US 20100130878A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2010/0130878 A1

(43) Pub. Date: May 27, 2010

Lasso et al.

(54) **SYSTEMS, APPARATUS AND PROCESSES FOR AUTOMATED BLOOD FLOW ASSESSMENT OF VASCULATURE**

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(21) Appl. No.: **12/276,483**

(22) Filed: **Nov. 24, 2008**

Publication Classification

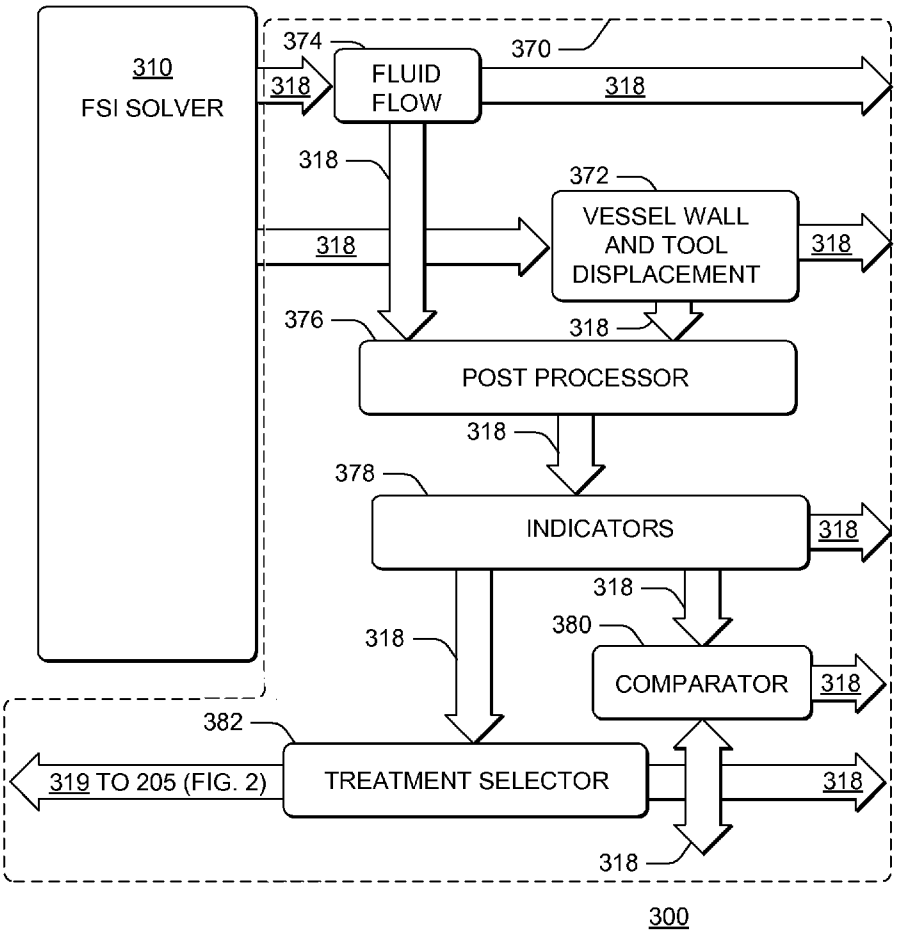
(51) **Int. Cl.**

A61B 5/026	(2006.01)
G06Q 50/00	(2006.01)
G06F 17/10	(2006.01)
G06G 7/57	(2006.01)
G06G 7/60	(2006.01)
A61B 5/02	(2006.01)

(52) **U.S. Cl.** **600/500**; 705/3; 703/2; 703/9; 703/11; 600/504

(57) **ABSTRACT**

A system, apparatus and process for characterizing aspects of vascular scenarios is described, and includes an input module and a database. The system also includes access to a FSI solver. The FSI solver accepts information from the input module and the database, and uses the accepted information to model a vascular site of interest and provide results from modeling the vascular site of interest. The system also includes interfaces for transmitting information from the input module and the database to the FSI solver and for receiving the results from the FSI solver, and an ensemble of analysis modules which is coupled to the interface for receiving results. The ensemble of analysis modules compares various treatment options, allows before-and-after comparisons of aspects of the vascular site of interest and provides quantitative assessments of parameters of interest describing the vascular site of interest.



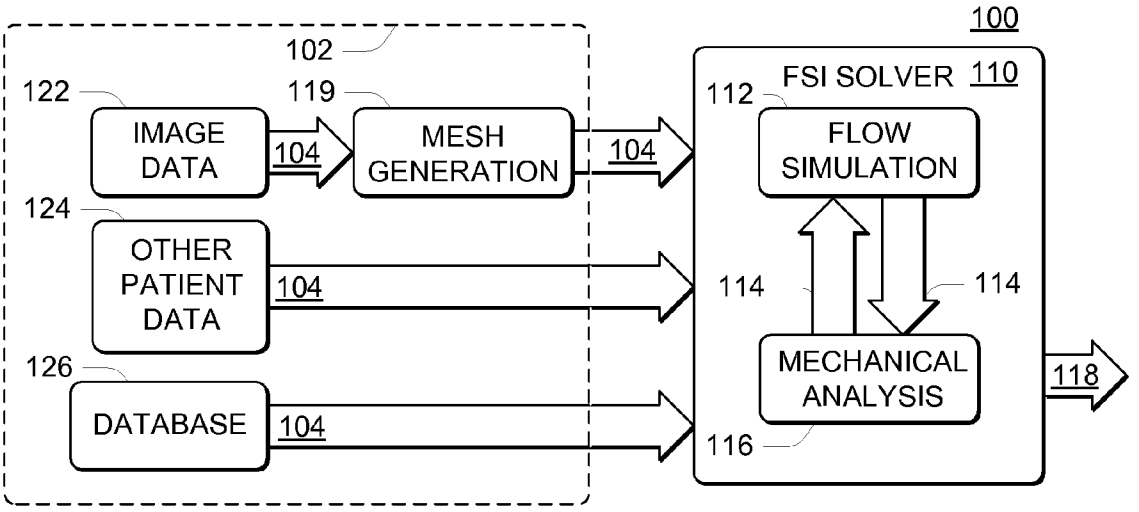


FIG. 1

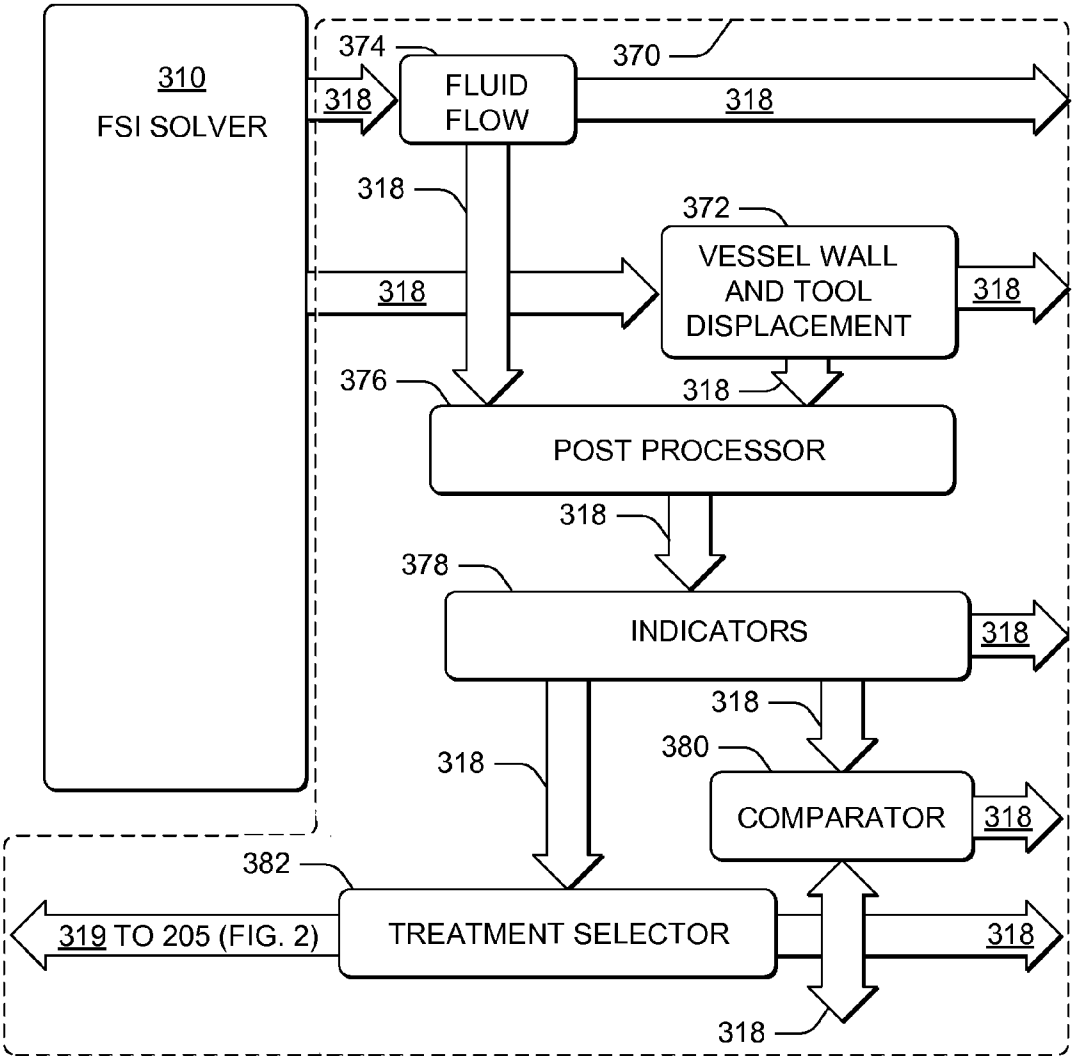


FIG. 3 300

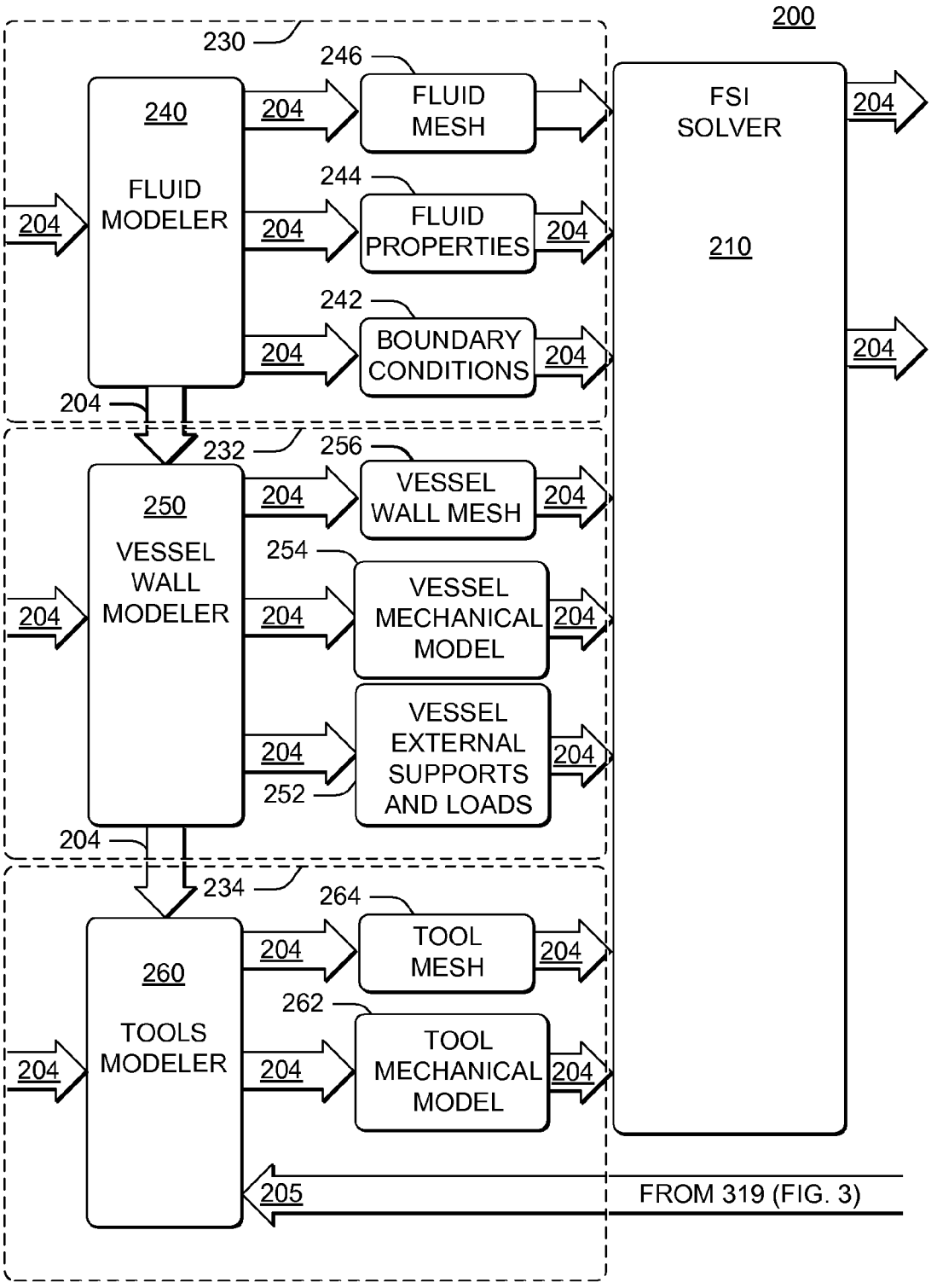

200
230
246
240
FLUID MODELER
204
FLUID MESH
FSI SOLVER
204
244
FLUID PROPERTIES
210
242
BOUNDARY CONDITIONS
204
232
256
250
VESSEL WALL MODELER
VESSEL WALL MESH
254
VESSEL MECHANICAL MODEL
VESSEL EXTERNAL SUPPORTS AND LOADS
252
234
264
260
TOOLS MODELER
TOOL MESH
262
TOOL MECHANICAL MODEL
205
FROM 319 (FIG. 3)

FIG. 2

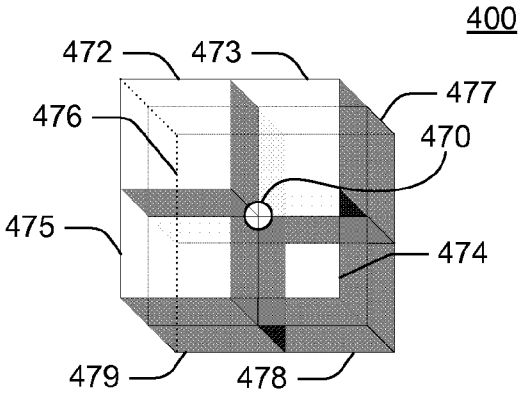


FIG. 4

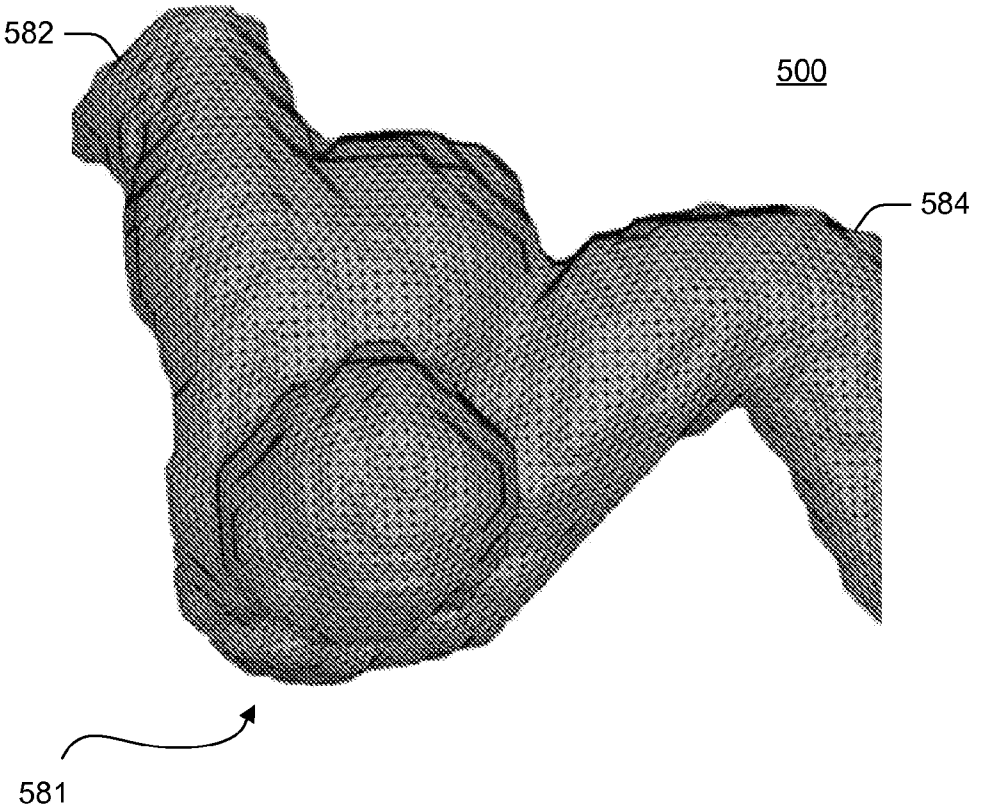


FIG. 5

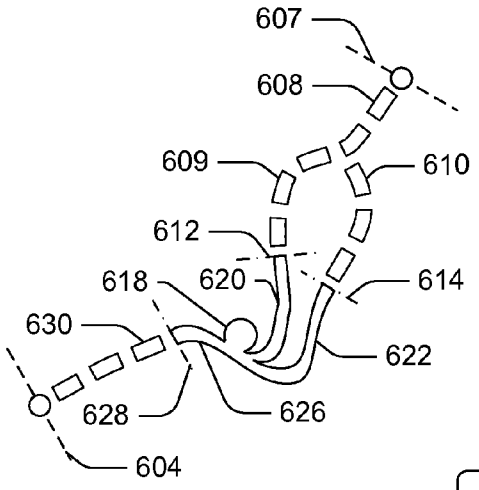


FIG. 6

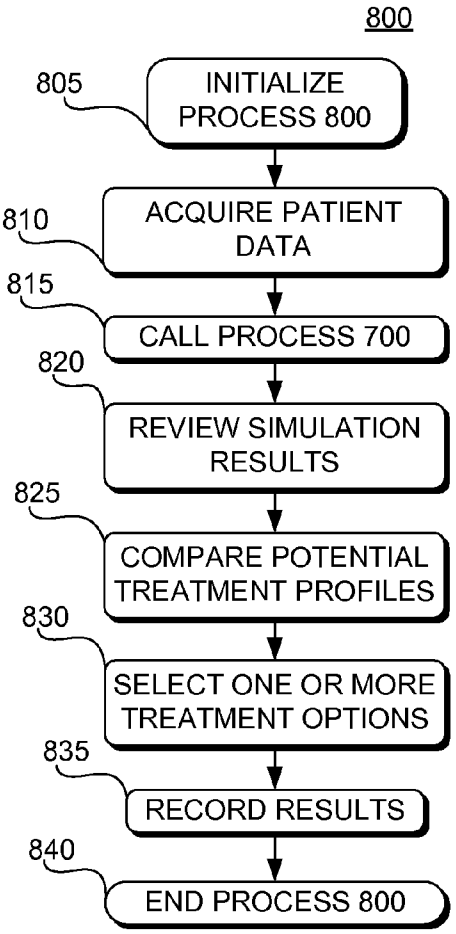


FIG. 8

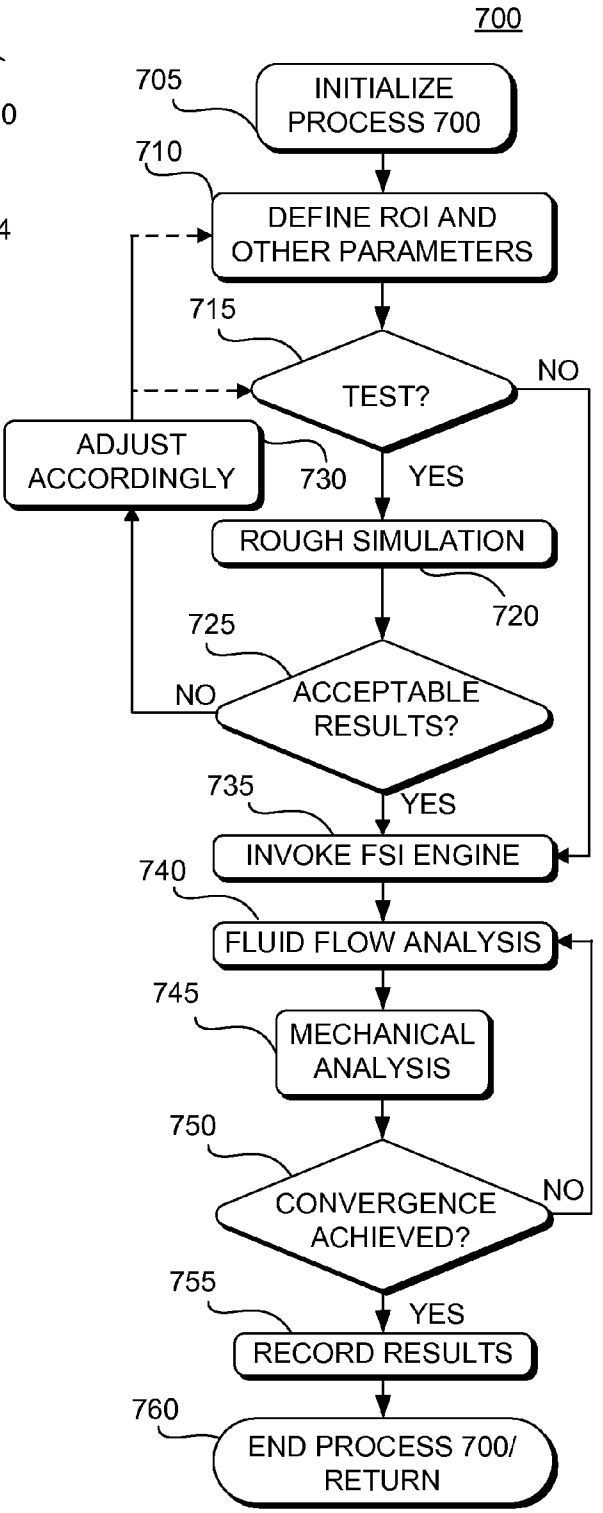


FIG. 7

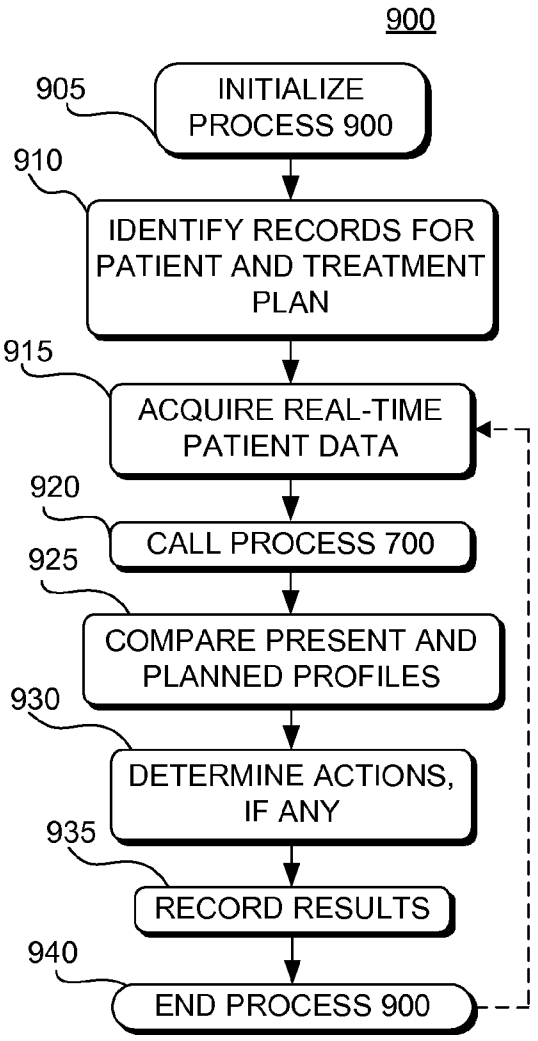

900
905
INITIALIZE PROCESS 900
910
IDENTIFY RECORDS FOR PATIENT AND TREATMENT PLAN
915
ACQUIRE REAL-TIME PATIENT DATA
920
CALL PROCESS 700
925
COMPARE PRESENT AND PLANNED PROFILES
930
DETERMINE ACTIONS, IF ANY
935
RECORD RESULTS
940
END PROCESS 900

FIG. 9

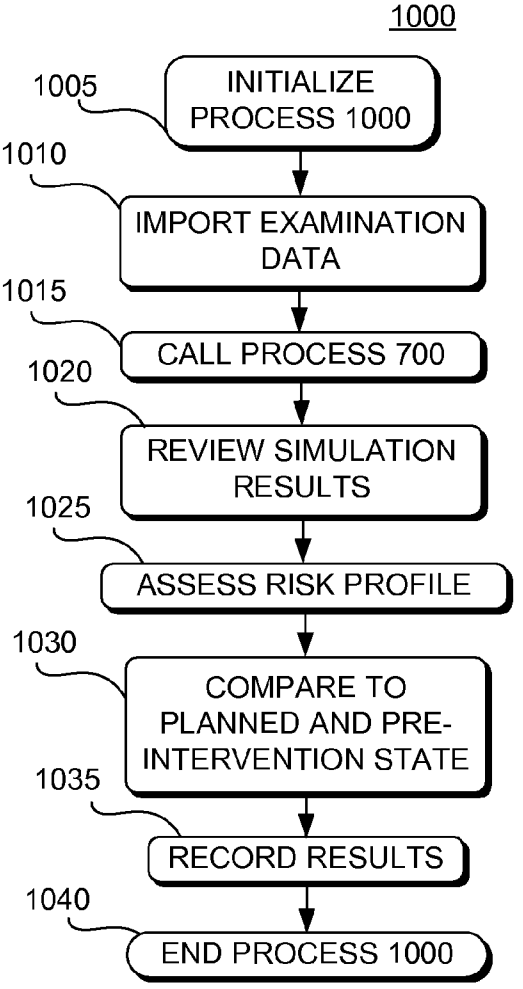

1000
1005
INITIALIZE PROCESS 1000
1010
IMPORT EXAMINATION DATA
1015
CALL PROCESS 700
1020
REVIEW SIMULATION RESULTS
1025
ASSESS RISK PROFILE
1030
COMPARE TO PLANNED AND PRE-INTERVENTION STATE
1035
RECORD RESULTS
1040
END PROCESS 1000

FIG. 10

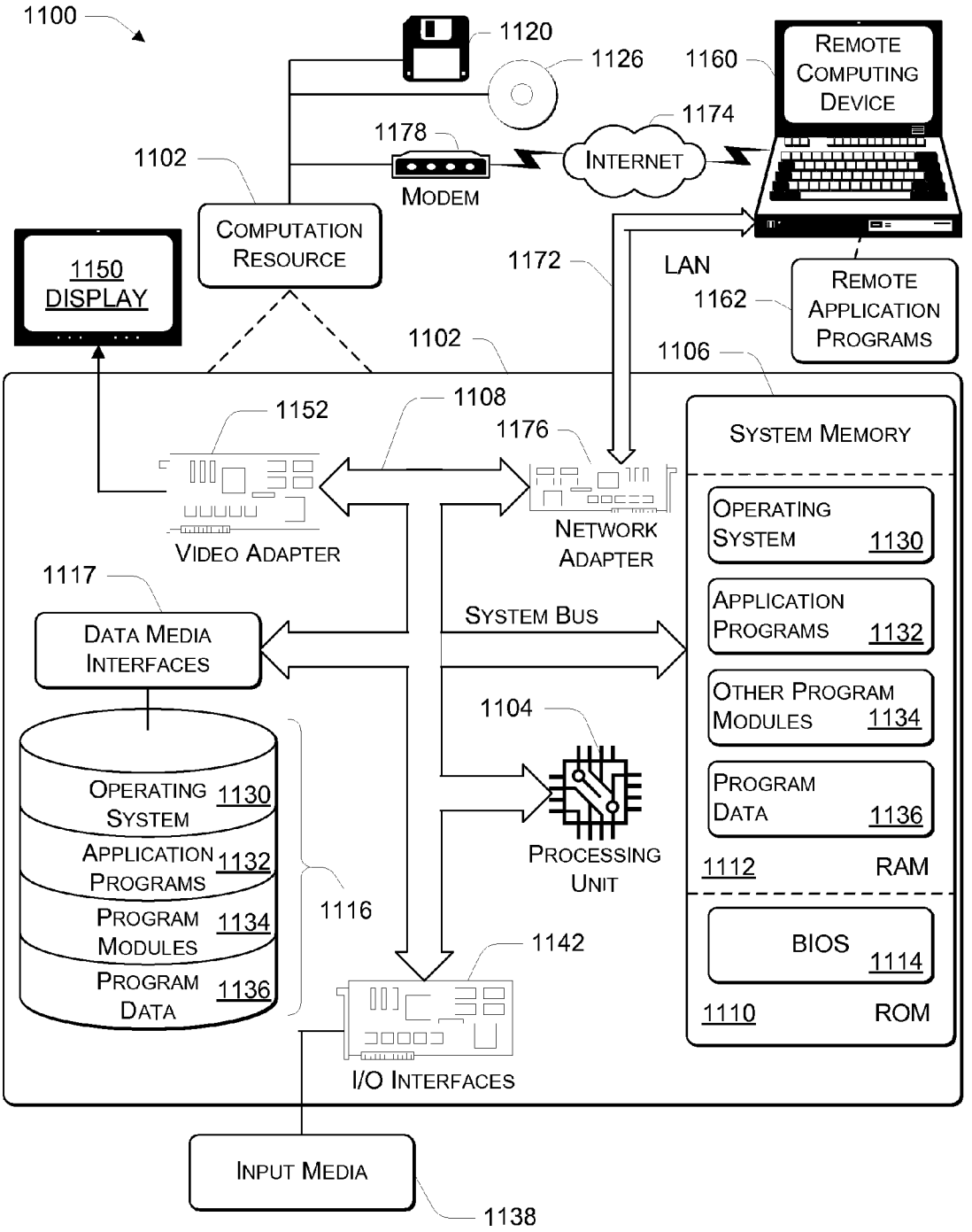

1100
1120
1126
1160
REMOTE COMPUTING DEVICE
1174
1178
1102
INTERNET
MODEM
COMPUTATION RESOURCE
1150 DISPLAY
1172
LAN
1162
REMOTE APPLICATION PROGRAMS
1102
1106
1152
1108
1176
SYSTEM MEMORY
VIDEO ADAPTER
NETWORK ADAPTER
OPERATING SYSTEM 1130
1117
SYSTEM BUS
APPLICATION PROGRAMS 1132
DATA MEDIA INTERFACES
OTHER PROGRAM MODULES 1134
1104
PROGRAM DATA 1136
OPERATING SYSTEM 1130
PROCESSING UNIT
1112 RAM
APPLICATION PROGRAMS 1132
1116
PROGRAM MODULES 1134
1142
BIOS 1114
PROGRAM DATA 1136
1110 ROM
I/O INTERFACES
INPUT MEDIA
1138

FIG. 11

SYSTEMS, APPARATUS AND PROCESSES FOR AUTOMATED BLOOD FLOW ASSESSMENT OF VASCULATURE

FIELD OF THE DISCLOSURE

[0001] This disclosure relates generally to anatomical data processing technology, and in particular to systems, apparatus and processes for accurately, rapidly, efficiently and robustly characterizing blood flow data and risk of vascular accident by using a situationally-variable, tailored blend of measured data and stored information, via a flexible, automated content enhancement tool.

BACKGROUND

[0002] Stroke and cerebrovascular diseases are a major cause of premature death, and also represent a leading cause of major disability in the United States, Canada and Japan, among others. Hemorrhagic strokes account for a substantial minority of all stroke cases, and involve bleeding into the brain. In turn, of those strokes which are hemorrhagic, as opposed to occlusive (i.e., caused by an obstruction, such as a blood clot, blocking blood flow to a portion of the brain), one-third to two-thirds may result in death. A substantial portion of non-fatal hemorrhagic strokes, believed to be in a range of from about ten percent to about twenty percent of all hemorrhagic strokes, result in severe brain damage. In turn, such cerebral vascular accidents give rise to need for intense therapy, and frequently necessitate long-term care, due to often-irreversible brain damage. Many of these hemorrhagic strokes are due to rupture of intracranial aneurysms.

[0003] Epidemiological evidence suggests that a large majority of intracranial aneurysms do not rupture. When considering which aneurysms to treat, and in the selection of suitable treatment methods, a physician must attempt to estimate the likelihood of rupture, and, when deemed warranted and appropriate, the relative risks associated with the various candidate mechanisms and approaches for attempting intervention or repair. Current recommendations are primarily based on patient factors (such as aneurismal subarachnoid hemorrhage, age, and other relevant medical conditions), aneurysm characteristics (including at least size, location and morphology) and management factors (e.g., experience of the surgical team, etc.). Although the aneurysm characteristics employed to date in making such decisions are relatively easily measured, they offer a very limited description of the relevant aneurysm characteristics, and they utilize a small fraction of information that frequently is already available from the acquired diagnostic data and images.

[0004] As a result, there are numerous difficult problems that cannot be effectively addressed though use of currently available tools. Examples of such limitations and drawbacks to the prior art approaches include high-risk cases, such as giant aneurysms, where standard recommendations have limited applicability. Consequently, in such instances, an individualized determination of relative risks is desirable.

[0005] While many new technological advances offer previously unknown treatment options, including advances in coil technology, liquid polymer techniques, balloons, stents, surgical equipment, techniques, and the like, this increased range of available treatment tools also increases the complexity involved in determining suitable, presently-realizable options for recommendation, and further in attempting to rank-order those to determine an preferred option or range of options as candidates for employment in a particular patient and presenting condition. Ideally, selection of preferred treatment tools and methods for each patient, and estimation of probabilities associated with pre-treatment, intra-treatment and post-treatment threats to life or health, should be based on assessment of the applicability of the available tools for the particular patient, the presenting aneurysm profile and other relevant factors.

[0006] Also, increasing the degree of post-treatment aneurysm occlusion strongly correlates with reduced risk of re-rupture. In turn, this justifies attempts to completely occlude those aneurysms which are deemed candidates for invasive treatment. However, case reports have shown that even aneurysms that appear to be completely occluded after surgery, or endovascular coil embolization, may later rupture.

[0007] Although evidence suggests that one-year outcomes in patients with a ruptured aneurysm may be better after endovascular coiling than after surgical clipping, the long-term efficacy of coiling versus clipping remains uncertain. Recent prospective cohort studies have found reassuringly low rates of rehemorrhage with both surgical and endovascular techniques. Despite such low rates, the consequences of rehemorrhage can be devastating—mortality is greater than 50%. Focus has, therefore, turned towards better understanding the factors that may predispose to rehemorrhage and identifying the best methods for surveillance.

[0008] Improving pre-operative planning and/or intra-operative assessment of expected final occlusion thus may significantly reduce subsequent risk of rupture or re-rupture.

[0009] Similar challenges arise in related areas of diagnostic and medical intervention or treatment of other vascular diseases, such as abdominal aortic aneurysms (e.g., difficultly in estimating risk of rupture), carotid artery stenosis (for example, in realistically estimating risk of plaque rupture, erosion and thromboemboli formation) and heart valve diseases.

[0010] For the reasons stated above, and for other reasons discussed below, which will become apparent to those skilled in the art upon reading and understanding the present disclosure, there are needs in the art to provide new and more highly automated simulation and analysis tools for estimating the properties and propensities of a variety of vascular abnormalities with greater accuracy than has been possible heretofore, and for more generally-applicable protocols for application and usage of an increasing range of treatment aids and options, in order to streamline and improve usage of available information in forming risk assessments, together with an appropriate, comprehensive and readily updatable menu of treatment options for further consideration and ultimately for implementation of a chosen option or options, and for continued risk assessment after initiation of invasive or non-invasive treatment.

BRIEF DESCRIPTION

[0011] The above-mentioned shortcomings, disadvantages and problems are addressed herein, which will be understood by reading and studying the following disclosure.

[0012] In one aspect, a system for characterizing aspects of vascular scenarios includes an input module and a database for storing characteristics of various types and conditions of vascular segments, a vascular site of interest and associated environments, properties of tools associated with treatment of vascular abnormalities, and patient-related information. The system also includes access to a FSI solver. The FSI solver

accepts information from the input module and the database, and uses the accepted information to model the vascular site of interest and to provide results from modeling the vascular site of interest. The system also includes interfaces for transmitting information from the input module and the database to the FSI solver and for receiving the results from the FSI solver, and an ensemble of analysis modules which is coupled to the interface for receiving results. The ensemble of analysis modules is for comparing various treatment options, allowing before-and-after comparisons of aspects of the vascular site of interest and providing quantitative assessments of parameters of interest describing the vascular site of interest.

[0013] In another aspect, a process for characterizing aspects of vascular scenarios is described. The process includes acts of accepting patient indicia via an input module and accessing relevant data records from a database using the indicia. The process includes an act of augmenting those data records, where needed, with stored data from a bank of representative data also stored in the database, to provide information including a description of the vascular scenario and defining a region of interest. The process then includes an act of sending the information to a FSI solver, and an act of receiving, responsive to sending, raw simulation results from the FSI solver. The process further includes an act of modifying the raw simulation results using selected items from a collection of analysis modules. The selected items from the collection are for comparing various treatment options, allowing before-and-after comparisons of aspects of the region of interest and providing quantitative assessments of parameters of interest describing the region of interest from the results.

[0014] In a further aspect, the present disclosure teaches a computation engine and a memory coupled to a data collection module, and computer-readable code embodied on a computer-readable medium and configured so that when the computer-readable code is executed by one or more processors associated with the computation engine, the computer-readable code causes the one or more processors to perform acts including accepting input indicia via an input module. The input indicia identifies a particular patient and enables access to stored records relating to prior measurements and simulations, if any, relative to that patient. The computer-readable code is further configured, when executed by one or more processors, to cause the one or more processors to perform acts including determining estimates for quantities not represented in a present measurement by extracting suitable data from a database which stores characteristics of various types and conditions of vascular segments associated with a defined vascular region of interest and associated environments, and determining appropriate properties of tools associated with treatment of vascular abnormalities, in conformance with patient-related indicia, or information identifying such. The computer-readable code is additionally configured, when executed by one or more processors, to cause the one or more processors to perform acts including accessing a FSI solver. The FSI solver accepts an information including at least some of the characteristics, conditions, a description of the vascular region of interest and associated environments, the properties of tools associated with treatment of vascular abnormalities, and the patient-related indicia, or information identifying such from the input module and the database, and uses the accepted information to model the region of interest and provide results from modeling the region of interest. The computer-readable code also is configured, when executed by one or more processors, to cause the one or more processors to perform acts including exchanging information between the input module, the database and the FSI solver, including providing results from the FSI solver to a collection of analysis modules, and using the collection of analysis modules, and the results from the FSI solver to: compare benefits and potential drawbacks of various treatment options; or allow before-and-after comparisons of aspects of the region of interest; or to provide quantitative assessments of parameters of interest describing the region of interest from the results.

[0015] Systems, processes, and computer-readable media of varying scope are described herein. In addition to the aspects and advantages described in this summary, further aspects and advantages will become apparent by reference to the drawings and by reading the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. **1** depicts a simplified block diagram providing a high-level overview of an exemplary embodiment of an iterative vascular analysis system, in accordance with an embodiment of the disclosed subject matter.

[0017] FIG. **2** is a block diagram providing a more detailed description of an exemplary embodiment of an input parameter side of the presently-disclosed analysis and modeling system than is offered via the block diagram of FIG. **1**, in accordance with an embodiment of the disclosed subject matter.

[0018] FIG. **3** is a block diagram showing an exemplary embodiment of an output parameter portion of the presently-disclosed analysis and modeling system in more depth than is offered in the simplified block diagram view of FIG. **1**, in accordance with an embodiment of the disclosed subject matter.

[0019] FIG. **4** provides an example of showing a centrally-disposed voxel corner point and eight neighboring voxels which are used for template matching, in accordance with an embodiment of the disclosed subject matter.

[0020] FIG. **5** illustrates an exemplary fluid mesh sample, in accordance with an embodiment of the disclosed subject matter.

[0021] FIG. **6** shows an example of how a model using information relating to a measurement scenario may be augmented, by adding artificial vessel segment models, to usefully employ data obtained from specific measurement locations, in accordance with an embodiment of the disclosed subject matter.

[0022] FIG. **7** is a flow chart describing acts in conformance with usage of the disclosed modeling and analysis system, in accordance with an embodiment of the disclosed subject matter.

[0023] FIG. **8** is a flow chart describing acts in conformance with an exemplary evaluation protocol employing the disclosed modeling and analysis system, in accordance with an embodiment of the disclosed subject matter.

[0024] FIG. **9** is a flow chart describing acts in conformance with an exemplary intra-operative protocol employing the disclosed modeling and analysis system, in accordance with an embodiment of the disclosed subject matter.

[0025] FIG. **10** is a flow chart describing acts in conformance with an exemplary post-treatment evaluation protocol

employing the disclosed modeling and analysis system, in accordance with an embodiment of the disclosed subject matter.

[0026] FIG. **11** illustrates an example of a general computation resource useful in implementation of one or more of the processes of FIGS. **7** though **10** in relation to the system shown and described above with reference to FIGS. **1** through **3**, in accordance with an embodiment of the disclosed subject matter.

DETAILED DESCRIPTION

[0027] In the following detailed description, reference is made to the accompanying drawings that form a part hereof, and in which are shown, by way of illustration, specific embodiments that may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the embodiments, and it is to be understood that other embodiments may be utilized, and that logical, mechanical, electrical and other changes may be made, without departing from the scope of the embodiments.

[0028] The detailed description is divided into six sections. In the first section, a system level overview is provided. In the second section, a more detailed discussion of implementation aspects is presented. In the third section, a new mesh model and the application of that new mesh model in the context of the present disclosure is discussed. In the fourth section, processes are described for several different implementations of the techniques and discoveries disclosed herein.

[0029] The fifth section discloses hardware and an operating environment, in conjunction with which embodiments may be practiced. The sixth section provides a conclusion which reviews aspects of the subject matter described in the preceding segments of the detailed description. A technical effect of the subject matter described herein includes employing coupled fluid dynamics and mechanical simulation to provide significantly enhanced accuracy information in comparison to a simple fluid dynamics simulation, where the information provided thereby, such as blood flow characteristics and vessel deformation, is important for increased accuracy in treatment planning by enabling richer diagnosis, increased reliability of prognosis of vascular diseases, estimation of the outcome of different treatment methods and determination of appropriate parameters for the selected treatment, such as selection of an appropriate coil or stent type and suitable placement in a user-specifiable region of interest.

[0030] Goals of the subject matter disclosed herein include supporting risk assessment, treatment planning, selection of appropriate treatment options in view of presently-available and future treatment modalities and techniques, with a general object of improving treatment and control of vascular diseases. Aspects involved in this process may include performing rupture analysis of the vasculature, modeling hemodynamic effects of different endovascular tools, estimating load-bearing capacity of an aneurysm, or calculating other clinically relevant indicators, including but not limited to parameters such as flow steadiness; average, peak value, gradient of wall shear stress, pressure, displacement, and analogous hemodynamic aspects.

[0031] All of these simulations or characterizations utilize detailed information regarding parameters describing a combination of measured and inferred blood flow characteristics, and data relating to time-varying vessel deformation. No generally applicable direct-solution method for measuring blood flow and vessel deformation in vivo is known. Consequently, the disclosed analysis system usefully employs a fluid-structure interaction (FSI) solver, which iteratively employs concatenated computational fluid dynamics and finite element mechanical modeling in order to accurately compute information describing these aspects. The FSI solver may start by employing a combination of presently-available patient-specific data, and tabulated data stored in a database, where the tabulated database includes data entries that correspond appropriately to physical measurements of cadaver-type tissues and other parameters relating to substantially similar scenarios.

[0032] The tabulated data entries may be employed in instances where desired aspects of patient-specific measurement results are absent, yet where other, relevant quantities provide information useful and suitable in arriving at appropriate approximations for modeling purposes. This may allow the disclosed tools and techniques to achieve robust support for treatment planning and risk assessment purposes, as is described below in more detail in §I below.

§I. System Overview

[0033] FIG. **1** depicts a simplified block diagram **100** providing a high-level overview of an exemplary embodiment of an iterative vascular analysis system, in accordance with an embodiment of the disclosed subject matter. The block diagram **100** shows a portion **102** of the input side of the system (in dashed outline), with buses **104** interconnecting various elements and coupling the portion **102** to a fluid structure interaction or FSI solver **110**, which employs coupled modules for describing the computational fluid dynamics aspects of the blood/fluid flow and a finite element mechanical analysis of the vasculature itself.

[0034] The FSI solver **110** includes a flow simulation module **112**, which employs computational fluid dynamics to model flow and pulsatile aspects relevant to hemodynamics, buses **114** for coupling data between the flow simulation module **112** and a finite mechanical analysis module **116**, and an output bus **118** for communication of raw simulation results to other system components.

[0035] The portion **102** includes a number of modules, represented in FIG. **1** as including a mesh generation module **119**, an image data importation or lookup module **122**, an input module for specifying or accessing other patient data **124** and one or more databases **126**, represented here by a single module **126** but which may be realized as multiple organized bodies of data and which may be physically stored in one location or in a variety of locations, depending on the implementation of a specific system **100**, as is well known to those of ordinary skill in the art to which the subject matter of this disclosure pertains. In general, the compilations of data represented by the block **126** are accessible to many or all of the elements of the system **100**, however, these alternatives and interconnections are not explicitly shown for simplicity of illustration and ease of understanding.

[0036] The database **126** may usefully be employed as well for other purposes. Further, the database **126** may be periodically or aperiodically augmented with revised or new information, descriptive of new treatment tools, of additional physical characteristics data via expansion of information obtained, for example, through dissection of relatively inaccessible or other portions of vascular systems, and other types of information. As such, the database **126** typically employs non-volatile read-write memory units for data storage.

[0037] When multiple systems **100** share a single database **126**, all of those systems **100** benefit from such data augmentation and are kept in data synchronism. The scope for which the information accrued in the database **126** over time may include applications such as are noted the following examples: providing estimates for those parameters that are not available for or could not be acquired for the given patient; comparison of indicators corresponding to examinations performed at different times (e.g., in the context of longitudinal studies); statistical analysis and trending, for example, to determine more and less successful treatment methods for a given problem, and/or to assist in selecting the more relevant indicators; and in calibration assessments such as estimations of reliability of the analysis system **100**, etc. Supporting data for such purposes relies strongly on the modeling capabilities provided via the FSI solver **110**.

[0038] In operation, the FSI solver **110** takes input information from the portion **102** and supplies that to the flow simulation module **112** which is coupled via buses **114** internal to the FSI solver **110** to the mechanical analysis module **116**. The flow simulation module **112** computes pulsatile variations of physical properties descriptive of the blood/fluid in a region of interest of vasculature to be modeled, and flow thereof, which initial result is then coupled from an output of the flow simulation module **112** via bus **114** to an input to the finite mechanical analysis module **116**.

[0039] In turn, that pulsatile loading of the vasculature results in stretching or other physical modulation of the vasculature, which is calculated by the mechanical analysis module **116**, responsive to the pulsatile loading as estimated by the flow simulation module **112**. The dynamic result of the mechanical analysis module **116** is coupled from an output of the mechanical analysis module **116** back to inputs of the flow simulation module **112** by another bus structure **114**. It will be understood that such bus structures **114** may or may not actually correspond to a physically realized bus structure as represented in FIG. **1**.

[0040] Iterative operation of computation modules **112** and **116** is represented in FIG. **1** by the bus structures **114**, and is described below in §IV in more detail with reference to process **700** of FIG. **7**. It will be appreciated that such functionality may be realized through other forms of hardware or software, as is well known to those of skill in the relevant arts.

[0041] In one embodiment, computer readable code is configured to cause one or more processors to evaluate convergence of concatenated simulations in the FSI solver **110** to an acceptable degree. Results from the concatenated simulations are then supplied to the collection of analysis modules for further processing.

[0042] This back and forth, or iterated, calculation process, whereby the distortions of the vasculature are estimated by the mechanical analysis module **116**, responsive to pulsatile loading thereof as estimated by the flow simulation module, and the effects which such mechanical distortions in turn impress upon the pulsatile flow as estimated by the flow simulation module **112**, etc., proceeds iteratively towards a desired level of convergence.

[0043] In practice, this may be determined in any of many ways, such as, by way of example and not intended to be limiting, that a predetermined number of iterations has occurred, or some quantitative measure of convergence, such as a reduction in variation of quantities between successive iterative cycles below some predetermined or user-adjustable threshold, is reached. Other empirically-determined bounds on the iteration process consistent with the quality of results desired may also be employed. When it is determined that convergence has occurred, results are output from the FSI solver via the bus **118**.

[0044] The kinds of information supplied by the portion **102** to the FSI solver **110** may include: multidimensional data suitable for forming a three-dimensional or four-dimensional image of vasculature geometry in a neighborhood of a region of interest; patient demographic information (patient age, gender, weight, any evidence of abnormalities, such as hypovolemia, or other factors relevant to modeling of properties of the blood/fluid itself, etc.) in order to estimate those parameters desirable for relatively complete analysis but which may not have been measured or possibly cannot be directly measured, specifications descriptive of one or more treatment method definitions, such as defining a region of interest, specification of a menu of tools to be considered for usage and the like, and, optionally, particularly when increased or more accurate patient-specific analysis is desired, additional two-dimensional (2D), three-dimensional (3D) or four-dimensional (4D) image sequences, blood flow and mechanical properties measurement data (a broad variety of other diagnostic data may be utilized, in conformance with the nature of the situation at hand and the judgment of the physician or team involved in the treatment protocol specification and/or implementation.

[0045] In order to convey appreciation of the enormous and potentially limitless scope of such information, as well as the seemingly infinite numbers of variations possible, and to demonstrate that an exhaustive listing is neither practical nor desirable in this disclosure, examples of such inputs to the system **100** may include but not necessarily be limited to information describing a three-dimensional aspect of the vasculature, such as voxel data collected via any suitable tool, such as MRI apparatus, fMRI or so-called "functional magnetic resonance imaging" devices and techniques, CAT scanner, X-ray angiography, SPECT or single photon emission compute tomography, ultrasound methodology and apparatus, positron emission tomography, and other modes for collecting information descriptive of blood flow and of vascular conditions and variability responsive to the beating of a heart under resting conditions or under conditions representing exercise. Additionally, information regarding fluid or blood flow, fluid or blood pressure, fluid or blood volume, fluid or blood viscosity and other parameters description of fluid or blood flow and/or vasculature shape and elasticity, fluid or blood leakage and other kinds of information associated with characterization of vasculature performance in vivo and potential for rupture or other undesirable abnormalities may comprise portions of the information useful as inputs to the system **100** or presented or inferable from outputs of the system **100**.

[0046] Information including one or more of these kinds of data is often linked to a patient record which may include cumulative data from a series of measurements made at different times, including information describing when such measurements were made and any other sorts of ancillary data typically involved in forming patient records, or measurements made via any of a variety of techniques and measurement tools, together with other information descriptive of the tools, techniques, contrast agents and other relevant data. A more detailed overview of the system **100**, coupled with somewhat more complex discussion of the elements and how they interact, follows in the descriptions of FIGS. **2** and **3** in

§II below, which should be interpreted in view of the broad-brush overview provided with regard to FIG. **1**, supra.

§II. Implementation Example

[0047] FIGS. **2** and **3** provide more detailed block diagrams **200** and **300** of the vascular analysis system **100** of FIG. **1** of the present disclosure, illustrating the input parameters and the modules which employ those parameters to derive a set of data suitable for modeling via the FSI modeling tool **110** of FIG. **1** which is described and taught in the present disclosure, and showing how these elements inter-relate and cooperate in determining data not present in the results of measurements carried out on the subject, and which then is able to automatically or interactively provide stored data presenting a "closest fit" to the presently-available measured information in order to accurately simulate hemodynamic quantities needed for a particular assessment or treatment-planning scenario.

[0048] FIG. **2** is a block diagram **200** providing a more detailed description of an exemplary embodiment of an input parameter side of the presently-disclosed analysis and modeling tool than is offered via the block diagram **100** of FIG. **1**, in accordance with an embodiment of the disclosed subject matter. In FIG. **2**, buses **204** interconnect various elements and portions of the system **200** to an embodiment of a FSI solver **210** (analogous to the FSI solver **110** of FIG. **1**; common or analogous features in different illustrations are frequently referenced by the portion of the reference character sequence following the initial descriptor indicative of the specific figure involved). Other major sub-systems such as a fluid-modeling module **230**, a vessel wall modeling module **232** and a tool-modeling module **234** each accept inputs, such as measured data relative to the patient or analogous information as provided via the database **126** of FIG. **1** (which is coupled to all relevant elements, although such interconnections are not explicitly shown, for simplicity of illustration and ease of understanding), and provide outputs which are in turn coupled to inputs to the FSI solver **210**.

[0049] The fluid-modeling module **230** includes a fluid modeler **240**, and sub-sub modules such as a boundary conditions calculator **242**, a fluid properties calculator **244** and a fluid mesh generator **246**, each having inputs coupled via buses **204** to the fluid modeler **240**. These each have outputs coupled to the FSI solver **210** via additional buses **204**. The fluid-modeling module **230** generates the blood, artificial blood or other fluid flow-related inputs (blood mesh, blood fluid properties and blood flow boundary conditions) to the FSI solver **210**.

[0050] The fluid dynamics simulation requires accurate description of the flow, at least at the boundaries of the mesh employed to model the blood or other fluid. On boundary mesh elements that have common surface with the vessel wall, no slip, and a hydraulically smooth wall is assumed. Blood flow for inlet and outlet mesh elements can be defined by mass flow rate (or equivalently velocity or volumetric flow rate, pressure) function in time.

[0051] There are two primary options for the determination of the mass flow rate function in time. A first option includes direct measurement, where three-dimensional flow is directly measured at multiple time instances (e.g., by MRI). It is advisable to define the function not only in the inflow and outflow, but in as many regions as possible. Alternatively, in a second option, indirect measurement is employed. When no full three-dimensional measurement in time is available or is not available right at the inflow and outflow the flow (e.g., 4D CT, ultrasound or blood pressure measurements), then additional artificial vessel segments are appended to the model (see FIG. **6**, infra) of the region of interest in order to simulate vasculature between the location of the measurement and the model.

[0052] All measurements are stored in the database **126** of FIG. **1**, so that when there is no available measurement data, or when just a few parameters can be determined (e.g., mean blood pressure), then flow rate function of a similar patient can be used.

[0053] The vessel wall modeling module **232** includes a vessel wall modeler **250**, coupled via buses **204** to sub-sub modules, such as vessel external supports and loads calculator **252**, a vessel mechanical model calculator **254** and a vessel wall mesh generator **256**. These each have outputs coupled to the FSI solver **210** via additional buses **204**. The vessel wall modeler **250** generates the vessel-wall-related inputs (vessel wall mesh, mechanical model, material properties and external supports) to the FSI solver **210**.

[0054] In addition to the forces induced by the flow of blood or other fluids, the tissues surrounding the vessel wall also have an influence on the deformation. The vessel external supports and loads calculator **252** in the vessel wall modeler **250** calculates the latter effect by applying three-dimensional elastic supports around the external wall of the vasculature. The parameters of the supports corresponding to the current patient are retrieved from the database. In addition to this uniform support, additional local constraints can be defined by the user, or automatically. Local constraints can be determined from the diagnostic image, and/or by analyzing the neighborhood of the vasculature (when it is close to a bone surface or other non-elastic structure then a local constraint shall be added).

[0055] The vessel mechanical model calculator **254** in the vessel wall modeling module **232** uses the conventional Mooney-Rivlin material model to describe the non-linear mechanical properties of the vessel wall. It will be appreciated that other material models may be alternatively employed, including but not limited to the conventional Ogden model. The model parameters are determined by measurements of dissected vasculature tissues, and the measurement results are stored in the database **126** of FIG. **1**. The data that is the most similar to the observed vessel segment is retrieved from the database and used for the analysis. The model parameters in one vessel segment can differ from the parameters of another segment (depending on vessel type, size, calcification, etc.) and the same segment may be a composite of multiple materials.

[0056] The vessel wall mesh generator **256** coupled to the vessel wall modeler **250** operates in coordination with the blood mesh generator **245**. Vessel wall thickness (and this varies along the vasculature) is a required parameter for this process. Vessel wall thickness can be determined in one of the following ways: (i) a direct measurement via three-dimensional characterization or intravascular ultrasound may be performed and employed; and/or (ii) indirect measurement can be done by measuring actual deformation of the vasculature due to blood pressure change within the cardiac cycle. This can be measured by high temporal resolution imaging modalities (e.g., X-ray fluoroscopy, ultrasound), or deformation between two time instances when the mean blood pressure is different can be measured by a high spatial resolution imaging modality. The wall thickness (and potentially other physiological parameters) can be determined based on the

deformation information, the blood flow induced forces acting on the wall and the wall material model.

[0057] A third approach is to estimate wall thickness by retrieval of similar data from the database **126** of FIG. **1**. When direct measurement is not available, then a database is used to estimate the wall thickness. The database **126** is built from measurements of dissected vasculature tissues (e.g., healthy vessel of different sizes at different places, aneurysm wall thickness of different parts of the aneurysm). The thickness is determined by selecting the data that is most alike the current vasculature.

[0058] The tool-modeling module **234** includes buses **204** coupling a tools modeler **260** to each of a tool mechanical model calculator **262** and a tool mesh generator **264**. The tool-modeling module **234** also accepts data via a bus **205**, as will be described below in more detail with reference to FIG. **3**. Common aspects of the fluid mesh generator **246**, vessel wall mesh generator **256** and tool mesh generator **264** will be described below in more detail with reference to §III.

[0059] The tools modeler **260** benefits from the fact that most of the tools that are used during vascular interventions already have a mechanical model (including mesh and material properties). As a result, during the treatment definition or optimization, the user specifies the size and position and other additional parameters of the tools, and a corresponding model and related data are extracted or recalled from the database **126** of FIG. **1**. All of this information is then sent to the FSI solver **210**.

[0060] Operation of the FSI solver **210** was discussed above with regard to FIG. **1**. However, in general, there are many commercially available solvers for finite element analysis. The requirement for the FSI solver **110**, **210** to be used in the vascular analysis system is **100**, **200** that it has to support the solution of two-way coupled fluid structure interaction for the material model and mesh types that are provided by the blood, vessel wall and tools modelers.

[0061] Before starting the full simulation a simplified solution is optionally generated (assuming rigid vessel wall and other simplification in the material model and simulation parameters). This gives just an approximate result, but such an approximation facilitates a quick verification of proper problem definition, prior to invoking the more time-consuming and resource-intensive full computation.

[0062] The problem definition and the display and post-processing of results can be performed optimally on an average workstation. However, a fast enough computation of the full FSI simulation requires high computing performance. The FSI solver module **110**, **210** may use the services of a remote computation server to achieve this, as is described below with regard to FIG. **11**, among other places. Examples of suitable software for such computation include the Ansys Multiphysics package, available from ANSYS, Inc. (ansys.com/products/default.asp) (leading portions of the URL have been omitted in order to avoid problems encountered by unsophisticated parties). An example computation of an FSI problem, using a mechanical model consisting of 12,000 nodes (see, e.g., FIGS. **4** and **5** in §III, infra) and a fluid model of 65,000 nodes, requires about six hours on a Core 2 Duo Q6600 3.2 gigaHertz machine. The performance of this machine is 2973.23 million operations per second or 2.97 gigaflops, as measured by Distributed Computing program Einstein(@)Home (parentheses added to preclude inadvertent browser-launching errors by unsophisticated parties).

[0063] Actual implementation of a conventional FSI computation engine **110**, **210** is complex, and may differ from the present description in a variety of ways, as is known to those of skill in the relevant arts. For example, the FSI solver **110**, **210** may initiate by invoking either fluidic or mechanical analysis, or the mechanical and fluid analyses may run in parallel, etc.). In this application, the fact that information and results from each of these analyses are employed in the other analysis approach during the course of iteration of the computations represents departure from conventional methodologies, particularly with reference to the field of application of the subject matter of the present disclosure.

[0064] The remote computation server can receive problem definitions from multiple workstations through network connections, quickly perform the resource-intensive computations and send back the raw computation results to the workstation. A computation server can be shared among multiple workstations in the same institution, or shared between multiple institutions. Outputs from the FSI solver **210** are conditioned further to provide a variety of different outputs, depending on the nature of the overall task at hand, as is described below in more detail with reference to FIG. **3**.

[0065] FIG. **3** is a block diagram **300** showing an exemplary embodiment of an output parameter portion of the presently-disclosed analysis and modeling modules in more depth than is offered in the simplified block diagram view **100** of FIG. **1**, in accordance with an embodiment of the disclosed subject matter. In FIG. **3**, the block diagram **300** shows a FSI solver **310** providing outputs via buses **318** to a variety of analysis modules.

[0066] The analysis modules include a vessel wall and tool displacement module **372** and a fluid flow module **374** which also each provide outputs to further system elements via buses **318**. A post-processor **376** accepts inputs from the fluid flow module **374** via a bus **318** and from the vessel wall and tool displacement module **372** via another bus **318** and supplies output signals to a module of indicators **378** via another bus **318**. The post-processor **376** computes derived quantities and various indicators from the raw simulation results (displacements, velocity and pressure fields), which are then displayed to the user and/or further analyzed.

[0067] A comparator **380** accepts input signals via buses **318** and supplies output signals via another bus **318**. The comparator **380** is used in analyses where two or more sets of outputs are being compared, such as with regard to the intra-operative process **900** of FIG. **9**, and the post-operative process **1000** of FIG. **10**, respectively, as described in more detail below in §IV.

[0068] A treatment selector module **382** is coupled to the indicators module **378** via a bus **318** and has one output coupled to further system elements via another bus **318** and sends data back to the input sections of FIG. **2** via a bus **319** which couples to the bus **205**. This may permit a selected treatment option to be analyzed in more detail. The treatment selector module **382** determines treatment parameters (treatment methods, parameters, positions of tools, etc.) that lead to preferred indicator values (minimum risk or rupture, minimum shear stress, maximum occlusion, minimum displacement amplitude in aneurysm, etc.) and hence result in facilitate in treatment selection, as is described below in more detail in §IV with reference to flow chart **800** of FIG. **8**.

[0069] By now it may be appreciated that the system **100** of FIG. **1**, as described in more detail with reference to FIGS. **2** and **3**, is able to address a broad variety of tasks through

accurate, robust and rapid modeling of vascular scenarios. Examples illustrating the richness of output data from the system may encompass patient-specific information including at least: three or four dimensional display of blood/fluid flow and structural information about the vasculature in any region or regions of interest, such as flow patterns, wall displacements, etc., for purposes such as qualitative visual assessment, at different time steps throughout a cardiac cycle; display of various indicators, such as hemodynamic aspects including flow steadiness, average, peak value, gradient of wall shear stress, pressure, occlusion, etc.; mechanical aspects including such elements as displacement amplitude, Von Mises stress, etc.; and aiding in deriving recommendations for treatment planning (described in more detail in §IV below with respect to flowchart **800** of FIG. **8**), for example, preferred sizes, placements, and suitable parameters of tools and devices used in treatment; and, clearly, comparison all the above information before, during and after treatment.

[0070] Thus, to briefly recapitulate, vessel deformation affects blood flow, and vice-versa. As a result, flow-induced loads are recomputed in order to provide more realistic and accurate results. In turn, those results are employed to derive revised estimates of vessel deformation, and, in the disclosed subject matter, iteration of such calculations is employed to rapidly derive robust estimates which account for the interactions of the coupled flow and mechanical aspects of vessel functionality.

[0071] In order to calculate effects due to pulsatile loading of vessel deformation, blood-flow-induced loads acting on the vessel wall are determined. Then, resultant vessel deformation is estimated via computation. In order to accomplish that efficiently in the context disclosed herein, a new methodology and modeling approach was developed. In this approach to volumetric mesh generation for finite element mechanical analysis, the main input of the system is the three-dimensional image of the vasculature. From that, a geometric model (viz., a volumetric mesh) is generated. Other parameters (boundary conditions, material properties, etc.), for example, those which are generally quite significant for the analysis, may be determined from patient specific measurements, or may be retrieved from the database **126**, predicated on correlation with patient-specific information, where applicable.

[0072] The system **100** also includes memory devices (not explicitly shown in FIGS. **1** through **3**), coupled via the buses **104** to elements of system **100** through suitable interfaces. The database **126** is one example of stored data desirably embodied in a non-volatile and possibly read-write memory, which may be a part of the system **100** or which may be included as a remote element couplable to the system **100**, as noted in more detail below with reference to FIG. **11**.

[0073] Memory devices providing non-volatile read-write capabilities are usefully employed to store patient information, records of various measurements, and software tools for analysis of such data and for formatting such information for display via a conventional monitor or other devices (not explicitly shown in FIGS. **1** through **3**). Memory devices also find utility in for storing one or more databases containing parameters descriptive of vessel characteristics, of the various kinds of tools available for treatment of vascular illness or abnormality, and the like, and the databases containing such kinds of information are accessible to the various system elements shown in FIGS. **1** through **3**, although illustration of such conventional interconnections has been omitted from those FIGs. in order to promote clarity of illustration and for ease of understanding.

[0074] Datasets representing four-dimensional (e.g., with time as a fourth dimension, in addition to the conventional three spatial dimensions, in other words, representing information analogous to a movie or other dynamic record of vascular system performance), three-dimensional data and image or two-dimensional data (i.e., data in pixel form or analogous representation schemes) typically conform to the digital imaging and communications in medicine (DICOM) standard, which is widely adopted for handling, storing, printing, and transmitting information in medical imaging. The DICOM standard includes a file format definition and a network communications protocol. The communication protocol is an application protocol that uses TCP/IP to communicate between systems. DICOM files can be stored in memory devices and retrieved therefrom, and may be exchanged between two entities that are capable of receiving image and patient data in DICOM format, for example via a network.

[0075] The memory devices include mass data storage capabilities and one or more removable data storage device ports, as is described later in more detail with reference to FIG. **11**. The one or more removable data storage device ports are adapted to detachably couple to portable data memories, which may include optical, magnetic and/or semiconductor memories and may have read and/or write capabilities, and which may be volatile or non-volatile devices or may include a combination of the preceding capabilities.

§III. Mesh Model

[0076] The most important patient-specific parameter is the volumetric mesh used to simulate the blood or fluid properties that is used for computational fluid dynamics (CFD) analysis. The mesh consists of thousands of basic geometric elements defined by points and connections between them. The mesh can be constructed from an image or equivalent data of any modality, which can capture the three-dimensional geometry of the vasculature lumen (typically contrasted three-dimensional X ray angiography, CT or MRI volume).

[0077] Although there are several methods for creating a volumetric mesh from an image volume or equivalent data, the present disclosure teaches a new method, having the following characteristics: (i) it is very simple, fast and robust; (ii) it generates tetrahedral mesh directly from the volume image/data at acceptable quality for FSI analysis by the FSI modeler **110**, **210**, **310** of FIGS. **1** through **3**, respectively; and (iii) it generates both the blood and the vessel wall mesh with common node elements at the boundary surface (which favors efficient FSI solution). The blood mesh is generated in the fluid mesh calculator **246** (FIG. **2**) by iterating through all the corners of blood voxels in the volume and matching a template to all the voxels that touch that specific voxel (a total of 8 voxels, see FIG. **4**).

[0078] As a pixel set consists of 8 voxels, and a voxel can have two possible values (blood or non-blood), there are altogether 256 possible templates. The template defines how many tetrahedron elements shall be added to the mesh for the given set of voxels and in what configuration. It works very similarly to the conventional and widely-used marching cubes algorithm. The main difference is that this new algorithm creates a volumetric mesh, which can be used for FEM analysis directly. The surface of an example of a resulting blood mesh is shown in FIG. **5**.

[0079] For the vessel wall mesh generation by the vessel wall mesh calculator **256** (FIG. **2**), the original image is modified by applying dilation on the blood voxels (by the thickness of vessel wall) and then the voxels corresponding to the blood mesh are removed. It also uses the same template-based meshing on the modified image that was used for the blood mesh. The templates are designed to be invertible, so that when the blood mesh elements are removed the internal surface of the blood mesh is perfectly aligned to the outer surface of the blood mesh (they have common node points, which facilitates an efficient numerical solution).

[0080] FIG. **4** provides an example **400** of showing a centrally-disposed voxel **470** corner point and eight neighboring voxels **472**, **473**, **474**, **475**, **476**, **477**, **478**, **479**, which are used for template matching, in accordance with an embodiment of the disclosed subject matter. Starting from the upper left-hand corner, the voxel **472** is part of a first or top layer of voxels which comprise a face of a cubic shape of the example **400** that is closest to the viewer, and, proceeding clockwise, a remaining three of the four total voxels forming that face are voxels **473** (upper right-hand corner), **474** (lower right-hand corner) and **475** (lower left-hand corner). A rearward face of the cubic shape is formed, again starting from a portion adjacent the upper left-hand corner, via a voxel **476**, and, proceeding clockwise, remaining voxels comprising that portion of the cubic shape **400** are voxels **477**, **478** and **479**.

[0081] A blood/fluid mesh is generated, corresponding to the operations associated with the mesh generation module **106** of FIG. **1**, and the fluid mesh generation module **246** of FIG. **2**, by iterating through all corners/vertices, e.g., analogous to the corner **470** illustrated above, of blood or fluid voxels in the volume being modeled, and matching a template to all of the eight voxels (as shown in FIG. **4**) touching that specific voxel corner. For the present purpose, a voxel, such as any of the voxels **472** through **479**, may have one of two possible values (blood/fluid or non-blood/non-fluid), and, accordingly, there are altogether two raised to the power of eight, or two hundred and fifty-six, possible different templates.

[0082] For the vessel wall mesh generation, the original image data, or information from which that may be constructed, is modified by applying dilation (or the equivalent thereof) on the blood/fluid voxels, magnifying them by an amount given by the thickness of vessel wall. As a result, those voxels corresponding to the blood/fluid mesh are removed. This operation is followed by the same template-based meshing on the modified image data that was used for the blood/fluid mesh generation. The templates are designed to be invertible, so that when the blood/fluid mesh elements are removed, the internal surface of the blood/fluid mesh is fully aligned to an outer surface of the blood/fluid mesh. A consequence of the above-noted procedure is that they have common node points, which facilitates efficient numerical solution.

[0083] In the computations associated with the fluidic physical properties module **244** in FIG. **2**, appropriate blood/fluid physical properties are retrieved from the database, based on the patient demographics data indexed through operation of the patient data module **124** of FIG. **1**. The database **126** includes a substantially complete set of actual measurements of such blood/fluid properties, spanning a full range over which such parameters vary in practice. For the simulations to conform to Newtonian fluidic behavior (e.g., viscosity is not a function of pressure in Newtonian fluids), constant viscosity and density for the blood/fluid are assumed.

[0084] FIG. **5** illustrates an exemplary fluid mesh sample **500**, in accordance with an embodiment of the disclosed subject matter. The exemplary mesh sample **500** includes a region of anomalous or diseased vasculature **581** that is part of the region of interest, as well as a first port **582** and a second port **584**, each corresponding to relatively normal vasculature and disposed at either end of the anomalous or diseased vasculature portion **581** to be modeled. The first **582** and second **584** ports correspond to the inlet and outlet (or vice versa) for the anomalous or diseased vasculature portion **581**, with all of the blood/fluid that passes through one of the first **582** or second **584** ports also passing through the corresponding other of the second **584** or first **582** ports. The example **500** of FIG. **5** may represent what in actuality is more than one vessel (such as furcations associated with progressively finer vasculature, ultimately supplying blood/fluid to capillary structures), as is described below in somewhat more detail with reference to FIG. **6**.

[0085] FIG. **6** illustrates an example **600** of a model of a region of interest having a first input measurement plane **604** (analogous to either the first port **582** or the second port **584** of FIG. **5**) and a second measurement locus **607** (analogous to either the second port **584** or the first port **582** of FIG. **5**). Artificial vessel segments **608** and **609**, **610** accommodate a furcation in the vessel being modeled, and planes **612**, **614** illustrate where those artificial model segments join to an aneurism **618** via blood vessel segments **620**, **622**. An additional blood vessel segment **626** couples another end of the aneurysm **618** in the vessel being modeled to a plane **628** that in turn is coupled via artificial model segments **630** to join the vessel with the first measurement locus **604**.

[0086] FIG. **6** shows an example **600** illustrating how information relating to a measurement scenario may be augmented, using artificial vessel segment models **605**, **608**, **609**, **610**, to usefully employ data obtained from specific measurement locations, in accordance with an embodiment of the disclosed subject matter. This permits more accurate modeling of a vessel segment when the segment itself cannot be directly measured, and is being modeled via data taken from a dissected specimen, for example. Aspects of the measurement processes, problems and analysis in several different contexts are discussed below with reference to §IV.

§IV. Processes

[0087] In the following section, some exemplary processes are described with reference to FIGS. **7** through **10** in the context of measurements corresponding to various phases of patient assessment and treatment. These include pre-operative characterization and treatment planning, intra-operative monitoring and post-operative follow-up and monitoring. A first aspect of these processes is described below with reference to FIG. **7**, which describes generalized operation of the FSI solver which is common to each of these phases of patient treatment.

[0088] FIG. **7** is a flow chart **700** describing acts in conformance with usage of the disclosed modeling and analysis modules, in accordance with an embodiment of the disclosed subject matter. The process **700** begins in a block **705**.

[0089] In the block **705**, data may be assembled and input to the FSI solver. Elements of data needed in order to complete an analysis, but which are not present in the results of mea-

surements performed on the patient, may be supplied from the database of representative vascular data, by selection of parameters in conformance with the data to be analyzed. Control then passes to a block **710**.

[0090] In the block **710**, a region of interest and parameters associated therewith are defined. Control then passes to a query task **715**.

[0091] In the query task **715**, a user is asked if there is desire to perform a limited, quick evaluation of the characteristics of various types and conditions of vascular segments in the context of a user-defined vascular region of interest and associated environments, as well as verification of suitable range of tools via the properties of tools associated with treatment of vascular abnormalities, and any patient-related indicia, or information identifying such, associated with the task at hand.

[0092] When the user indicates that there is desire to perform a limited, quick evaluation, in order to confirm that the correct information is present and that the region of interest is appropriately defined, control passes to a block **720**.

[0093] In the block **720**, a rough simulation, which does not involve the detailed FSI solver **110**, **210**, **310** (FIGS. **1** through **3**, respectively) operation, but instead utilizes a highly simplified model, such as one which assumes rigid vessel walls, and other simplifications in the material model and simulation parameters. This gives an approximate result, useful for quick verification of appropriate problem definition, and allows for adjustment when the problem definition appears to require refinement, prior to invoking the more time consuming and resource-intensive full FSI-solver computation. Control then passes to a query task **725**.

[0094] In the query task **725**, the user has opportunity to determine that the region of interest appears to be correctly identified, and that the information being presented conforms to what is expected from a rough estimation of the scenario at hand. When the query task **725** determines that something appears to be awry with the problem definition, control passes to a block **730**.

[0095] In the block **730**, adjustments are made in conformance with the irregularities noted by the operator or user, and control then reverts to either the block **710**, when the region of interest and similar information appears to be inappropriate specified, and from there to the query task **715**, or passes directly to the query task **715**, as appropriate, and the sequence resumes as described.

[0096] When the response determined by the query task **715** does not indicated need or desire for a rough estimate, or when the query task **725** determines that the results of the rough simulation were acceptable, control passes to a block **735**.

[0097] In the block **735**, the FSI engine or solver (i.e., as shown at **110** in FIG. **1**, **210** in FIG. **2** and **310** in FIG. **3**) is invoked. The FSI engine (**110**, **210**, **310**) then initiates the fluid flow analysis (see, e.g., block **112**, FIG. **1**) in a block **740**, as described supra with reference to FIGS. **1** through **3**, and control passes to a block **745**, where mechanical analysis (as described above, for example, with reference to block **116**, FIG. **1**) of the vasculature throughout the region of interest as defined above in the block **710** is performed, in light of the results obtained from the fluid flow analysis of the block **740**. Control then passes to a query task **750**, or the processes of the blocks **740** and **745** may be iterated a predetermined or user-determined number of times (which may be set in the course of the problem definition phase associated with the blocks **705** and **710**), prior to control passing to the query task **750**.

[0098] In the query task **750**, conventional convergence testing is performed. As noted previously, any of a variety of criteria may be employed, and either pre-set criteria may be used to determine an acceptable degree of convergence, a user may select from a menu of such pre-determined set-points, or a user may determine both the manner in which convergence is tested and thresholds relative to that act. Irrespective of how that is handled, a "backup" test determines if or when the process **700** is failing to converge and a suitable error signal and possibly some diagnostic criteria are generated and made available to the user. When the query task **750** determines that convergence is not satisfactory, control reverts to the fluid flow analysis of the block **740**, and this proceeds from the juncture at which the query task **750** was invoked. When the query task **750** determines that convergence is satisfactory, control passes to a block **755**.

[0099] In the block **755**, the results from the process **700** are recorded. Generally, these may be recorded in a storage media accessible to the system **100** of FIG. **1**, **200** of FIG. **2** and **300** of FIG. **3**, and may also be recorded in storage media accessible to the FSI solver or engine **110**, **210**, **310**. Control then passes to a block **760**.

[0100] In the block **760**, control returns to the process (e.g., as described with reference to FIGS. **8** through **10**, infra) which called the process **700**. The process **700** then ends.

[0101] FIG. **8** is a flow chart **800** describing acts in conformance with an exemplary evaluation protocol employing the disclosed modeling and analysis modules, in accordance with an embodiment of the disclosed subject matter. The process described with reference to FIG. **8** is appropriate at least in situations where an aneurism is being detected or investigated for treatment after initial detection. After the detection of an aneurysm, the analysis system can be used before, during and after the treatment.

[0102] In a pre-operative context, the sequence of acts might follow as described below with reference to FIG. **8**. The process **800** of FIG. **8** initiates in a block **805**.

[0103] In the block **805**, the process **800** is initialized. In one embodiment, initialization of the process **800** includes acts such as entry or importation of patient demographics information. Control then passes to a block **810**.

[0104] In the block **810**, appropriate available diagnostic data (e.g., three-dimensional descriptive data or images, four-dimensional descriptive data or images, such as time sequences of spatial descriptions, relevant flow measurements and the like) may be invoked, measured or recalled from prior assessment results stored via the database (e.g., the database **126** as described above with reference to FIG. **1**).

[0105] Also, optionally, in the block **810**, treatment approaches to be analyzed may be selected, for example via definition treatment method(s) which are supported by available tools, or which are consistent with tools which have been selected for use or for consideration for usage. Parameters such as placement of such tools vis-à-vis the region of interest, and other suitable and/or allied types of information may be added or adjusted in the block **810**.

[0106] In some instantiations, the acts associated with the block **810** may include definition of a region of interest, or the definition of such may benefit from refinement. Control then passes to a block **815**.

[0107] In the block **815**, the process **700** of FIG. **7** is invoked. Following return **760** from the process **700**, control will be passed to a block **820**.

[0108] In the block **820**, results from the FSI solver are reviewed. As noted above with regard to the query tasks **715** and **725** and other associated aspects of the process **700**, review of a rough estimate, or of a full simulation, may suggest benefit to adjustment of boundary conditions, "tweaking" or adjustment of aspects affecting the defined region of interest, or modification of one or more of the other simulation data inputs, or evaluation of the sensitivity of desired results to various parameters may be desirable. When those aspects have been resolved satisfactorily, control passes to a block **825**.

[0109] In the block **825**, potential treatment profiles and anticipated results of specific treatments may be compared, based on results for each anticipated potential venue being evaluated. Strengths or weaknesses of one treatment approach or another may be flagged as having particular or dispositive significance with regard to various of the treatment options under contemplation at the time. Control then passes to a block **830**.

[0110] In the block **830**, one or more treatment options may be selected for further consideration, or a particular treatment option may be determined to be preferred, and/or one or more treatment possibilities may be deferred from further consideration and study at this time. Control then passes to a block **835**.

[0111] In the block **835**, results of the adjustments and selection processes and comparisons of various potential alternatives are recorded. For example, such results may be stored in a patient records portion of the database **126** described above, and/or may be exported to other types of resources, along with a preferred treatment plan, if such has been selected. Control then passes to a block **835**, and the process **800** terminates.

[0112] FIG. **9** is a flow chart **900** describing acts in conformance with an exemplary intra-operative protocol employing the disclosed modeling and analysis modules, in accordance with an embodiment of the disclosed subject matter. The process **900** begins in a block **905**.

[0113] In the block **905**, the process **900** is initialized. In other words, the patient is identified. Control then passes to a block **910**.

[0114] In the block **910**, data descriptive of a region of interest which has been previously determined is recalled from storage, or is imported from other resources. Also, in the block **910**, a treatment plan is identified among records associated with the identified patient, and which has been previously selected for this patient is identified in the records, along with identification of results from the previous analysis. These selections may either be determined by an operator, or may automatically be identified using stored information derived from a prior analysis and selection, note of which previously had been stored together with the other patient information. In either event, the results of that prior analysis are brought forward. Control then passes to a block **915**.

[0115] In the block **915**, real-time images are acquired which are relevant to the region of interest. These real-time images, and results from any other appropriate measurements which are contemporaneously performed with the acquisition of real-time descriptive information are collectively transferred to the input portions (such as the portion **102** of FIG. **1** of the system **100**, or analogous aspects of the system **200** of FIG. **2**, for example). Control then passes (transparently, with regard to the operator or physician) to a block **920**.

[0116] In the block **920**, the process **700** of FIG. **7** is invoked, passing the contemporaneous information gleaned with regard to the block **915** above to the FSI solver **110** of FIG. **1** or **210** of FIG. **2**. Control then passes to a block **925**.

[0117] In the block **925**, the present profile, resulting from analysis of the information derived via the acts noted above with regard to the block **915**, is compared to the analysis of the previously-selected scenario as determined above in conjunction with the block **910**. Anomalies are noted, as well as congruencies and suitable similarities with anticipated or hoped-for results. Control then passes to a block **930**.

[0118] In the block **930**, any actions which are deemed appropriate, based on informed comparison of the presently-achieved scenario, and the previously-designated preferred plan profile, are implemented. Control then passes to a block **935**.

[0119] In the block **935**, information derived from the comparisons, as well as any actions determined to be appropriate, as well as the anticipated or measured influences manifested in conformance with any actions determined to be appropriate in the block **930**, are recorded, and/or exported, as has been described supra with regard to the block **830** of FIG. **8**, for example. Control then passes to a block **940**, and the process **900** terminates.

[0120] In some embodiments, a practical aspect of the termination noted at the block **940** is actually to continuously re-iterate those aspects of the process **900** from, for example, block **915** forward, to realize a continuously-updated real-time observational tool for tracking process during a procedure, as indicated by the dashed arrow extending from the block **940** up to and pointing toward the block **915**. This may continue until such time as an affirmative "STOP" command is input from a user console, or is otherwise effectuated (for example, when disconnection of probes or other measurement tools from the patient results in affirmative "NO GO" signals being automatically generated within the system **100** of FIG. **1**, or analogous other representations).

[0121] Optionally, in conjunction with the tasks associated with the block **925**, information (such as, by way of example, fluid flow patterns, tool position, degree of occlusion, etc.) may be superposed atop the live image, and may be correctly registered therewith, as an overlay, or may be displayed in a separate view. As well, geometrical and flow information may be gleaned or retrieved from the live images (although they maybe incomplete and of limited accuracy). Using such information, the pre-operative model definition may be updated. Optionally, a quick simulation (e.g., as described above with reference to the block **720** of FIG. **7**) may be performed in order to compute indicators and to assist in deriving a modified treatment plan.

[0122] FIG. **10** is a flow chart **1000** describing acts in conformance with an exemplary post-treatment evaluation protocol employing the disclosed modeling and analysis modules, in accordance with an embodiment of the disclosed subject matter. Such follow-up is highly desirable, at least in part because recurrent aneurysms can be due to coil compaction or migration or dislocation. Also, in some cases, a de novo basilar tip aneurysm may develop within a few months after treatment via clipping, for example. When such events occur after treatment of a rupture, the probability of fatality in the event of re-rupture is quite high. The process **1000** begins in a block **1005**.

[0123] In the block **1005**, the process **1000** is initialized, by providing indicia identifying the patient. Those indicia are used to identify and extract data from prior measurements of the region of interest, as described above with reference to the database **126** of FIG. **1**. Control then passes to a block **1010**.

[0124] In the block **1010**, data from a present examination of this patient are imported into the system **100**. Control then passes to a block **1015**.

[0125] In the block **1015**, the process **700** is invoked, to process the data collected in the block **1010**. Control then passes to a block **1020**.

[0126] In the block **1020**, results from the simulation derived from the process **700**, using the contemporary data collected in the block **1010**, are reviewed. Control then passes to a block **1025**.

[0127] In the block **1025**, a presently-applicable risk profile is derived from the results from the simulation of the block **1015** is developed. Control then passes to a block **1030**.

[0128] In the block **1030**, the risk profile developed in the block **1025** is compared to the planned results and risk profile, and to the pre-intervention state data for the patient, as retrieved in the block **1005**. Control then passes to a block **1035**.

[0129] In the block **1035**, results from the preceding blocks are integrated into the patient record and are stored in the database **126** of FIG. **1**, and/or are exported to other resources. Generally, these results may be recorded in a storage media accessible to the system **100** of FIG. **1**, **200** of FIG. **2** and **300** of FIG. **3**, and may also be recorded in storage media accessible to the FSI solver or engine **110**, **210**, **310**. Control then passes to a block **1040**, and the process **1000** ends.

[0130] It will be appreciated that in order to determine outputs with robustness, repeatability and relevance, the system **100** functions at qualitatively better levels in conformance with increasingly precise descriptions of the blood/fluid flow in vasculature, and particularly arteries. In turn, assessing and providing such information is one of the most difficult problems of current vascular fluid mechanics research.

[0131] The flow of blood/fluid is unsteady, the vessel walls are deformable, and also have complex elastic properties. Additionally, the vascular geometry can be extremely complex. Living tissue reacts to fluid mechanical changes in erratic ways, which, in turn, influences the flow properties. Huge variations in relevant parameters are known to exist from one patient to another patient (or even across time with physiological changes occurring in a single patient).

[0132] As a result, use of patient-specific models and parameters to a fullest possible extent is very desirable. Further, in vivo measurements (especially in the skull) are notoriously extremely difficult to effectuate, particularly with the precision and reliability desired in order to directly determine or verify the computed indicators.

[0133] To attempt to render these issues more tractable in ways applicable in routine clinical practice, the disclosed system may use one or more of the following techniques: estimation of complex blood flow and vessel wall interaction via the disclosed comprehensive mechanical and fluid dynamics model (such as coupled fluid structure interaction analysis using an elastic vessel wall model); huge variations in parameters from patient to patient may be accommodated via use of patient-specific parameters; vasculature geometry may be accurately determined from multidimensional image or volumetric data from measurements made on the patient; flow information may be determined by measurements on the actual patient, or may be estimated using automatically retrieved data corresponding to similar patients; and material properties may be determined using a database containing biomechanical properties measurements of real vessel wall tissue specimens. These and other variations are all ways of utilizing the information which is available or obtainable to leverage the benefits obtainable from the processes **700** through **1000** of FIGS. **7** through **10**, respectively, to derive increased accuracy and robustness of patient needs, via appropriately exercising the FSI solver **110** of FIG. **1**, **210** of FIG. **2** and/or **310** of FIG. **3**.

[0134] The processes **700**, **800**, **900** and **1000** of FIGS. **7** through **10**, respectively, thus provide improved, automated modeling of vascular pathologies, even in the context of ongoing medical procedures, facilitates care and intervention planning, and allows comparisons to be made to prior assessments, in order to track progress and to determine if or when further intervention may be appropriate. An example of a computer useful in implementing this type of process is described below with reference to §V.

§V. Hardware and Operating Environment

[0135] FIG. **11** illustrates an example of a general computation resource **1100** useful in implementation of one or more of the processes **700** through **1000** of FIGS. **7** though **10**, respectively, in relation to the system **100**, **200**, **300** shown and described above with reference to FIGS. **1** through **3**, respectively, in accordance with an embodiment of the disclosed subject matter. The general computer environment **1100** includes a computation resource **1102** capable of implementing the processes described herein. It will be appreciated that other devices may alternatively used that include more components, or fewer components, than those illustrated in FIG. **11**.

[0136] The illustrated operating environment **1100** is only one example of a suitable operating environment, and the example described with reference to FIG. **11** is not intended to suggest any limitation as to the scope of use or functionality of the embodiments of this disclosure. Other well-known computing systems, environments, and/or configurations may be suitable for implementation and/or application of the subject matter disclosed herein.

[0137] The computation resource **1102** includes one or more processors or processing units **1104**, a system memory **1106**, and a bus **1108** that couples various system components including the system memory **1106** to processor(s) **1104** and other elements in the environment **1100**. The bus **1108** represents one or more of any of several types of bus structures, including a memory bus or memory controller, a peripheral bus, an accelerated graphics port and a processor or local bus using any of a variety of bus architectures, and may be compatible with SCSI (small computer system interconnect), or other conventional bus architectures and protocols.

[0138] The system memory **1106** includes nonvolatile read-only memory (ROM) **1110** and random access memory (RAM) **1112**, which may or may not include volatile memory elements. A basic input/output system (BIOS) **1114**, containing the elementary routines that help to transfer information between elements within computation resource **1102** and with external items, typically invoked into operating memory during start-up, is stored in ROM **1110**.

[0139] The computation resource **1102** further may include a non-volatile read/write memory **1116**, represented in FIG. **11** as a hard disk drive, coupled to bus **1108** via a data media

interface **1117** (e.g., a SCSI, ATA, or other type of interface); a magnetic disk drive (not shown) for reading from, and/or writing to, a removable magnetic disk **1120** and an optical disk drive (not shown) for reading from, and/or writing to, a removable optical disk **1126** such as a CD, DVD, or other optical media.

[0140] The non-volatile read/write memory **1116** and associated computer-readable media provide nonvolatile storage of computer-readable instructions, data structures, program modules and other data for the computation resource **1102**. For example, data recorded as described above in §IV with reference to FIGS. **8** through **10**, e.g., such as noted in blocks **755**, **830**, **935** or **1035**, may be written to the non-volatile read/write memory **1116**, removable magnetic disk **1120** or removable optical disk **1126**. Similarly, data which are being recalled or imported as noted in blocks **910** or **1010** or is being extracted from a database, as described above in §I with references to FIGS. **1** to **3**, may be read from the non-volatile read/write memory **1116**, removable magnetic disk **1120** or removable optical disk **1126**.

[0141] Although the exemplary environment **1100** is described herein as employing a non-volatile read/write memory **1116**, a removable magnetic disk **1120** and a removable optical disk **1126**, it will be appreciated by those skilled in the art that other types of computer-readable media which can store data that is accessible by a computer, such as magnetic cassettes, FLASH memory cards, random access memories (RAMs), read only memories (ROM), and the like, may also be used in the exemplary operating environment.

[0142] A number of program modules may be stored via the non-volatile read/write memory **1116**, magnetic disk **1120**, optical disk **1126**, ROM **1110**, or RAM **1112**, including an operating system **1130**, one or more application programs **1132**, other program modules **1134** and program data **1136**. Examples of computer operating systems conventionally employed for some types of three-dimensional and/or two-dimensional medical image data include the NUCLEUS® operating system, the LINUX® operating system, and others, for example, providing capability for supporting application programs **1132** using, for example, code modules written in the C++® computer programming language.

[0143] A user may enter commands and information into computation resource **1102** through input devices such as input media **1138** (e.g., keyboard/keypad, tactile input or pointing device, mouse, foot-operated switching apparatus, joystick, touchscreen or touchpad, microphone, antenna etc.). Such input devices **1138** are coupled to the processing unit **1104** through a conventional input/output interface **1142** that is, in turn, coupled to the system bus. A monitor **1150** or other type of display device is also coupled to the system bus **1108** via an interface, such as a video adapter **1152**.

[0144] The computation resource **1102** may include capability for operating in a networked environment using logical connections to one or more remote computers, such as a remote computer **1160**. The remote computer **1160** may be a personal computer, a server, a router, a network PC, a peer device or other common network node, and typically includes many or all of the elements described above relative to the computation resource **1102**. In a networked environment, program modules depicted relative to the computation resource **1102**, or portions thereof, and/or patient records may be stored in a remote memory storage device such as may be associated with the remote computer **1160**. By way of example, remote application programs **1162** reside on a memory device of the remote computer **1160**. In one embodiment,

[0145] the FSI solver module **110**, **210**, **310** of FIGS. **1** through **3** may use the services of or reside on a remote computation server **1160** to achieve this. The remote computation server **1160** may receive problem definitions from multiple workstations through network connections, and provides rapid real-time capability for performing the resource-intensive computations needed for the FSI processing. Raw computation results are then returned to the workstation, which may be a computation resource such as the computer **1102**. A computation server **1160** can be shared among multiple workstations **1102**, which may be located within the same institution or on a common campus, or may be shared between multiple institutions/locations.

[0146] The logical connections represented in FIG. **11** may include interface capabilities, e.g., such as interface capabilities **152** (FIG. **1**) a storage area network (SAN, not illustrated in FIG. **11**), local area network (LAN) **1172** and/or a wide area network (WAN) **1174**, but may also include other networks. Such networking environments are commonplace in modern computer systems, and in association with intranets and the Internet. In certain embodiments, the computation resource **1102** executes an Internet Web browser program (which may optionally be integrated into the operating system **1130**), such as the "Internet Explorer®" Web browser manufactured and distributed by the Microsoft Corporation of Redmond, Wash.

[0147] When used in a LAN-coupled environment, the computation resource **1102** communicates with or through the local area network **1172** via a network interface or adapter **1176**. When used in a WAN-coupled environment, the computation resource **1102** typically includes interfaces, such as a modem **1178**, or other apparatus, for establishing communications with or through the WAN **1174**, such as the Internet. The modem **1178**, which may be internal or external, is coupled to the system bus **1108** via a serial port interface.

[0148] In a networked environment, program modules depicted relative to the computation resource **1102**, or portions thereof, may be stored in remote memory apparatus. It will be appreciated that the network connections shown are exemplary, and other means of establishing a communications link between various computer systems and elements may be used.

[0149] A user of a computer may operate in a networked environment using logical connections to one or more remote computers, such as a remote computer **1160**, which may be a personal computer, a server, a router, a network PC, a peer device or other common network node. Typically, a remote computer **1160** includes many or all of the elements described above relative to the computer **1100** of FIG. **11**.

[0150] The computation resource **1102** typically includes at least some form of computer-readable media. Computer-readable media may be any available media that can be accessed by the computation resource **1102**. By way of example, and not limitation, computer-readable media may comprise computer storage media and communication media.

[0151] Computer storage media include volatile and non-volatile, removable and non-removable media, implemented in any method or technology for storage of information, such as computer-readable instructions, data structures, program modules or other data. The term "computer storage media"

includes, but is not limited to, RAM, ROM, EEPROM, FLASH memory or other memory technology, CD, DVD, or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other media which can be used to store computer-intelligible information and which can be accessed by the computation resource **1102**.

[0152] Communication media typically embodies computer-readable instructions, data structures, program modules or other data, represented via, and determinable from, a modulated data signal, such as a carrier wave or other transport mechanism, and includes any information delivery media. The term "modulated data signal" means a signal that has one or more of its characteristics set or changed in such a manner as to encode information in the signal in a fashion amenable to computer interpretation.

[0153] By way of example, and not limitation, communication media include wired media, such as wired network or direct-wired connections, and wireless media, such as acoustic, RF, infrared and other wireless media. The scope of the term computer-readable media includes combinations of any of the above.

[0154] As such, the computer **1102** may function as one or more of the elements shown in FIGS. **1** through **3**, for example, via implementation of the processes **700**, **800**, **900** and/or **1000** of FIGS. **7** through **10**, respectively, as one or more computer program modules. A conclusion is presented below in §VI.

§VI. Conclusion

[0155] The disclosed examples combine a number of useful features and present advantages in modern hospital settings. These examples address, among other things, a key problem with segmenting and quantifying lesions, and particularly liver lesions, due to a lack of repeatability. The inconsistent repeatability results from a number of causes, including various inconsistencies in the contrast uptakes of the lesions due to variations in timing between contrast agent injection and/or variations in timing of the phases, and the imaging. The combination of multiple contrast-agent enhanced datasets taught by the present disclosure provides additional enhancement of the anatomy to create a more robust contrast between the lesion and the surrounding parenchyma. In turn, this tends to improve consistent segmentation and quantification that can be relied on for growth/change analysis, surgical planning, radiotherapy planning and other purposes.

[0156] Additionally, compatibility with existing tools and modes for image data representation, and conventional image data storage and exchange standards facilitate interoperability with existing modules developed for those purposes, as well as promoting compatibility with newer approaches, such as integrated surgical navigation. The disclosed capabilities also benefit from compatibility with existing systems, and thus coordinate with other operator training, reducing probability of error, such as may occur in time-critical scenarios.

[0157] Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement which is calculated to achieve the same purpose may be substituted for the specific embodiments shown. This disclosure is intended to cover any adaptations or variations. For example, although described in procedural terms, one of ordinary skill in the art will appreciate that implementations can be made in a procedural design environment or any other design environment that provides the required relationships.

[0158] In particular, one of skill in the art will readily appreciate that the names or labels of the processes and apparatus are not intended to limit embodiments. Furthermore, additional processes and apparatus can be added to the components, functions can be rearranged among the components, and new components to correspond to future enhancements and physical devices used in embodiments can be introduced without departing from the scope of embodiments. One of skill in the art will readily recognize that embodiments are applicable to future communication devices, different file systems, and new data types. The terminology used in this disclosure is meant to include all object-oriented, database and communication environments and alternate technologies which provide the same functionality as described herein.

What is claimed is:

1. A system for characterizing aspects of vascular scenarios, comprising:

an input module;

a database for storing characteristics of various types and conditions of vascular segments, a vascular region of interest and associated environments, properties of tools associated with treatment of vascular abnormalities, and patient-related indicia, or information identifying such;

access to a FSI solver, the FSI solver for accepting an ensemble including at least some of the characteristics, conditions, a description of the vascular region of interest and associated environments, the properties of tools associated with treatment of vascular abnormalities, and the patient-related indicia, or information identifying such from the input module and the database, and using the accepted ensemble to model the region of interest and provide results from modeling the region of interest;

interfaces for transmitting information from the input module and the database to the FSI solver and for receiving the results from the FSI solver; and

a collection of analysis modules, coupled to the interface for receiving results, the collection for comparing various treatment options, allowing before-and-after comparisons of aspects of the region of interest and providing quantitative assessments of parameters of interest describing the region of interest from the results.

2. The system of claim **1**, wherein the access to the FSI solver is via a bus, which fulfills, at least in part, the functions of the interfaces for transmitting and for receiving, and wherein the FSI solver is a part of the system.

3. The system of claim **1**, wherein the access to the FSI solver is via a network, which fulfills, at least in part, the functions of the interfaces for transmitting and for receiving, and wherein the FSI solver is remote from other portions of the system.

4. The system of claim **1**, wherein the FSI solver is operable to iteratively perform a computational fluid dynamic analysis of pulsatile fluid flow, and, with results from the fluid analysis, employ a finite-element mechanical analysis of vessel properties including deformation due to the pulsatile loading by the fluid, and then, using the results from the finite-element mechanical analysis, re-engage the computational fluid dynamic analysis of pulsatile fluid flow, followed by further finite element mechanical analysis of vessel properties, until a predetermined convergence criterion is achieved, and then

to provide raw simulation data from the iteratively-performed analyses to other analysis modules for further, application-specific processing.

5. The system of claim **1**, wherein results from the FSI solver are employed in a pre-operative, characterization phase, to compare benefits and drawbacks of various treatment protocols and tools and aid in selection of an appropriate one or ones of treatment modalities for implementation or further evaluation.

6. The system of claim **1**, wherein results from the FSI solver are employed in a intra-operative mode, to compare present status to a planned-for result, and to determine from that comparison what actions, if any, are suggested.

7. The system of claim **1**, wherein results from the FSI solver are employed in a post-operative mode, to facilitate comparison of a present risk profile to a planned result and associated risk profile, and to determine from that comparison what actions, if any, are suggested.

8. A process for characterizing aspects of vascular scenarios, comprising acts of:

accepting patient indicia via an input module;

accessing relevant data records from a database using the indicia, and augmenting those data records, where needed, with stored data from a bank of representative data also stored in the database, to provide information including a description of the vascular scenario and defining a region of interest;

sending the information to a FSI solver;

receiving, responsive to sending, raw simulation results from the FSI solver; and

modifying the raw simulation results using selected items from a collection of analysis modules, the selected items from the collection for comparing various treatment options, allowing before-and-after comparisons of aspects of the region of interest and providing quantitative assessments of parameters of interest describing the region of interest from the results.

9. The process of claim **8**, wherein the act of sending includes invoking the FSI solver to accept an ensemble including at least some of:

characteristics and conditions associated with the indicia,

a description of the vascular scenario including a region of interest and associated environments,

properties of tools associated with treatment of vascular abnormalities, and

the patient-related indicia, or information identifying such; and

using the accepted ensemble to model the region of interest and provide results from modeling the region of interest.

10. The process of claim **8**, wherein the act of accepting patient indicia comprises accepting indicia identifying prior assessment and simulation results for comparison to present simulation results derived from a present measurement as part of a post-treatment evaluation process.

11. The process of claim **8**, further comprising importing present examination data on a continuing real-time basis as part of an intra-operative process, and comparing simulation results derived from the present examination data via the FSI solver to a planned treatment profile in order to determine what actions, if any, are warranted in order to promote achievement of the planned treatment profile.

12. The process of claim **8**, wherein, following definition of a region of interest, present measured data are collected and are employed together with the information including a description of the vascular scenario by the FSI solver to provide a present simulation of the region of interest.

13. The process of claim **8**, further comprising, prior to sending, optionally invoking a simplified model in order to obtain a rough estimation indicative of whether or not the values to be sent to the FSI solver via sending appear to be appropriate or appear to require adjustment prior to sending.

14. The process of claim **8**, wherein the FSI solver, after sending and prior to receiving, determines, via a predetermined convergence criterion, when to terminate iteration of alternative modeling of flow simulation using computational fluid dynamics, and coupling result from flow simulation to a mechanical analysis to determine impact of the flow simulation on vasculature properties, and then employing results from the mechanical analysis to refine the modeling of flow simulation.

15. A computation engine and a memory coupled to a data collection module; and

computer-readable code embodied on a computer-readable medium and configured so that when the computer-readable code is executed by one or more processors associated with the computation engine, the computer-readable code causes the one or more processors to:

accept input indicia from the data collection module, the input indicia identifying a particular patient and allowing access to stored records relating to prior measurements and simulations, if any, relative to that patient;

determine estimates for quantities not represented in a present measurement from a database storing characteristics of various types and conditions of vascular segments associated with a defined vascular region of interest and associated environments, to determine appropriate properties of tools associated with treatment of vascular abnormalities, in conformance with patient-related indicia, or information identifying such;

access a FSI solver, the FSI solver for accepting an ensemble including at least some of the characteristics, conditions, a description of the vascular region of interest and associated environments, the properties of tools associated with treatment of vascular abnormalities, and the patient-related indicia, or information identifying such from the input module and the database, and using the accepted ensemble to model the region of interest and provide results from modeling the region of interest;

exchange information between the input module and the database and the FSI solver, including providing results from the FSI solver to a collection of analysis modules; and

using the collection of analysis modules, and the results from the FSI solver to:

compare benefits and potential drawbacks of various treatment options; or

allow before-and-after comparisons of aspects of the region of interest; or

provide quantitative assessments of parameters of interest describing the region of interest from the results.

16. The apparatus of claim **15**, wherein the computer readable code is further configured so that, when executed by the one or more processors, the computer readable code configured to cause the one or more processors to compare includes causing the one or more processors to compare benefits and potential drawbacks of various treatment options as part of a pre-treatment evaluation of one or more potential treatment plans.

17. The apparatus of claim **15**, wherein the computer readable code is further configured so that, when executed by the one or more processors, the computer readable code configured to cause the one or more processors to compare includes causing the one or more processors to compare benefits and potential drawbacks of various treatment options as part of a intra-treatment process for evaluation of differences between present and planned treatment profiles, and, when warranted, determine actions, if any, appropriate for correction of apparent deviations from a planned treatment profile.

18. The apparatus of claim **15**, wherein the computer readable code is further configured so that, when executed by the one or more processors, the computer readable code configured to cause the one or more processors to compare includes causing the one or more processors to compare benefits and potential drawbacks of various treatment options as part of a pre-operative risk assessment and treatment planning process.

19. The apparatus of claim **15**, wherein the computer readable code is further configured so that, when executed by the one or more processors, the computer readable code is configured to cause the one or more processors to evaluate convergence, using a predetermined convergence criterion, of a process involving successive iteration of a computational fluid dynamics computation of fluid flow simulation, with an output from the fluid flow simulation being coupled to a mechanical analysis of vasculature to determine variations in the vasculature as a result of the fluid flow, and with an output of the mechanical analysis of vasculature being coupled to an input to the computational fluid dynamics computation of fluid flow simulation, and to cease iteration when the convergence criteria is achieved.

20. The apparatus of claim **15**, wherein the computer readable code is further configured so that, when executed by the one or more processors, the computer readable code is configured to cause the one or more processors to evaluate convergence of concatenated simulations in the FSI solver to an acceptable degree and to then supply results from the concatenated simulations to the collection of analysis modules for further processing.

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