any other component.

(153) The method **1600** is an additional embodiment of the present disclosure. Various steps of the method **1600** may be substantially similar to steps of the method **1500** previously described. Specifically, the steps **1605-1620** of the method **1600** are the same as the steps **1505-1520** of the method **1500**.

(154) Steps **1625**, **1630**, and **1635** of the method **1600** may be substantially similar to the steps **725**, **730**, and **735** of the method **700**. Specifically, step **1625** of the method **1600** includes projecting the CT-based 3D model **1810** to a 2D plane at a projection angle **1891** to generate a CT-based 2D pathway **1820**. The model **1810** may be projected to a 2D plane at the projection angle **1891** using any of the previously mentioned transformation matrices or may involve any of the previously mentioned image processing or machine learning techniques as the step **725** of the method **700**. Only one CT-based 2D pathway **1820** is created at the step **1625**. Similar to the steps **725**, **730**, and **735**, the system may incrementally adjust the projection angle **1891** after comparing each CT-based 2D pathway **1820** if the differences between the CT-based 2D pathway **1820** and the vessels of the angiography image **1700** are within a predetermined threshold. One difference between the step **1630** and the step **730** is that the CT-based 2D pathways **1820** are compared to the angiography image **1700** rather than the fluoroscopy-based 2D pathway **1040** of FIG. **10**. However, the steps **1625**, **1630**, and **1635** may include any of the description of the steps **720**, **730**, and **735** previously described with reference to the method **700** of FIG. **7**.

(155) As shown in FIG. **16**, the steps **1640-1650** of the method **1600** are the same as the steps **1535-1545** of the method **1500**. Therefore, no specific description will be given with reference to steps **1640-1650** because the description of steps **1640-1650** is the same as the description of the steps **1535-1545**.

(156) It is noted that the procedures described herein, including obtaining CT data to generate a CT-based model **800** (FIG. **8**), obtaining intravascular data **1030** and fluoroscopy images **1010**

(FIG. 10), or obtaining angiography image 1700 (FIG. 17) may be performed at various times in relation to one another. In some embodiments, each procedure may be performed concurrently such that one procedure is completed immediately following another. In other embodiments, more time may pass between each procedure. The amount of time between each procedure may be limited to prevent significant change to the patient anatomy between each procedure. Such change may be a result of natural growth, trauma, healing, therapy, or any other event or process which may alter the patient anatomy between procedures.

(157) One or more fluoroscopy-based or angiography-based 2D pathway(s) and one or more CT-based 2D pathway(s) can be representative of the same vessel and/or the same portion of the same vessel. In that sense, the fluoroscopy-based or angiography-based 2D pathways and CT-based 2D pathways can be considered the same and/or representative of the same location of the patient body. Thus, fluoroscopy-based or angiography-based 2D pathways and CT-based 2D pathways can be the same shape or similar shape. The fluoroscopy-based or angiography-based 2D pathways and CT-based 2D pathways can be determined in different ways. In that sense, the fluoroscopy-based or angiography-based 2D pathways and CT-based 2D pathways can be considered different views or different forms of the same pathway, same vessel, and/or same location of the patient body. The fluoroscopy-based 2D pathways can be generated by tracking the position of the intravascular device in the x-ray fluoroscopy images (e.g., the shape traced out by movement of the intravascular device). The angiography-based 2D pathways can be the shape occupied by contrast agent within the vessel. The CT-based 2D pathways can be generated by projecting the CT-based 3D model at different angles.

(158) Persons skilled in the art will recognize that the apparatus, systems, and methods described above can be modified in various ways. Accordingly, persons of ordinary skill in the art will appreciate that the embodiments encompassed by the present disclosure are not limited to the particular exemplary embodiments described above. In that regard, although illustrative embodiments have been shown and described, a wide range of modification, change, and substitution is contemplated in the foregoing disclosure. It is understood that such variations may be made to the foregoing without departing from the scope of the present disclosure. Accordingly, it is appropriate that the appended claims be construed broadly and in a manner consistent with the present disclosure.

## Claims

1. A co-registration system, comprising: a processor circuit configured for communication with a display, an x-ray fluoroscopy device, and an intravascular catheter or guidewire, wherein the processor circuit is configured to: receive, from the x-ray fluoroscopy device, a plurality of x-ray fluoroscopy images of the blood vessel while the intravascular catheter or guidewire moves through the blood vessel; receive, from the intravascular catheter or guidewire, intravascular data representative of the blood vessel while the intravascular catheter or guidewire moves through the blood vessel; generate, using the plurality of x-ray fluoroscopy images, a first two-dimensional (2D) pathway of the blood vessel based on the intravascular catheter or guidewire moving through the blood vessel; generate a second 2D pathway of the blood vessel using a three-dimensional (3D) model of the blood vessel based on computed tomography (CT) imaging data; perform a first co-registration between the intravascular data and the second 2D pathway based on a mapping between corresponding locations of the first 2D pathway and the second 2D pathway; perform a second co-registration between the intravascular data and the 3D model based on the first co-registration; and output, to the display, the 3D model and a graphical representation of the intravascular data at a co-registered location of the 3D model.

2. The system of claim 1, wherein the processor circuit is configured to: determine if the first 2D pathway and the second 2D pathway are comparable; and perform the first co-registration only in

- response to determining that the first 2D pathway and the second 2D pathway are comparable.
3. The system of claim 2, wherein the processor circuit is configured to: compute a similarity measure representative of if the first 2D pathway and the second 2D pathway are comparable; determine that the first 2D pathway and the second 2D pathway are comparable when the similarity measure satisfies a threshold.
  4. The system of claim 2, wherein the processor circuit is configured to: generate a plurality of 2D pathways of the blood vessel using the 3D model of the blood vessel based on CT imaging data; and select a given 2D pathway of the plurality of 2D pathways as the second 2D pathway when the given 2D pathway and the first 2D pathway are comparable.
  5. The system of claim 4, wherein the plurality of 2D pathways correspond to a plurality of angles for projecting the 3D model to a 2D plane.
  6. The system of claim 1, wherein the processor circuit is configured to use an angle at which the plurality of x-ray fluoroscopy images were obtained to generate the second 2D pathway.
  7. The system of claim 1, wherein the processor circuit is configured to compute a first projection of the 3D model to a 2D plane to generate the second 2D pathway.
  8. The system of claim 7, wherein the processor circuit is configured to compute a second projection from the second 2D pathway to the 3D model to perform the second co-registration, wherein second projection is an inverse of the first projection.
  9. The system of claim 1, wherein the intravascular data comprises at least one of pressure data, flow data, or imaging data.
  10. The system of claim 1, wherein the first 2D pathway and the second 2D pathway are representative of a same portion of the blood vessel.
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