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(54) METHOD AND SYSTEM FOR SENSITIVITY ANALYSIS IN MODELING BLOOD FLOW CHARACTERISTICS

VERFAHREN UND SYSTEM ZUR SENSITIVITÄTSANALYSE BEI DER MODELLIERUNG VON BLUTFLUSSEIGENSCHAFTEN

PROCÉDÉ ET SYSTÈME POUR UNE ANALYSE DE SENSIBILITÉ EN MODÉLISATION DE CARACTÉRISTIQUES DE DÉBIT SANGUIN

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DescriptionPriority

5 **[0001]** This application claims priority to U.S. Application No. 13/864,996, filed April 17, 2013, which claims the benefit of priority from U.S. Provisional Application No. 61/772,401, filed March 4, 2013.

Technical Field

10 **[0002]** Embodiments of the present disclosure relate to methods and systems for patient-specific modeling of blood flow and, more particularly, to methods and systems for sensitivity analysis in patient-specific modeling of blood flow.
[0003] Several embodiments and examples are disclosed throughout the present text. The scope of protection is however defined in the appended claims.

Background

15 **[0004]** Coronary artery disease may cause the blood vessels providing blood to the heart to develop lesions, such as a stenosis (abnormal narrowing of a blood vessel). As a result, blood flow to the heart may be restricted. A patient suffering from coronary artery disease may experience chest pain, referred to as chronic stable angina during physical exertion or unstable angina when the patient is at rest. A more severe manifestation of disease may lead to myocardial infarction, or heart attack.

20 **[0005]** A need exists to provide more accurate data relating to coronary lesions, e.g., size, shape, location, functional significance (e.g., whether the lesion impacts blood flow), etc. Patients suffering from chest pain and/or exhibiting symptoms of coronary artery disease may be subjected to one or more tests that may provide some indirect evidence relating to coronary lesions. For example, noninvasive tests may include electrocardiograms, biomarker evaluation from blood tests, treadmill tests, echocardiography, single positron emission computed tomography (SPECT), and positron emission tomography (PET). These noninvasive tests, however, typically do not provide a direct assessment of coronary lesions or assess blood flow rates. The noninvasive tests may provide indirect evidence of coronary lesions by looking for changes in electrical activity of the heart (e.g., using electrocardiography (ECG)), motion of the myocardium (e.g., using stress echocardiography), perfusion of the myocardium (e.g., using PET or SPECT), or metabolic changes (e.g., using biomarkers).

25 **[0006]** For example, anatomic data may be obtained noninvasively using coronary computed tomographic angiography (CCTA). CCTA may be used for imaging of patients with chest pain and involves using computed tomography (CT) technology to image the heart and the coronary arteries following an intravenous infusion of a contrast agent. However, CCTA also cannot provide direct information on the functional significance of coronary lesions, e.g., whether the lesions affect blood flow. In addition, since CCTA is purely a diagnostic test, it can neither be used to predict changes in coronary blood flow, pressure, or myocardial perfusion under other physiologic states (e.g., exercise), nor can it be used to predict outcomes of interventions.

30 **[0007]** Thus, patients may require an invasive test, such as diagnostic cardiac catheterization, to visualize coronary lesions. Diagnostic cardiac catheterization may include performing conventional coronary angiography (CCA) to gather anatomic data on coronary lesions by providing a doctor with an image of the size and shape of the arteries. CCA, however, does not provide data for assessing the functional significance of coronary lesions. For example, a doctor may not be able to diagnose whether a coronary lesion is harmful without determining whether the lesion is functionally significant. Thus, CCA has led to a procedure referred to as an "oculostenotic reflex", in which interventional cardiologists insert a stent for every lesion found with CCA regardless of whether the lesion is functionally significant. As a result, CCA may lead to unnecessary operations on the patient, which may pose added risks to patients and may result in unnecessary health care costs for patients.

35 **[0008]** During diagnostic cardiac catheterization, the functional significance of a coronary lesion may be assessed invasively by measuring the fractional flow reserve (FFR) of an observed lesion. FFR is defined as the ratio of the mean blood pressure downstream of a lesion divided by the mean blood pressure upstream from the lesion, e.g., the aortic pressure, under conditions of increased coronary blood flow, e.g., when induced by intravenous administration of adenosine. Blood pressures may be measured by inserting a pressure wire into the patient. Thus, the decision to treat a lesion based on the determined FFR may be made after the initial cost and risk of diagnostic cardiac catheterization has already been incurred.

40 **[0009]** WO2011/128806 describes a system in which a contrast agent is injected into a patient by means of a catheterization procedure and then vasculature is imaged by means of an angiogram. Calculations are performed on the angiogram data to compute various parameters, and new image data is computed corresponding to a virtual (or reconstructed) angiogram. Quality measures are assigned to the different parameters, to represent the accuracy thereof,

based on the difference between the reconstructed angiogram and the original angiogram image data. An error probability indicating the trustability of the simulation result is computed by combining the various quality measures assigned to the different parameters and the value of this single error probability may be displayed overlaid on an image of vasculature.

5 [0010] To reduce the above disadvantages of invasive FFR measurements, HeartFlow Inc. has developed methods for assessing coronary anatomy, myocardial perfusion, and coronary artery flow noninvasively. Specifically, computational fluid dynamics (CFD) simulations have been successfully used to predict spatial and temporal variations of flow rate and pressure of blood in arteries, including FFR. Such methods and systems benefit cardiologists who diagnose and plan treatments for patients with suspected coronary artery disease, and predict coronary artery flow and myocardial perfusion under conditions that cannot be directly measured, e.g., exercise, and to predict outcomes of medical, inter-
10 ventional, and surgical treatments on coronary artery blood flow and myocardial perfusion.

[0011] However, computational modeling of hemodynamics involves reconstructed geometry of the patients' arteries, which is facilitated through high-resolution imaging. For example, many CFD frameworks for noninvasively calculating FFR assume that: (i) the geometry is known with certainty, (ii) clinical variables such as blood pressure, hematocrit, myocardial mass, etc. are known with certainty, and/or (iii) boundary conditions at the inlet and outlets of the computational
15 model are known with certainty. However, in reality, the FFR predicted using CFD varies based on the accuracy of the available data and mathematical models that describe hemodynamics in the arteries. As a result, there is a need for methods and systems for incorporating and quantifying the effects of uncertainties in the available data, as well as mathematical models. In addition, there is a need for methods and systems for assigning confidence intervals to determined FFR values as well as rank the sensitivity of the FFR calculation to different parameters.

20 [0012] The foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the disclosure.

SUMMARY

25 [0013] In accordance with an embodiment, systems are disclosed for determining cardiovascular information for a patient. A system includes at least one computer system configured to:

30 receive non-invasively obtained patient-specific data regarding a geometry of at least the patient's vasculature;
create an anatomic model representing at least a portion of the patient's vasculature based on the patient-specific data;
create a computational model of a blood flow characteristic based on the anatomic model;
identify one or more of an uncertain parameter, an uncertain clinical variable, and an uncertain geometry;
initialize a probability model by constructing a stochastic space for one or more of the identified uncertain parameter,
35 uncertain clinical variable, and uncertain geometry;
determine a blood flow characteristic, and pressure drop, within the patient's vasculature based on the anatomic model and the computational model of the blood flow characteristic of the patient's vasculature;
identify at least one location in the anatomic model where the pressure drop is the highest; and
calculate, based on the probability model and the determined blood flow characteristic, a sensitivity of the determined
40 blood flow characteristic to one or more of the identified uncertain parameter, uncertain clinical variable, and uncertain geometry by simulating or estimating the blood flow characteristic for each point in a set of points in the stochastic space, and repeatedly refining the stochastic space and simulating or estimating the blood flow characteristic for each point in a set of points in the refined stochastic space until a termination criterion is met, locations where the pressure drop in the model is highest being chosen as candidate locations to determine said termination criterion;
wherein the initializing of the probability model comprises initializing stochastic collocation points, each point corresponding to a unique combination of parameters, and said refining of the stochastic space comprises incrementing
45 the collocation level.

[0014] In accordance with another embodiment, corresponding methods are disclosed for determining cardiovascular information for a patient, using at least one computer system.

50 [0015] Additional embodiments and advantages will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the disclosure. The embodiments and advantages will be realized and attained by means of the elements and combinations particularly pointed out below.

BRIEF DESCRIPTION OF THE DRAWINGS

55 [0016] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate several embodiments and together with the description, serve to explain the principles of the disclosure.

Fig. 1 is a schematic diagram of a system for providing various information relating to coronary blood flow in a specific patient, in which the invention may be implemented;

Fig. 2 is a flow chart of a method for providing various information relating to blood flow in a specific patient; and

Fig. 3 is a flow chart that describes an exemplary process for defining input uncertainties, calculating analysis sensitivities, and calculating confidence intervals in FFR, according to an exemplary embodiment of the invention.

DESCRIPTION OF THE EMBODIMENTS

[0017] Reference will now be made in detail to exemplary embodiments, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0018] In an exemplary embodiment, a method and system determines information relating to blood flow in a specific patient using information retrieved from the patient noninvasively. Various embodiments of such a method and system are described in greater detail in U.S. Patent No. 8,315,812, filed January 25, 2011, and entitled "Method and System for Patient-Specific Modeling of Blood Flow," which is hereby incorporated by reference in its entirety.

[0019] In some embodiments, the information determined by the method and system may relate to blood flow in the patient's coronary vasculature. Alternatively, the determined information may relate to blood flow in other areas of the patient's vasculature, such as carotid, peripheral, abdominal, renal, and cerebral vasculature. The coronary vasculature includes a complex network of vessels ranging from large arteries to arterioles, capillaries, venules, veins, etc. The coronary vasculature circulates blood to and within the heart and includes an aorta that supplies blood to a plurality of main coronary arteries (e.g., the left anterior descending (LAD) artery, the left circumflex (LCX) artery, the right coronary (RCA) artery, etc.), which may further divide into branches of arteries or other types of vessels downstream from the aorta and the main coronary arteries. Thus, the exemplary method and system may determine information relating to blood flow within the aorta, the main coronary arteries, and/or other coronary arteries or vessels downstream from the main coronary arteries. Although the aorta and coronary arteries (and the branches that extend therefrom) are discussed below, the disclosed method and system may also apply to other types of vessels.

[0020] In an exemplary embodiment, the information determined by the disclosed methods and systems may include, but is not limited to, various blood flow characteristics or parameters, such as blood flow velocity, pressure (or a ratio thereof), flow rate, and FFR at various locations in the aorta, the main coronary arteries, and/or other coronary arteries or vessels downstream from the main coronary arteries. This information may be used to determine whether a lesion is functionally significant and/or whether to treat the lesion. This information may be determined using information obtained noninvasively from the patient. As a result, the decision whether to treat a lesion may be made without the cost and risk associated with invasive procedures.

[0021] Fig. 1 shows aspects of a system for providing information relating to coronary blood flow in a specific patient. A three-dimensional model 10 of the patient's anatomy may be created using data obtained noninvasively from the patient as will be described below in more detail. Other patient-specific information may also be obtained noninvasively. In an example, the portion of the patient's anatomy that is represented by the three-dimensional model 10 may include at least a portion of the aorta and a proximal portion of the main coronary arteries (and the branches extending or emanating therefrom) connected to the aorta.

[0022] Various physiological laws or relationships 20 relating to coronary blood flow may be deduced, e.g., from experimental data as will be described below in more detail. Using the three-dimensional anatomical model 10 and the deduced physiological laws 20, a plurality of equations 30 relating to coronary blood flow may be determined as will be described below in more detail. For example, the equations 30 may be determined and solved using any numerical method, e.g., finite difference, finite volume, spectral, lattice Boltzmann, particle-based, level set, finite element methods, etc. The equations 30 can be solved to determine information (e.g., pressure, velocity, FFR, etc.) about the coronary blood flow in the patient's anatomy at various points in the anatomy represented by the model 10.

[0023] The equations 30 may be solved using a computer 40. Based on the solved equations, the computer 40 may output one or more images or simulations indicating information relating to the blood flow in the patient's anatomy represented by the model 10. For example, the image(s) may include a simulated blood pressure model 50, a simulated blood flow or velocity model 52, a computed FFR (cFFR) model 54, etc., as will be described in further detail below. The simulated blood pressure model 50, the simulated blood flow model 52, and the cFFR model 54 provide information regarding the respective pressure, velocity, and cFFR at various locations along three dimensions in the patient's anatomy represented by the model 10. cFFR may be calculated as the ratio of the blood pressure at a particular location in the model 10 divided by the blood pressure in the aorta, e.g., at the inflow boundary of the model 10, under conditions of increased coronary blood flow, e.g., conventionally induced by intravenous administration of adenosine.

[0024] In an example, the computer 40 may include one or more non-transitory computer-readable storage devices that store instructions that, when executed by a processor, computer system, etc., may perform any of the actions described herein for providing various sources of information relating to blood flow in the patient. The computer 40 may

include a desktop or portable computer, a workstation, a server, a personal digital assistant, or any other computer system. The computer 40 may include a processor, a read-only memory (ROM), a random access memory (RAM), an input/output (I/O) adapter for connecting peripheral devices (e.g., an input device, output device, storage device, etc.), a user interface adapter for connecting input devices such as a keyboard, a mouse, a touch screen, a voice input, and/or other devices, a communications adapter for connecting the computer 40 to a network, a display adapter for connecting the computer 40 to a display, etc. For example, the display may be used to display the three-dimensional model 10 and/or any images generated by solving the equations 30, such as the simulated blood pressure model 50, the simulated blood flow model 52, and/or the cFFR model 54.

[0025] Fig. 2 shows aspects of a method for providing various sources of information relating to blood flow in a specific patient. The method may include obtaining patient-specific anatomical data, such as information regarding the patient's anatomy (e.g., at least a portion of the aorta and a proximal portion of the main coronary arteries (and the branches extending therefrom) connected to the aorta), and preprocessing the data (step 100). The patient-specific anatomical data may be obtained noninvasively, e.g., by CCTA.

[0026] A three-dimensional model of the patient's anatomy may be created based on the obtained anatomical data (step 200). For example, the three-dimensional model may be the three-dimensional model 10 of the patient's anatomy described above in connection with Fig. 1.

[0027] The three-dimensional model may be prepared for analysis and boundary conditions may be determined (step 300). For example, the three-dimensional model 10 of the patient's anatomy described above in connection with Fig. 1 may be trimmed and discretized into a volumetric mesh, e.g., a finite element or finite volume mesh. The volumetric mesh may be used to generate the equations 30 described above in connection with Fig. 1.

[0028] Boundary conditions may also be assigned and incorporated into the equations 30 described above in connection with Fig. 1. The boundary conditions provide information about the three-dimensional model 10 at its boundaries, e.g., inflow boundaries, outflow boundaries, vessel wall boundaries, etc. The inflow boundaries may include the boundaries through which flow is directed into the anatomy of the three-dimensional model, such as at an end of the aorta near the aortic root. Each inflow boundary may be assigned, e.g., with a prescribed value or field for velocity, flow rate, pressure, or other characteristic, by coupling a heart model and/or a lumped parameter model to the boundary, etc. The outflow boundaries may include the boundaries through which flow is directed outward from the anatomy of the three-dimensional model, such as at an end of the aorta near the aortic arch, and the downstream ends of the main coronary arteries and the branches that extend therefrom. Each outflow boundary can be assigned, e.g., by coupling a lumped parameter or distributed (e.g., a one-dimensional wave propagation) model. The prescribed values for the inflow and/or outflow boundary conditions may be determined by noninvasively measuring physiologic characteristics of the patient, such as, but not limited to, cardiac output (the volume of blood flow from the heart), blood pressure, myocardial mass, etc. The vessel wall boundaries may include the physical boundaries of the aorta, the main coronary arteries, and/or other coronary arteries or vessels of the three-dimensional model 10.

[0029] The computational analysis may be performed using the prepared three-dimensional model and the determined boundary conditions (step 400) to determine blood flow information for the patient. For example, the computational analysis may be performed with the equations 30 and using the computer 40 described above in connection with Fig. 1 to produce the images described above in connection with Fig. 1, such as the simulated blood pressure model 50, the simulated blood flow model 52, and/or the cFFR model 54.

[0030] The method may also include providing patient-specific treatment options using the results (step 500). For example, the three-dimensional model 10 created in step 200 and/or the boundary conditions assigned in step 300 may be adjusted to model one or more treatments, e.g., placing a coronary stent in one of the coronary arteries represented in the three-dimensional model 10 or other treatment options. Then, the computational analysis may be performed as described above in step 400 in order to produce new images, such as updated versions of the blood pressure model 50, the blood flow model 52, and/or the cFFR model 54. These new images may be used to determine a change in blood flow velocity and pressure if the treatment option(s) are adopted.

[0031] The systems and methods disclosed herein may be incorporated into a software tool accessed by physicians to provide a noninvasive means to quantify blood flow in the coronary arteries and to assess the functional significance of coronary artery disease. In addition, physicians may use the software tool to predict the effect of medical, interventional, and/or surgical treatments on coronary artery blood flow. The software tool may prevent, diagnose, manage, and/or treat disease in other portions of the cardiovascular system including arteries of the neck (e.g., carotid arteries), arteries in the head (e.g., cerebral arteries), arteries in the thorax, arteries in the abdomen (e.g., the abdominal aorta and its branches), arteries in the arms, or arteries in the legs (e.g., the femoral and popliteal arteries). The software tool may be interactive to enable physicians to develop optimal personalized therapies for patients.

[0032] For example, the software tool may be incorporated at least partially into a computer system, e.g., the computer 40 shown in Fig. 1 used by a physician or other user. The computer system may receive data obtained noninvasively from the patient (e.g., data used to create the three-dimensional model 10, data used to apply boundary conditions or

perform the computational analysis, etc.). For example, the data may be input by the physician or may be received from another source capable of accessing and providing such data, such as a radiology or other medical lab. The data may be transmitted via a network or other system for communicating the data, or directly into the computer system. The software tool may use the data to produce and display the three-dimensional model 10 or other models/meshes and/or any simulations or other results determined by solving the equations 30 described above in connection with Fig. 1, such as the simulated blood pressure model 50, the simulated blood flow model 52, and/or the cFFR model 54. Thus, the software tool may perform steps 100-500. In step 500, the physician may provide further inputs to the computer system to select possible treatment options, and the computer system may display to the physician new simulations based on the selected possible treatment options. Further, each of steps 100-500 shown in Fig. 2 may be performed using separate software packages or modules.

[0033] Alternatively, the software tool may be provided as part of a web-based service or other service, e.g., a service provided by an entity that is separate from the physician. The service provider may, for example, operate the web-based service and may provide a web portal or other web-based application (e.g., run on a server or other computer system operated by the service provider) that is accessible to physicians or other users via a network or other methods of communicating data between computer systems. For example, the data obtained noninvasively from the patient may be provided to the service provider, and the service provider may use the data to produce the three-dimensional model 10 or other models/meshes and/or any simulations or other results determined by solving the equations 30 described above in connection with Fig. 1, such as the simulated blood pressure model 50, the simulated blood flow model 52, and/or the cFFR model 54. Then, the web-based service may transmit information relating to the three-dimensional model 10 or other models/meshes and/or the simulations so that the three-dimensional model 10 and/or the simulations may be displayed to the physician on the physician's computer system. Thus, the web-based service may perform steps 100-500 and any other steps described below for providing patient-specific information. In step 500, the physician may provide further inputs, e.g., to select possible treatment options or make other adjustments to the computational analysis, and the inputs may be transmitted to the computer system operated by the service provider (e.g., via the web portal). The web-based service may produce new simulations or other results based on the selected possible treatment options, and may communicate information relating to the new simulations back to the physician so that the new simulations may be displayed to the physician.

[0034] As described above, the above described techniques for computational modeling for noninvasively calculating FFR may assume that: (i) the geometry is known with certainty, (ii) clinical variables such as blood pressure, hematocrit, myocardial mass, etc. are known with certainty, and/or (iii) boundary conditions at the inlet and outlets of the computational model are known with certainty. However, in reality, the FFR predicted using CFD varies based on the accuracy of the available data and mathematical models that describe hemodynamics in the arteries.

[0035] Accordingly, the present disclosure also describes methods and systems for incorporating and quantifying the effects of uncertainties in the available data, as well as mathematical models. In addition, the present disclosure describes methods and systems for assigning confidence intervals to determine FFR values, as well as rank the sensitivity of FFR calculations to different parameters.

[0036] For example, Fig. 3 is a flow chart that describes an exemplary method 600 for defining input uncertainties, calculating FFR analysis sensitivities, and calculating confidence intervals in FFR, according to an exemplary embodiment. As shown in Fig. 3, method 600 may include a plurality of pre-processing steps, including defining sources of uncertainty and their magnitude. For example, method 600 may include generating a list of uncertain parameters (step 602), determining uncertainty in clinical variables (step 604), such as myocardial mass, hematocrit/viscosity, pressure, body/surface area, and/or geometric variables such as maximal stenosis diameter, stenosis length, etc., and determining uncertainty in patient geometry (step 606).

[0037] Method 600 may also include assigning a probability and/or error associated with each of the variables. By way of example, hematocrit may have a uniform distribution between 40 and 50 (any value between 40 and 50 is equally probable), blood pressure may be a Gaussian distribution with mean 100 mm Hg and standard deviation 10 mm Hg (the probabilities to pressure around 100 mm Hg may be assigned based on the Gaussian distribution). A stochastic space may therefore be defined as the range of these values. Although the present disclosure describes computing sensitivities using a stochastic collocation method, any other equivalent statistical technique for evaluating input sensitivities may be used. Moreover, although the present disclosure describes a stochastic collocation method based on the Smolyak quadrature method, again, any other equivalent method to compute sensitivities may be used. The Smolyak quadrature method is an exemplary method for interpolating and integrating functions when the number of input variables is higher than, e.g., 3 or 4. The stochastic collocation method may apply the Smolyak quadrature method to evaluate sensitivities and quantify the effect of input uncertainties on the outputs.

[0038] Method 600 may then include simulation and analysis steps for computing the effect of input uncertainty on outputs (step 608). For example, method 600 may include initializing collocation points, each of which corresponds to a unique combination of parameters, e.g., using a coarse sparse grid (depending on the number of parameters, n , the number of initial collocation points would be of the order of $2n$ or so). In one embodiment, the presently disclosed adaptive

stochastic collocation method may split the created stochastic space into frozen and active patches (based on how the quantity-of-interest varies in the parameter space), and only the active patches may be further refined. Moreover, in one embodiment, adaptive refinement criterion may be chosen based on a difference in FFR between two successive grids. In addition, the solution at each collocation point may be initialized based on the solution obtained at the previous collocation point. Finally, the input uncertainties may be tailored to various blood flow and/or cardiac parameters, such as myocardial mass, viscosity, brachial pressure, etc.

[0039] For each of a plurality of collocation points, method 600 may optionally include performing various "pre-solving" techniques (step 610). For example, method 600 may include performing any of the various presolving techniques described in U.S. Application No. 13/625,628, filed September 24, 2012.

[0040] Method 600 may then include, for each of a plurality of collocation points, executing a coronary solver (step 612) for performing simulations to non-invasively, and computationally, obtain one or more FFR values. For example, method 600 may include performing any of the various computational FFR modeling techniques described in U.S. Patent No. 8,315,812, filed January 25, 2011.

[0041] Thus, as described in the '812 patent, FFR values may be obtained by generating a flow approximation or surrogate computational model based on an anatomic model of a patient, and analyzing the surrogate computational model to estimate an FFR value for one or more locations in a patient's vasculature. For example, an anatomic model may be created by generating a three-dimensional anatomic model of a patient's coronary vasculature. A surrogate computation model or flow approximation of the anatomic model may then be created, e.g., by generating a reduced-order model of the patient's vasculature. In one embodiment, the reduced-order model may be a one-dimensional or lumped parameter model of the patient's vasculature. In one embodiment, the anatomic model may be a one-dimensional wave propagation model and the surrogate computational model may also be a one-dimensional wave propagation model.

[0042] In one embodiment, FFR values may be obtained using machine learning estimates as opposed to physics-based simulations. In other words, instead of executing a coronary solver, such as in the '812 patent, for each of the plurality of collocation points, method 600 may efficiently estimate blood flow characteristics based on knowledge gleaned from analyzing blood flow of numerous other patients. For example, method 600 may include performing any of the various machine learning techniques described in U.S. Provisional Patent Application No. 61/700,213, filed September 12, 2012. Thus, in one embodiment, FFR values may be obtained by training a machine learning algorithm to estimate FFR values for various points of patient geometry based on feature vectors of patient physiological parameters and measured blood flow characteristics, and then applying the machine learning algorithm to a specific patient's geometry and physiological parameters to obtain predicted FFR values.

[0043] Based on these results, method 600 may construct an approximation to FFR in the stochastic space. In one embodiment, method 600 may include reading the FFR solution(s) (step 614) and, for example, computing various means, standard deviations, and confidence intervals based on the reconstructed FFR.

[0044] Method 600 may then include determining whether "statistics converged" based on whether termination criteria were met, in which case method 600 may proceed to post processing steps (step 616), or they were not met, in which case method 600 may perform adaptive refinement and return to initializing collocation points for performing simulations (step 608). In one embodiment, termination criterion may determine whether the algorithm terminates based on whether all collocation points belong to a frozen set. A collocation point may be considered frozen if either (a) all of its neighbors are frozen, or (b) the FFR value at this collocation point between two consecutive refinement levels is less than a cutoff.

[0045] If termination criterion were met (i.e., statistics converged), then method 600 may include performing post-processing steps, such as evaluating statistics of the outputted FFR values (step 616). For example, using the reconstructed FFR, method 600 may evaluate a probability density function of the FFR at each spatial point (surface nodes). From this, the standard deviation of FFR and confidence intervals can be evaluated throughout the computational model.

[0046] One or more confidence interval values may be generated for each predicted FFR value, based on probability information generated in step 616. For example, the method may involve generating a confidence value for a specific generated FFR value (e.g., 90% confidence in an FFR value of .85). In one embodiment, the method may include recalculating or re-estimating an FFR value if the determined confidence level is below a predetermined threshold (e.g., 90%). By outputting and displaying a confidence level in relation to each estimated FFR value, physicians may be provided with more information, insights, and certainty regarding the reliability of an estimated FFR value. For example, if a patient exhibits a problematic FFR value (e.g., less than .80) and the generated confidence level is high, a physician may be more confident in prescribing a treatment or intervention. By contrast, if a patient's FFR value is borderline problematic (e.g., .80 to .85) and the generated confidence level is low, a physician may be more inclined to perform further testing before prescribing a treatment or intervention.

[0047] As an alternative or additional embodiment, the method may include generating a range of FFR values consistent with a desired confidence interval. For example, given a desired confidence interval of 95%, the method may include generating a range of FFR values for which there is a 95% chance that the actual FFR value falls within the output range (e.g., there is a 95% confidence that FFR is .82-.87). It will be appreciated that reducing the desired confidence value may cause narrowing of the outputted FFR range, whereas increasing the desired confidence value may cause expanding

of the outputted FFR range. In one embodiment, any indication of a calculated sensitivity or confidence level may be displayed in relation to an output FFR value.

[0048] The exemplary method 600 of Fig. 3 may be performed by computer 40 of Fig. 1, or by any other computer(s), server(s), or handheld electronic device(s). Additional exemplary embodiments of method 600 will now be described with respect to both general and specific embodiments, any of which may be performed in combination with any of the techniques of U.S. Application No. 13/625,628, filed September 24, 2012, and/or of U.S. Patent No. 8,315,812, filed January 25, 2011. Accordingly, the above method 600 and the below described general and specific exemplary embodiments may be used to determine sensitivity of computed FFR values to input uncertainties, and/or calculate confidence intervals of computed FFR values based on determined sensitivity.

Exemplary Embodiment

[0049] In an exemplary general embodiment, a method for quantifying uncertainties in FFR calculations involves acquiring a digital representation of a CCTA scan of the patient, including all the arteries of interest. This scan may be stored and converted to a computational model of the patient-specific geometry of all the relevant blood vessels. The computational model may be trimmed at locations (determined by geometrical parameters) where specific boundary conditions are enforced, thus quantifying the effect of all vessels and micro-vessels downstream of that location. Values of clinical variables such as patient hematocrit, brachial blood pressure, etc. may be obtained.

[0050] In addition, uncertain parameters/variables may be identified and assigned, such as by identifying inputs that are uncertain, such as clinical variables, e.g., hematocrit, pressure, body surface area, and/or geometric variables, such as lesion size, lesion length, etc. A probability/error may be assigned and associated with each of the variables. The probability may model a combination of diurnal variation in the entity, noise in the data, inadequate information, and/or error incurred in using generalized empirical models. The method may involve analyzing which variables affect the quantity(ies) of interest, and choosing an optimal subset of the variables that might affect the quantities of interest.

[0051] The exemplary general method for quantifying uncertainties may also include certain pre-processing steps, such as constructing a coarse stochastic space for all identified variables. The method may include initializing stochastic collocation (e.g., quadrature) points using, for example, the Smolyak sparse grid algorithm, with each point corresponding to a unique combination of parameters. The number of collocation points may depend on the collocation (quadrature) level. Collocation levels may be nested, with level 0 corresponding to only one simulation and the number increasing with levels. The actual number may depend on the number of stochastic variables.

[0052] In one embodiment, if the technique identifies, e.g., n variables, then initially the collocation points may correspond to the quadrature points of a coarse (e.g., level 1) Smolyak sparse grid. These collocation points lie in a $[0,1]$ hypercube space. The collocation points may be mapped from $[0,1]$ to clinically relevant values using transformations employing the inverse cumulative distribution function. Then, each collocation point may correspond to a unique set of inputs to the simulations, and each collocation point may be assigned a status, i.e., "active" or "frozen." In one embodiment, all collocation points may be initially assigned "active."

[0053] The exemplary general method for quantifying uncertainties may then include performing CFD simulations at one or more of the collocation points. For example, in one embodiment, a CFD simulation may be performed at each identified point. If at least one active collocation point exists, the quadrature level may be incremented and only collocation points with at least one active neighbor may be picked. The quadrature level may be incremented, and for each new collocation point, the method may calculate the difference between a quantity of interest's interpolated value (e.g., using Lagrange polynomials) using the previous quadrature level and its actual value using a simulation. If this difference is less than a preset threshold, this collocation point may be labeled "frozen." Otherwise, the point may be labeled "active."

[0054] Finally, the exemplary general method for quantifying uncertainties may include certain post-processing steps, such as calculating variability in quantities of interest. For example, the method may include constructing Lagrange polynomial interpolates of a quantity of interest in the stochastic space, such as for predicting a quantity of interest corresponding to parameter combinations where simulations were not performed. In addition, the method may include computing a probability distribution function of the quantity of interest by sampling the stochastic space according to the assigned probabilities.

Exemplary Embodiment

[0055] Described below is a specific embodiment of the technique to quantify the effect of uncertainties and compute confidence intervals in the output.

1. Acquire a digital representation of the following information for a patient suspected to have coronary disease.

a. A CCTA of the patient may be performed to visualize and compute all the vessels of interest, including ascending aorta, left/right coronary artery, left circumflex artery, left obtuse marginal, and/or all other vessels of interest that

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are visible. The scanned images may be cleaned and post-processed to obtain a computational domain within which simulations will be performed.

b. In addition to CCTA, a set of clinical parameters may be measured, including heart-rate, systolic and diastolic brachial blood pressures, hematocrit, patient height and weight, and patient history, such as smoking status, presence/absence of diabetes, etc.

c. A set of derived quantities may be calculated from steps (a) and (b). These derived quantities may include:

i. Myocardial mass (m_{myo}) - Obtained by image segmentation of the left ventricle to calculate the volume of myocardium and multiplying it with a density (usually assumed constant-1.05 g/cm³).

ii. Body surface area - Calculated from the patient height (h) and weight (w) as

$$BSA = \sqrt{\frac{hw}{3600}}$$

iii. Viscosity - calculated from the hematocrit (hem) as

$$\eta = \frac{c}{\left(1 - \frac{hem}{100}\right)^{2.5}}$$

where c is 0.0012.

iv. Inlet aortic flow rate (Q) - Calculated from scaling studies as

$$Q = \frac{1}{60} BSA^{1.15}$$

v. Coronary flow rate (q_{cor}) - Calculated from myocardial mass as

$$q_{cor} = c_{dil} \frac{5.09}{60} m_{myo}^{0.75}$$

where c_{dil} is the dilation factor.

vi. Coronary resistance - The net coronary resistance is calculated from the desired coronary flow, and the value for individual outlets is calculated based on their areas.

vii. Resistance of outlet aorta - This may be calculated based on aortic pressure, aortic flow rate and desired coronary flow rate.

2. For each patient that underwent CCTA, identify and model the input uncertainties in the following exemplary manner:

a. Clinical variables: Clinical parameters, especially those derived (1c), may be uncertain. They may be modeled using a probability distribution function, typically Gaussian, unless the exact form is known.

b. Geometry variables: Size of vessel wall (especially near lesions), length of lesions and location of trim planes.

c. Modeling assumptions: Coronary flow rate versus mass (dependence on other parameters), aortic flow rate on BSA, outflow resistances on the area of trimmed outlets.

3. Construct a coarse stochastic space of all uncertain entities:

a. Each combination of parameters may correspond to a quadrature or collocation point. For one dimension, the collocation points may correspond to Chebyshev nodes (zeros of the Chebyshev polynomials) in the interval 0 to 1. These can be extended to multiple dimensions by constructing a tensor product of the one-dimensional Chebyshev nodes. The Smolyak sparse grid may choose a subset of these nodes to accelerate convergence but still maintaining accuracy.

b. For a given variable, say α , the transformation from $\xi \in [0,1]$ to $[\alpha_L, \alpha_U]$ may follow the inverse cumulative distribution function (cdf) of α , $\alpha = \mu_\alpha + \sigma_\alpha \text{cdf}^{-1}(2\xi - 1)$ where μ_α is the mean value of α and σ_α is its standard deviation. To prevent unbounded transformations for pdf's with infinite support (e.g., Gaussian distribution), ξ may be initially mapped to $[0.01, 0.99]$ prior to the inverse CFD transformation in such cases. If α is a Gaussian variable, this may transform to $\alpha = \mu_\alpha + \text{erf}^{-1}(0.99 * (2\xi - 1))$. Each abscissa of the collocation point may be transformed based on this function.

c. The following variables may be assumed Gaussian with a mean and standard deviation. Standard deviations for blood pressure, myo-mass scaling coefficient, and viscosity may be derived from literature studies. Standard deviation for the myocardial mass may be obtained from an in-house gage study (density may be assumed constant).

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variable	mean	coefficient of variation
viscosity	$\eta = \frac{c}{\left(1 - \frac{hem}{100}\right)^{2.5}}$	10%
blood pressure	$(p_{sys} + 2p_{dias})/3$	10%
myocardial mass	myocardium segmentation	7.5%
coefficient	0.083	15%

d. For calculating sensitivity due to geometry, each segment of vessel between two ostia points may be assumed to be represented using a single random variable, which dilates or contracts the segment. If there are multiple stenoses in serial, correlated random variables may also be used to model uncertainty in geometry. The amount of vaso-dilation or vaso-contraction may be determined on a lesion-specific basis. Other techniques for dilating and contracting, such as using the radius along the centerline, 3D position of each node, and/or grouping together nodes between ostia, may also be used.

e. Each grouping of the vessel may be further analyzed. For instance, if the sensitivity of a group is deemed high, it may be split into two groups, and procedure (e) is repeated until sufficient localization of high sensitivity regions is achieved.

4. Processing:

a. At each active collocation point, CFD simulations may be performed using resistance boundary conditions (the ratio of pressure drop to flow rate is a constant). The pressure and velocity solutions at each collocation point may be initialized based on the solution obtained at the previous collocation point. Lumen locations where the pressure drop in the model is the highest may be chosen as candidate locations to determine termination criterion of the collocation algorithm. Based on these results, an approximation to FFR in the stochastic space may be constructed.

b. The collocation level may be incremented. At the new collocation points, the difference in the FFR at the ten identified locations between simulation and interpolated value using the previous collocation level may be calculated. A tolerance of 10^{-2} may be set, and hence the status of a point may be changed to frozen if $|FFR_{sim} - FFR_{interp}| \leq 10^{-2}$. This step may be repeated until all collocation points are frozen.

5. Post-processing:

a. Mean, standard deviation, and lower order moments of FFR may be obtained by integrating the FFR at each spatial location in the stochastic space. This may be performed by integrating products of Lagrange polynomials (offline) and summing the result with corresponding FFR solution obtained through the solution.

b. Confidence intervals may be calculated by sampling the stochastic space at between 50000-100000 points, extracting a histogram, and subsequently extracting the cumulative distribution function.

[0056] One or more of the steps described herein may be performed by one or more human operators (e.g., a cardiologist or other physician, the patient, an employee of the service provider providing the web-based service or other service provided by a third party, other user, etc.), or one or more computer systems used by such human operator(s), such as a desktop or portable computer, a workstation, a server, a personal digital assistant, etc. The computer system(s) may be connected via a network or other method of communicating data.

[0057] Any aspect set forth in any embodiment may be used with any other embodiment set forth herein. Every device and apparatus set forth herein may be used in any suitable medical procedure, may be advanced through any suitable body lumen and body cavity, and may be used for imaging any suitable body portion.

[0058] Various modifications and variations can be made in the disclosed systems and processes without departing from the scope of the disclosure. Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosure disclosed herein. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the disclosure being indicated by the following claims.

Claims

1. A system for determining cardiovascular information for a patient, the system comprising:
at least one computer system configured to:

5 receive non-invasively obtained patient-specific data regarding a geometry of at least the patient's vasculature;
create an anatomic model representing at least a portion of the patient's vasculature based on the patient-specific data;
10 create a computational model of a blood flow characteristic based on the anatomic model;
identify one or more of an uncertain parameter, an uncertain clinical variable, and an uncertain geometry;
initialize a probability model by constructing a coarse stochastic space for one or more of the identified uncertain parameter, uncertain clinical variable, and uncertain geometry;
15 determine a blood flow characteristic, and pressure drop, within the patient's vasculature based on the anatomic model and the computational model of the blood flow characteristic of the patient's vasculature;
identify at least one location in the anatomic model where the pressure drop is the highest; and

20 calculate, based on the probability model and the determined blood flow characteristic, a sensitivity of the determined blood flow characteristic to one or more of the identified uncertain parameter, uncertain clinical variable, and uncertain geometry by simulating or estimating the blood flow characteristic for each point in a set of points in the stochastic space, and repeatedly refining the stochastic space and simulating or estimating the blood flow characteristic for each point in a set of points in the refined stochastic space until a termination criterion is met, locations where the pressure drop in the model is highest being chosen as candidate locations to determine said termination criterion;

and

25 the initializing of the probability model comprises initializing stochastic collocation points, each point corresponding to a unique combination of parameters, and said refining of the stochastic space comprises incrementing the collocation level.

- 30 2. The system of claim 1, wherein the computational model of the blood flow characteristic is a reduced order model or a one dimensional model.

- 35 3. The system of claim 1, wherein the anatomic model is a three-dimensional model, a four-dimensional model, or a one-dimensional wave propagation model.

- 40 4. The system of claim 1 wherein the sensitivity is calculated based on the Smolyak quadrature method.

- 45 5. The system of claim 1, wherein:

40 the uncertain clinical variable is one or more of a myocardial mass, hematocrit, viscosity, pressure, body or surface area, heart-rate, systolic and diastolic brachial blood pressures, patient height, patient weight, patient history, smoking status, and presence/absence of diabetes; and
the uncertain geometry is one or more of maximal stenosis diameter, stenosis length, stenosis location, lesion size, lesion length, or healthy segments with image-based artifacts.

- 50 6. The system of claim 1, wherein:

blood flow characteristic is a fractional flow reserve value;

the fractional flow reserve indicates a ratio between a pressure in the aorta and a pressure at a location in the vasculature; and

55 the at least one computer system is configured to determine the fractional flow reserve at a plurality of locations in the vasculature.

7. The system of claim 1, wherein the patient-specific data includes data obtained from computer tomography or magnetic resonance imaging techniques.

8. The system of claim 1, wherein the at least one computer system is configured to create the anatomic model based on the imaging data by locating boundaries of lumens of the patient's vasculature using the imaging data.

9. The system of claim 1, wherein the model of the blood flow characteristic includes at least one lumped parameter model representing a blood flow through boundaries of the anatomic model.
10. The system of claim 1, wherein the at least one computer system is configured to determine the blood flow characteristic using a parameter associated with at least one of a level of hyperemia, a level of exercise, or a medication.
11. The system of claim 10 wherein the at least one computer system is configured to determine the blood flow characteristic using a parameter associated with the level of hyperemia, and the parameter relates to a coronary artery resistance of the patient, an aortic blood pressure of the patient, or a heart rate of the patient.
12. The system of claim 1, wherein the at least one computer system is configured to display an indicator of the calculated sensitivity in relation to the determined blood flow characteristic.

Patentansprüche

1. System zum Bestimmen kardiovaskulärer Informationen für einen Patienten, das System umfassend: mindestens ein Computersystem, das dafür ausgelegt, ist:

nichtinvasiv erlangte patientenspezifische Daten bezüglich einer Geometrie mindestens des Gefäßsystems des Patienten zu empfangen,
 ein anatomisches Modell, das mindestens einen Teil des Gefäßsystems des Patienten darstellt, basierend auf den patientenspezifischen Daten zu erstellen,
 ein Berechnungsmodell einer Blutflusseigenschaft basierend auf dem anatomischen Modell zu erstellen,
 einen oder mehrere von einem unsicheren Parameter, einer unsicheren klinischen Variablen und einer unsicheren Geometrie zu erkennen,
 ein Wahrscheinlichkeitsmodell durch Aufbauen eines groben stochastischen Raums für einen oder mehrere von dem unsicheren Parameter, der unsicheren klinischen Variablen und der unsicheren Geometrie zu initialisieren,
 eine Blutflusseigenschaft und einen Druckabfall innerhalb des Gefäßsystems des Patienten basierend auf dem anatomischen Modell und dem Berechnungsmodell der Blutflusseigenschaft des Gefäßsystems des Patienten zu ermitteln,
 mindestens eine Stelle im anatomischen Modell zu identifizieren, wo der Druckabfall am höchsten ist, und basierend auf dem Wahrscheinlichkeitsmodell und der ermittelten Blutflusseigenschaft, eine Sensitivität der ermittelten Blutflusseigenschaft auf einen oder mehrere von dem erkannten unsicheren Parameter, der erkannten unsicheren klinischen Variablen und der erkannten unsicheren Geometrie durch Simulieren oder Abschätzen der Blutflusseigenschaft für jeden Punkt in einem Satz von Punkten in dem stochastischen Raum und wiederholtes Verfeinern des stochastischen Raums und Simulieren oder Abschätzen der Blutflusseigenschaft für jeden Punkt in einem Satz von Punkten in dem verfeinerten stochastischen Raum zu berechnen, bis ein Beendigungskriterium erreicht ist, wobei die Stellen, an denen der Druckabfall am höchsten ist, als in Frage kommende Stellen zum Bestimmen des Beendigungskriteriums gewählt werden, und wobei das Initialisieren des Wahrscheinlichkeitsmodells das Initialisieren stochastischer Kollokationspunkte umfasst, wobei jeder Punkt einer einzigartigen Kombination von Parametern entspricht, und wobei das Verfeinern des stochastischen Raums das schrittweise Erhöhen des Kollokationsniveaus umfasst.

2. System nach Anspruch 1, wobei das Berechnungsmodell der Blutflusseigenschaft ein Modell reduzierter Ordnung oder ein eindimensionales Modell ist.
3. System nach Anspruch 1, wobei das I ein dreidimensionales Modell, ein vierdimensionales Modell oder ein eindimensionales Wellenausbreitungsmodell ist.
4. System nach Anspruch 1, wobei die Sensitivität basierend auf dem Smolyak-Quadraturverfahren berechnet wird.
5. System nach Anspruch 1, wobei:

die unsichere klinische Variable eine oder mehrere ist von einer elektrokardiographischen Masse, Hämatokrit, Viskosität, Druck, Körper- oder Oberflächenbereich, Herzfrequenz, systolische und diastolische Oberarmblutdrücke, Patientengröße, Patientengewicht, Patientengeschichte, Rauchverhalten und Vorliegen/Nichtvorliegen

von Diabetes, und
die unisichere Geometrie eine oder mehrere ist von maximalem Stenosedurchmesser, Stenosenlänge, Stenoseposition, Läsionsgröße, Läsionslänge oder gesunden Segmenten mit bildbasierten Artefakten.

- 5 6. System nach Anspruch 1, wobei:
- die Blutflusseigenschaft ein fraktioneller Flussreservewert ist,
die fraktionelle Flussreserve ein Verhältnis zwischen einem Druck in der Aorta und einem Druck an einer Stelle
im Gefäßsystem angibt, und
10 das mindestens eine Computersystem dafür ausgelegt ist, die fraktionelle Flussreserve an mehreren Stellen
im Gefäßsystem zu ermitteln.
7. System nach Anspruch 1, wobei die patientenspezifischen Daten aus bildgebenden Computertomographie- oder
Magnetresonanz-Verfahren erlangte Daten umfassen.
15
8. System nach Anspruch 1, wobei das mindestens eine Computersystem dafür ausgelegt ist, ein anatomisches Modell
basierend auf den bildgebenden Daten durch Ortung von Grenzen von Lumen des Gefäßsystems des Patienten
unter Verwendung der bildgebenden Daten zu erstellen.
- 20 9. System nach Anspruch 1, wobei das Modell der Blutflusseigenschaft mindestens ein konzentriertes Parametermodell
aufweist, das einen Blutfluss durch Grenzen des anatomischen Modells darstellt.
10. System nach Anspruch 1, wobei das mindestens eine Computersystem dafür ausgelegt ist, eine Blutflusseigenschaft
unter Verwendung eines Parameters, der mit wenigstens einem von einem Hyperämiegrad, einem Trainingszustand
und einem Medikament verbunden ist, zu ermitteln.
25
11. System nach Anspruch 10, wobei das mindestens eine Computersystem dafür ausgelegt ist, die Blutflusseigenschaft
unter Verwendung eines Parameters zu ermitteln, der mit dem Hyperämiegrad verbunden ist, wobei sich der Pa-
rameter auf einen Herzkranzgefäßwiderstand des Patienten, einen Aorten-Blutdruck des Patienten oder eine Herz-
frequenz des Patienten bezieht.
30
12. System nach Anspruch 1, wobei das mindestens eine Computersystem dafür ausgelegt ist, einen Indikator der
berechneten Sensitivität in Bezug auf die ermittelte Blutflusseigenschaft anzuzeigen.

35

Revendications

1. Système pour déterminer des informations cardiovasculaires pour un patient, le système comprenant :
au moins un système informatique configuré pour :
40
- recevoir des données obtenues de façon non invasive spécifiques au patient concernant une géométrie d'au
moins le système vasculaire du patient ;
créer un modèle anatomique représentant au moins une partie du système vasculaire du patient sur la base
des données spécifiques au patient ;
45 créer un modèle de calcul d'une caractéristique de circulation sanguine sur la base du modèle anatomique ;
identifier l'un ou plusieurs parmi un paramètre incertain, une variable clinique incertaine et une géométrie
incertaine ;
initialiser un modèle de probabilité par construction d'un espace stochastique grossier pour l'un ou plusieurs
parmi le paramètre incertain, la variable clinique incertaine, et la géométrie incertaine identifié ;
50 déterminer une caractéristique de circulation sanguine, et une chute de pression, dans le système vasculaire
du patient sur la base du modèle anatomique et le modèle de calcul de la caractéristique de circulation sanguine
du système vasculaire du patient ;
identifier au moins un emplacement dans le modèle anatomique où la chute de pression est la plus élevée ; et
calculer, sur la base du modèle de probabilité et de la caractéristique de circulation sanguine déterminée, une
55 sensibilité de la caractéristique de circulation sanguine déterminée à un ou plusieurs parmi le paramètre incertain,
la variable clinique incertaine et la géométrie incertaine identifié par simulation ou estimation de la caractéristique
de circulation sanguine pour chaque point dans un ensemble de points dans l'espace stochastique, et l'affinage
répété de l'espace stochastique et la simulation ou l'estimation de la caractéristique de circulation sanguine

pour chaque point dans un ensemble de points dans l'espace stochastique affiné jusqu'à ce qu'un critère de terminaison soit satisfait, les emplacements où la chute de pression dans le modèle est la plus élevée étant choisis en tant qu'emplacements candidats pour déterminer ledit critère de terminaison ; et l'initialisation du modèle de probabilité comprend l'initialisation de points de colocalisation stochastiques, chaque point correspondant à une combinaison unique de paramètres, et ledit affinage de l'espace stochastique comprend l'incrémentement du niveau de colocalisation.

2. Système selon la revendication 1, dans lequel le modèle de calcul de la caractéristique de circulation sanguine est un modèle d'ordre réduit ou un modèle unidimensionnel.

3. Système selon la revendication 1, dans lequel le modèle anatomique est un modèle tridimensionnel, un modèle à quatre dimensions ou un modèle de propagation d'onde unidimensionnel.

4. Système selon la revendication 1, dans lequel la sensibilité est calculée sur la base du procédé de quadrature de Smolyak.

5. Système selon la revendication 1, dans lequel :

la variable clinique incertaine est l'un ou plusieurs parmi la masse myocardique, l'hématocrite, la viscosité, la pression, la surface corporelle ou la superficie, la fréquence cardiaque, les pressions artérielles brachiales systolique et diastolique, la taille du patient, le poids du patient, les antécédents du patient, le statut fumeur/non-fumeurs et la présence/absence de diabète ; et

la géométrie incertaine est l'un ou plusieurs parmi un diamètre maximal de sténose, une longueur de sténose, un emplacement de sténose, une taille de lésion, une longueur de lésion ou des segments sains avec des artefacts à base d'image.

6. Système selon la revendication 1, dans lequel :

la caractéristique de circulation sanguine est une valeur de réserve coronaire ;
la réserve coronaire indique un rapport entre une pression dans l'aorte et une pression à un emplacement dans le système vasculaire ; et
l'au moins un système informatique est configuré pour déterminer la réserve coronaire à une pluralité d'emplacements dans le système vasculaire.

7. Système selon la revendication 1, dans lequel les données spécifiques au patient comprennent des données obtenues par des techniques de tomodensitométrie ou d'imagerie par résonance magnétique.

8. Système selon la revendication 1, dans lequel l'au moins un système informatique est configuré pour créer le modèle anatomique sur la base des données d'imagerie par localisation des limites de lumières du système vasculaire du patient au moyen des données d'imagerie.

9. Système selon la revendication 1, dans lequel le modèle de la caractéristique de circulation sanguine comprend au moins un modèle agrégé représentant une circulation sanguine par l'intermédiaire des limites du modèle anatomique.

10. Système selon la revendication 1, dans lequel l'au moins un système informatique est configuré pour déterminer la caractéristique de circulation sanguine en utilisant un paramètre associé à au moins l'un parmi un niveau d'hyperémie, un niveau d'effort ou une médication.

11. Système selon la revendication 10, dans lequel l'au moins un système informatique est configuré pour déterminer la caractéristique de circulation sanguine au moyen d'un paramètre associé au niveau d'hyperémie, et le paramètre concerne une résistance d'artère coronaire du patient, une pression sanguine aortique du patient ou une fréquence cardiaque du patient.

12. Système selon la revendication 1, dans lequel l'au moins un système informatique est configuré pour afficher un indicateur de la sensibilité calculé en fonction de la caractéristique de circulation sanguine déterminée.

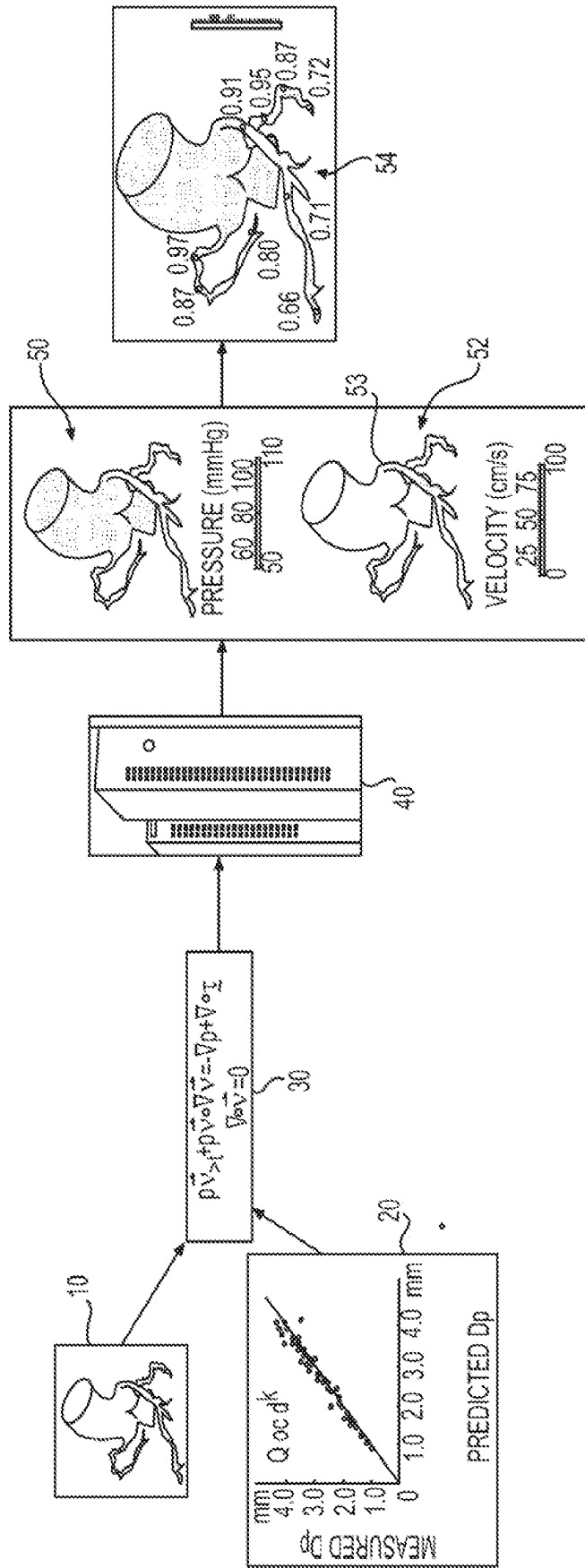


FIG. 1

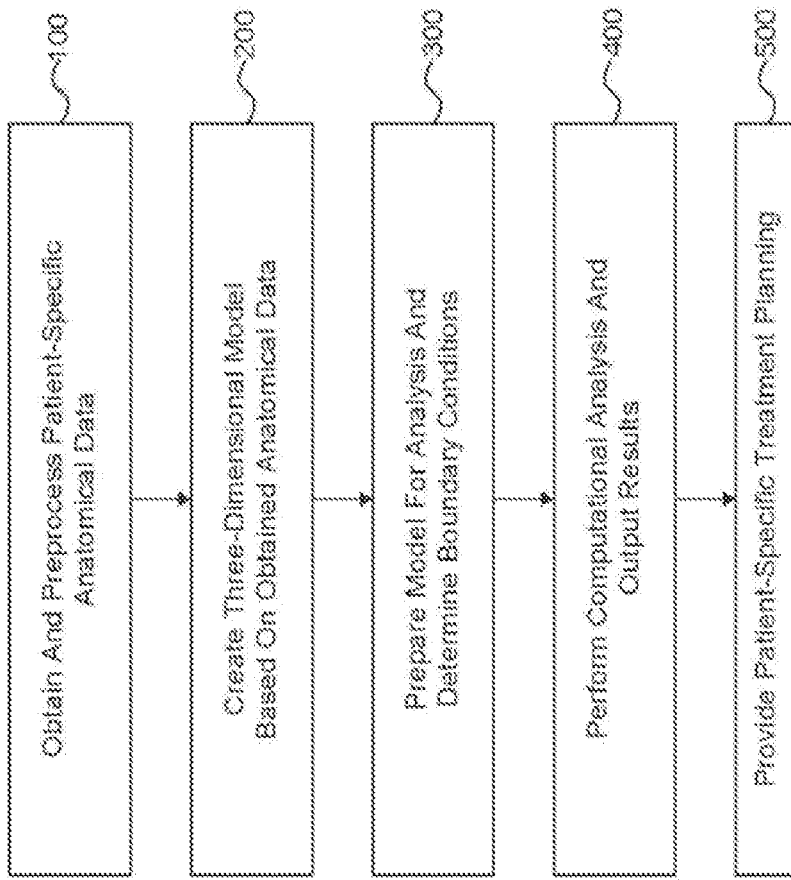


FIG. 2

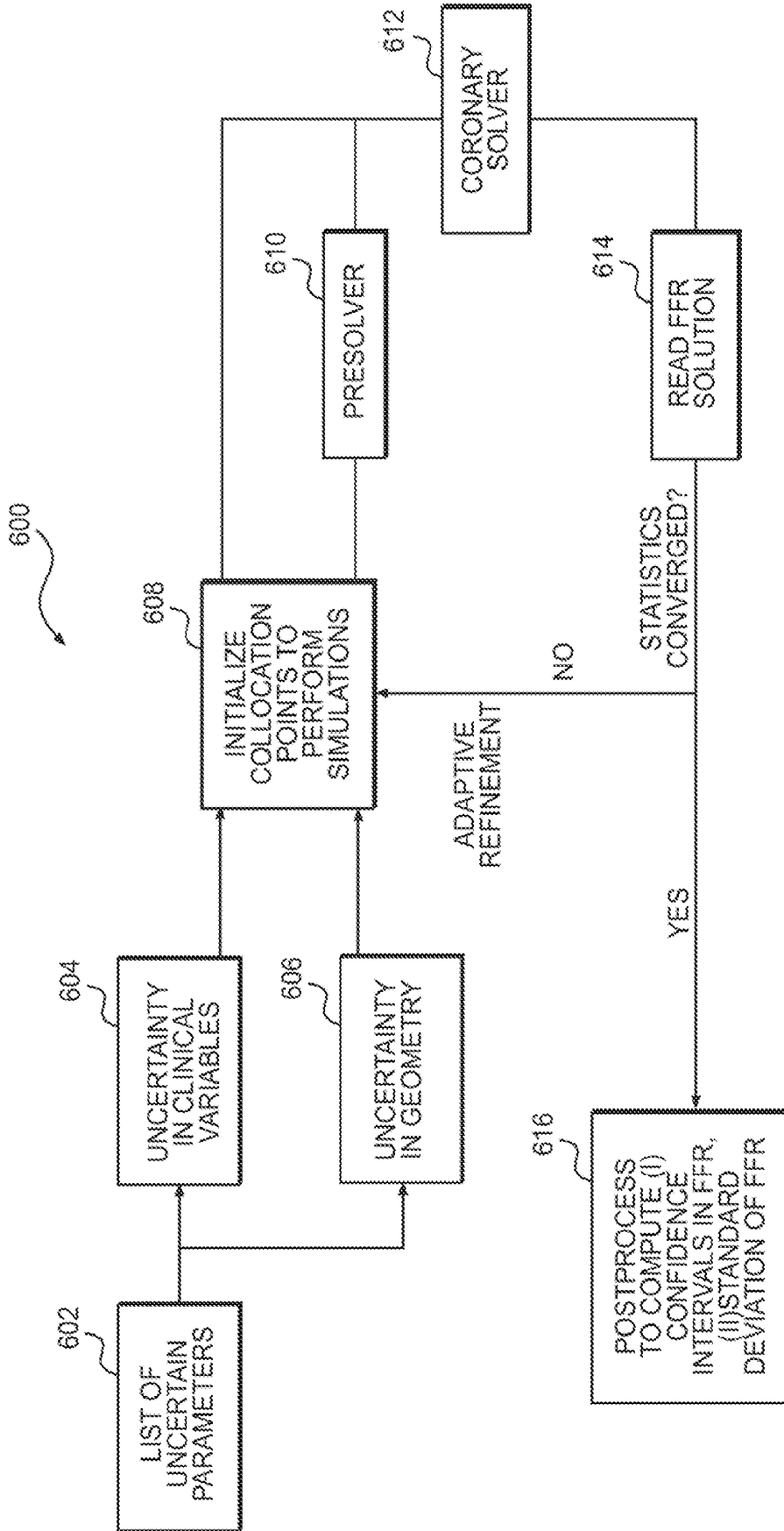


FIG. 3

REFERENCES CITED IN THE DESCRIPTION

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摘要(译)

用于确定患者的心血管信息的方法包括接收关于患者脉管系统的几何形状的患者特异性数据;基于患者特异性数据创建表示患者脉管系统的至少一部分的解剖模型;并基于解剖模型创建血流特征的计算模型。该方法还包括识别不确定参数, 不确定临床变量和不确定几何中的一个或多个;基于所识别的不确定参数, 不确定临床变量或不确定几何中的一个或多个来修改概率模型;基于解剖模型和计算模型确定患者脉管系统内的血流特征;基于概率模型和确定的血流特征, 计算所确定的分数流量储备对所识别的不确定参数, 不确定临床变量或不确定几何中的一个或多个的灵敏度。

$$BSA = \sqrt{\frac{hw}{3600}}$$