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(19) **United States**(12) **Patent Application Publication**
PETERS et al.(10) **Pub. No.: US 2015/0317429 A1**(43) **Pub. Date: Nov. 5, 2015**(54) **METHOD AND APPARATUS FOR
SIMULATING BLOOD FLOW UNDER
PATIENT-SPECIFIC BOUNDARY
CONDITIONS DERIVED FROM AN
ESTIMATED CARDIAC EJECTION OUTPUT**(71) Applicants: **PHILIPS DEUTSCHLAND GMBH**,
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Holger SCHMITT, Hamburg (DE)(21) Appl. No.: **14/651,705**(22) PCT Filed: **Dec. 12, 2013**(86) PCT No.: **PCT/IB2013/060841**

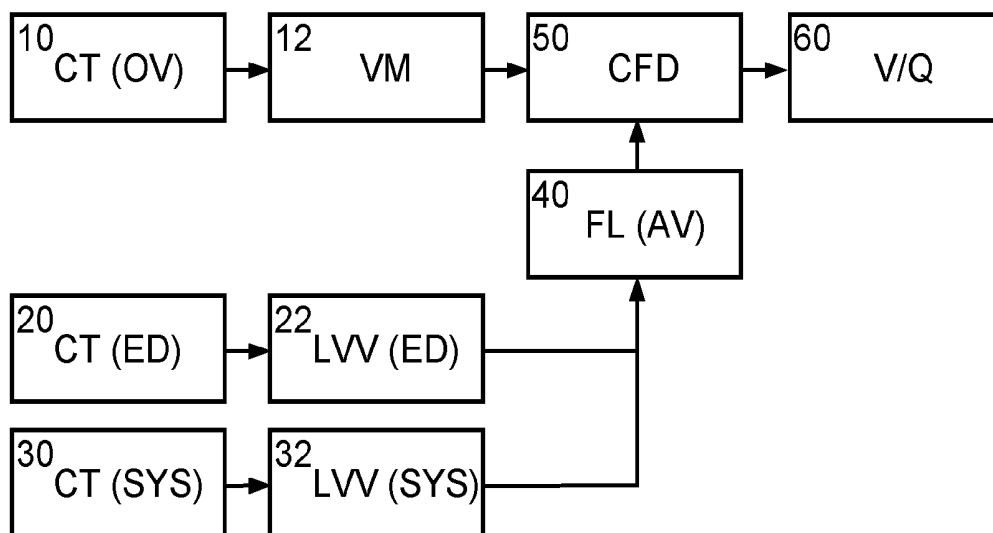
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18, 2012.**Publication Classification**(51) **Int. Cl.****G06F 19/12** (2006.01)**A61B 5/00** (2006.01)**A61B 8/06** (2006.01)**A61B 5/026** (2006.01)**A61B 6/03** (2006.01)(52) **U.S. Cl.**CPC **G06F 19/12** (2013.01); **A61B 5/0263**(2013.01); **A61B 6/032** (2013.01); **A61B 8/06**(2013.01); **A61B 5/7285** (2013.01)

(57)

ABSTRACT

The present invention relates to a method and apparatus for simulating blood flow through a cardiovascular structure, e.g. a blood cavity such as the left ventricle outflow tract, the aortic root including the AV, plus ascending aorta, a ventricle volume, the aorta or any other cavity where blood flows through, under patient-specific boundary conditions derived from the cardiac ejection output per heart stroke. The cardiac ejection output can be estimated from volumes of a heart chamber of the patient in different filling states at two or more different points in time. The results of the flow simulation can be used to derive at least one physiological parameter or can be visualized and virtual Doppler ultrasound images may be generated to allow a physician assessing the result.



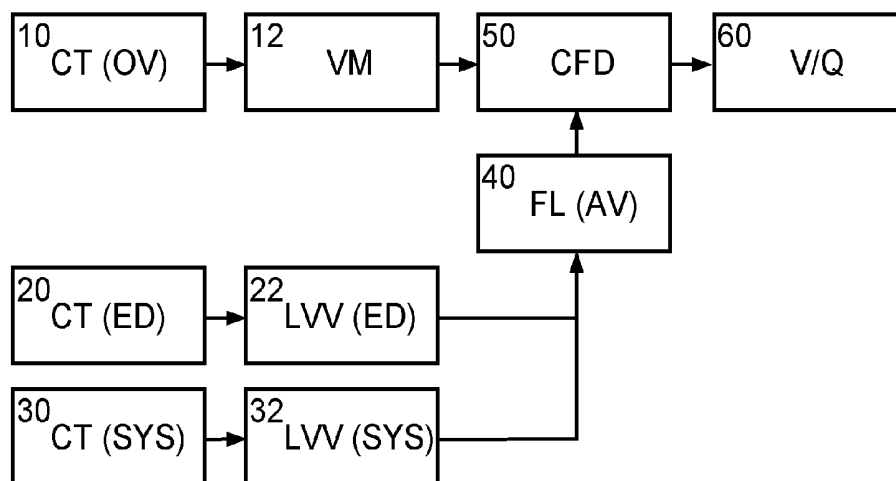


FIG. 1

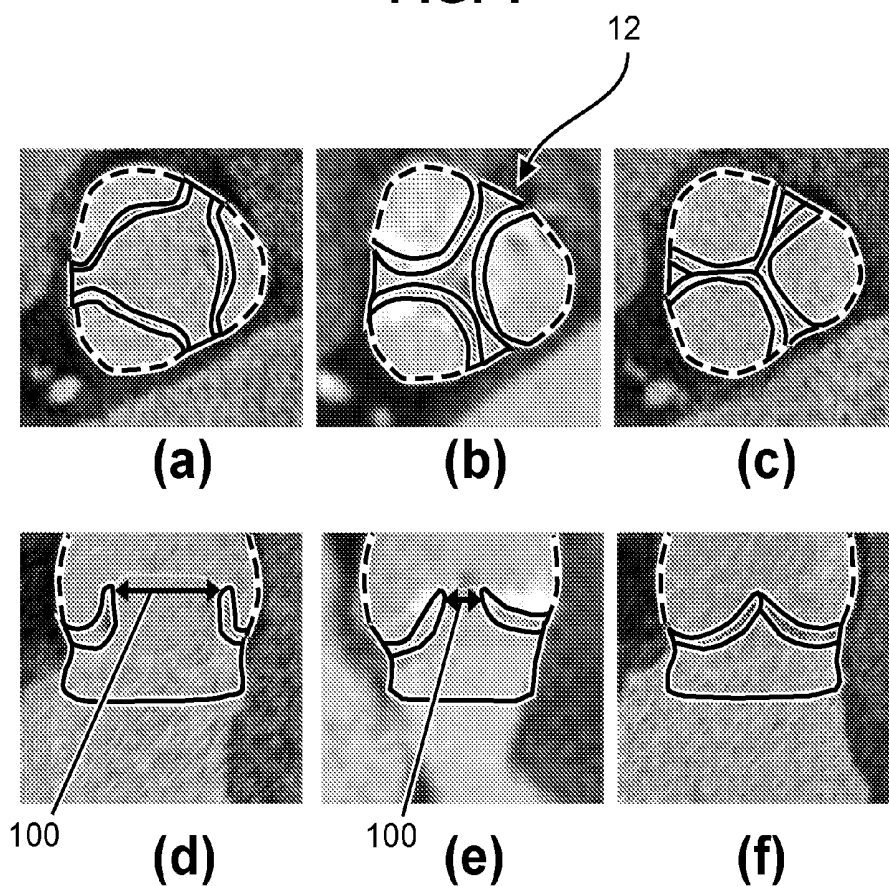


FIG. 2

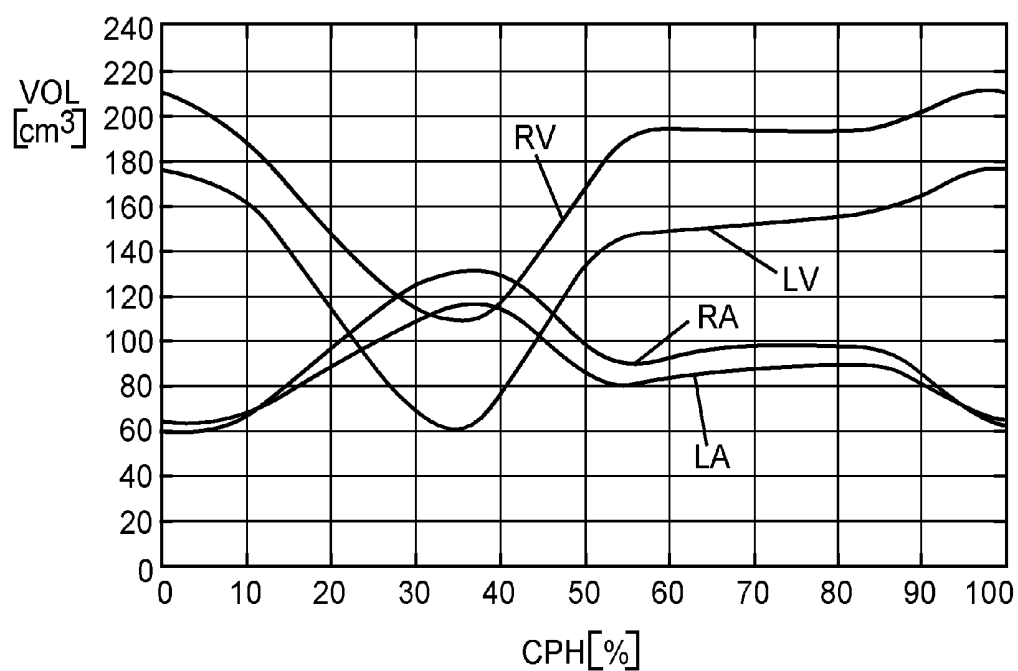


FIG. 3

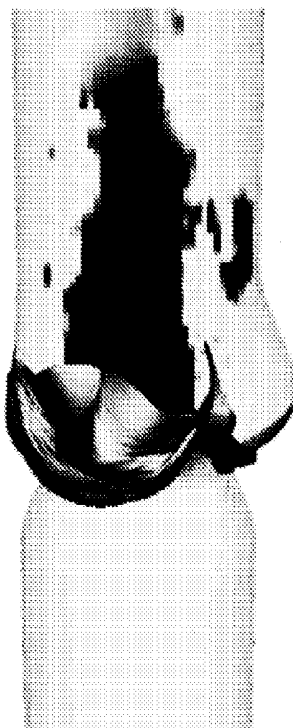


FIG. 4

**METHOD AND APPARATUS FOR
SIMULATING BLOOD FLOW UNDER
PATIENT-SPECIFIC BOUNDARY
CONDITIONS DERIVED FROM AN
ESTIMATED CARDIAC EJECTION OUTPUT**

FIELD OF THE INVENTION

[0001] The invention relates to the field of simulation of blood flow through a target cardiovascular structure, such as—but not limited to—a patient-specific geometry of the left ventricular outflow tract, the aortic root including the aortic valve (AV) and the ascending aorta, based on information acquired through medical imaging techniques.

BACKGROUND OF THE INVENTION

[0002] Degenerative aortic valve stenosis (AS) is the second most common cardiovascular disease with an incidence of 2-7% in the Western European and North American populations aged beyond 65 years, as described in G. M. Feuchtnner, W. Dichtl, et al. “Multislice Computed Tomography for Detection of Patients With Aortic Valve Stenosis and Quantification of Severity”, *Journal of the American College of Cardiology* 2006, 47 (7), 1410-1417.

[0003] Management of patients with degenerative AS depends on the severity of the disease. Assessment of the severity of the stenosis of an aortic valve (AV) can involve different imaging modalities. Current assessment of the severity is mostly based on ultrasound and Doppler measurements or on geometric measurements derived from magnetic resonance imaging (MRI) or computed tomography (CT) images of the AV area.

[0004] For ca. 60-70% of the patients, ultrasound can be used to image the valve and to measure blood velocities via Doppler measurements. For a stenosed valve, due to the reduced effective opening area, the blood has to flow at higher velocities and the results of the Doppler measurements can be taken as indicator of aortic stenosis (AS).

[0005] Using electrocardiography (ECG) gating, CT and MM allows to reconstruct or acquire images from a selected narrow cardiac phase interval and gives access to images that show the valve in the relatively short open state. G. M. Feuchtnner, W. Dichtl, et al. “Multislice Computed Tomography for Detection of Patients With Aortic Valve Stenosis and Quantification of Severity”, *Journal of the American College of Cardiology* 2006, 47 (7), 1410-1417 and Y. Westermann, A. Geigenmüller, et al. “Planimetry of the aortic valve orifice area: Comparison of multi-slice spiral CT and MRI”, *European Journal of Radiology* 2011, 77, 426-435, suggest using images of the open valve to measure the valve opening using a few selected angulated cut planes and delineating the apparent valve orifice. The measured area of this orifice is then used to assess the degree of stenosis. This technique is called AV area planimetry.

[0006] However, for planimetry measurements of the AV area from CT or MRI, only a two-dimensional (2D) cut is analyzed. Whether the valve leaflets meet at commissure lines in some other region downstream is not analyzed. The impact on the three-dimensional (3D) blood flow can therefore not be fully assessed by such 2D measurements. The relation between such measured areas and the physiological impact of a stenosed valve, such as increased pressure gradients, is thus unclear.

SUMMARY OF THE INVENTION

[0007] It is an object of the invention to derive objective values for physiological parameters of a patient under consideration from patient-specific boundary conditions.

[0008] This object is achieved by an apparatus as claimed in claim 1, a method as claimed in claim 5, and a computer program product as claimed in claim 15.

[0009] Accordingly, a volumetric mesh of the cardiovascular structure (e.g. a blood cavity such as the left ventricle outflow tract, the aortic root including the aortic valve (AV), plus ascending aorta, a ventricle volume, the aorta or any other cavity where blood flows through) is generated based on a partitioned digital image of the cardiovascular structure, and a cardiac ejection output per heart stroke is estimated in terms of its amount or temporal behavior from volumes of a heart chamber of the patient in different filling states at two or more different points in time. At least one patient-specific boundary condition (which may include a time-dependent boundary condition) of the cardiovascular structure is then derived from the cardiac ejection output per heart stroke and the simulated blood flow is obtained by simulating a blood flow through the volumetric mesh under consideration of the patient-specific boundary conditions.

[0010] Thus, blood flow through a patient-specific geometry of a target cardiovascular structure under patient-specific boundary conditions is derived from the cardiac ejection output per heart stroke. The result of the simulation yields objective values for physiologically relevant parameters such as one or more of pressure drop, average blood residence time, flow rate, wall shear stress and blood swirl in said cardiovascular structure. According to a first aspect, a modeling circuit may be provided for generating the volumetric mesh of the cardiovascular structure based on a partitioned segmented digital image of the cardiovascular structure. Thereby, the volumetric mesh can be directly generated and does not need to be derived or loaded from a remote device or network.

According to a second aspect which can be combined with the above first aspect, the digital image may be a CT image or an MM image or an ultrasonic image. Thus, the proposed solution can be used for a wide range of medical imaging systems.

According to a third aspect which can be combined with the above first or second aspect, the digital image may be partitioned by using a model-based segmentation to obtain a surface mesh of the target cardiovascular structure. Thereby, the volumetric mesh can be readily obtained by converting or transforming the surface mesh into the volumetric mesh.

[0011] According to a fourth aspect which can be combined with any one of the above first to third aspects, the simulation may be done by computational fluid dynamics (CFD) or fluid-solid interaction (FSI) simulation. This facilitates automation of the process of creating computer models.

According to a fifth aspect which can be combined with any one of the above first to fourth aspects, the cardiac ejection output per heart stroke may be estimated based on electrocardiography (ECG) gated digital images. This measure ensures proper timing of image generation.

[0012] According to a sixth aspect which can be combined with any one of the above first to fifth aspects, the cardiac ejection output per heart stroke may be estimated based on digital images of the ventricle in a maximum filling state and a minimum filling state. This provides a straight forward solution based on the two images. In a specific example, the cardiac ejection output per heart stroke may be estimated

based on volumes of the at least one heart chamber of the patient at an end of systole and at an end of a diastole.

[0013] According to a seventh aspect which can be combined with any one of the above first to sixth aspects, the estimated cardiac ejection output per heart stroke may be used to define a blood flow from a cardiac chamber to the cardiovascular structure. According to a specific example of the fifth aspect, the at least one patient-specific boundary condition may be derived by estimating a flow profile across the ventricular outflow tract and its temporal behavior. Hence, (flow) boundary conditions (e.g. to estimate the pressure drop across the target cardiovascular structure via (CFD or FSI) simulation) can be determined based on the ventricular ejection fraction by image analysis. Thereby, a complete heart simulation is no longer required, which is extremely time consuming, extremely complicated and cannot always be done with available clinical data. The flow profile may be estimated by defining a quadratic profile or a velocity profile of a pulsatile flow.

It shall be understood that the apparatus of claim 1, the method of claim 5 and the computer program product of claim 15 have similar and/or identical preferred embodiments, in particular, as defined in the dependent claims.

It shall be understood that a preferred embodiment of the invention can also be any combination of the dependent claims with the respective independent claim.

[0014] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] In the drawings:

[0016] FIG. 1 shows a schematic block diagram of generation and use of patient-specific boundary conditions for simulating blood flow according to an embodiment of the present invention;

[0017] FIGS. 2a-f show schematic reformatted views of segmented valves for the cases of an open, calcified medium open and closed valve, respectively;

[0018] FIG. 3 shows a diagram with volume curves of heart chambers extracted by model-based segmentation; and

[0019] FIG. 4 shows a schematic exemplary visualization of a simulation of blood flow through an aortic valve.

DETAILED DESCRIPTION OF EMBODIMENTS

[0020] Embodiments are now described based on a simulation of the blood flow through a patient-specific geometry of a left ventricle (LV) outflow tract plus ascending aorta (as an example for a blood cavity or cardiovascular structure close to the heart) under patient-specific boundary conditions derived from the cardiac ejection output per heart stroke, which blood volume can be calculated from (at least) two images of the LV in maximum and minimum filling state (e.g., end of diastole, end of systole). The geometry of the LV outflow tract, the aortic root including the AV, plus ascending aorta and the ventricle volumes can automatically be obtained by model-based segmentation.

[0021] FIG. 1 shows a schematic block diagram illustrating the generation and use of patient-specific boundary conditions for simulating the flow through the aortic valve. The blocks of FIG. 1 can be regarded as hardware circuits adapted to perform the respective function or as steps of a corresponding method or process which may be implemented as soft-

ware programs comprising code means for producing the related function when run on a computer or processor system.

[0022] First, in a segmentation step or circuit (CT (OV)) 10, the LV outflow tract, the aortic root including the AV, plus ascending aorta is segmented for an open valve (OV) state in a CT image to obtain a surface mesh of the complete blood cavity. This can be done using model-based segmentation as described for example in O. Ecabert, et al. "Segmentation of the heart and great vessels in CT images using a model-based adaptation framework" Medical Image Analysis 2011, 15(6), 863-876. In general, segmentation is the process of partitioning a digital image into multiple segments (i.e. sets of pixels). In the segmentation, a voxel is allocated to a specific structure, e.g., by adding a label or flag or color or outline or the like. This may be achieved by typical image segmentation methods such as thresholding, edge detection, region growing or the like. Then, in a modeling step or circuit (VM) 12, from the surface mesh obtained from the segmentation step or circuit 10, a volumetric mesh for computational fluid dynamics (CFD) or fluid-solid interaction (FSI) or other types of simulations is generated using known meshing tools. Suitable meshing tools (e.g. TetGen or NetGen) may involve techniques to generate different tetrahedral meshes from three-dimensional point sets or domains with piecewise linear boundaries.

[0023] According to the present embodiment, the model-based segmentation (MBS) as described above is used in first (LVV (ED)) and second (LVV (SYS)) extracting steps or circuits 22, 23 to extract a change of the left ventricle volume (LVV) over time (cf. FIG. 3 below) from electrocardiography (ECG) gated CT images obtained in first and second imaging steps or circuits 20, 30. More specifically, the left ventricle (LV) in maximum and minimum filling state (end-diastole, end-systole) can be obtained from the first and second imaging steps 20, 30, respectively, and can be used to estimate the flow or volume or temporal behavior of the blood (i.e. cardiac ejection output) pumped per heart beat. This flow or volume or temporal behavior of the blood is then used in an estimation step or circuit (FL (AV)) 40 to define the blood flow from the left ventricular outflow tract through the aortic valve orifice into the aorta.

[0024] FIGS. 2a to 2f show schematic reformatted cross-sectional top and side views, respectively, of sample results of segmented valves for open (FIG. 2a (top view), FIG. 2d (side view)), calcified medium open (FIG. 2b (top view), FIG. 2e (side view)), and closed valve (FIG. 2c (top view), FIG. 2f (side view)). The marked double arrows 100 in FIGS. 2d and 2f indicate the width of the valve orifice.

[0025] FIG. 3 shows a diagram with volume curves of the four heart chambers (left atrium (LA), left ventricle (LV), right atrium (RA), right ventricle (RV)) as extracted by the model-based segmentation of the extracting steps or circuits 22, 23 from a ECG gated CT data set.

[0026] To define patient-specific boundary conditions (i.e., flow at LV outflow tract), a flow profile across the outflow tract and its temporal behavior can be estimated in the estimation step or circuit 40. For the temporal behavior, it can, for instance, be assumed that there is no flow through the aortic valve during a predetermined portion (e.g. between 40% and 10%) of the cardiac phase. In between (e.g. ~10%-40%), a constant flow or a volume flow curve derived from the LV volume curve in FIG. 3 may be used. The flow across the LV outflow tract can, for instance, be defined by a quadratic

profile (profile for constant flow in a tube) or the velocity profile of pulsatile flow using a Womersley number.

[0027] In a subsequent CFD simulation step or circuit **50**, the flow through the open valve is simulated by CFD to estimate the pressure drop for the open valve. This can be achieved by specifying the blood flow behavior and properties at the boundaries of the volumetric mesh of the blood cavity obtained from modeling step or circuit **12**, while taking into account the above patient-specific boundary conditions obtained from the estimation step or circuit **40**. Additionally, to obtain a complete simulation of blood flow through the aortic valve, fluid-solid interaction may be taken into account so as to also consider interactions with the elastic vascular wall. The result of the CFD simulation can be analyzed to estimate e.g. the pressure drop across the aortic valve or other physiological parameters, such as average blood residence time, flow rate, wall shear stress and blood swirl at the aortic valve.

[0028] Finally, the results of the flow simulation can also be visualized and/or quantified in an optional visualization and/or quantification step or circuit (V/Q) **60** and virtual Doppler ultrasound images may be generated to allow a physician assessing the result. This visualization may be based on analytical methods that analyze the simulated blood flow and show properties like, e.g., streamlines, streaklines, and pathlines. The blood flow can either be given in a finite representation or as a smooth function. As an alternative, texture advection methods can be used, that “bend” textures (or images) according to the flow. Numerical values or qualitative values of one or more of the above physiological parameters may be added to the visualization to allow comparison with standard values

[0029] FIG. **4** shows a visualization of an exemplary simulation of a blood flow through an aortic valve.

[0030] The proposed solution can be used to quantify AS or other cardiovascular diseases or even other blood-flow related characteristics of cardiovascular structures by simulation in a clinical workstation or other computer system based on image data obtained from CT or MRI or ultrasound or other imaging modalities.

[0031] To summarize, a method and apparatus have been described for simulating blood flow through a patient-specific geometry of a cardiovascular structure, e.g. a blood cavity such as the left ventricle outflow tract, the aortic root including the AV, plus ascending aorta, a ventricle volume, the aorta or any other cavity where blood flows through, under patient-specific boundary conditions derived from the cardiac ejection output per heart stroke. The cardiac ejection output can be estimated from volumes of a heart chamber of the patient in different filling states at two or more different points in time. In the case of AV-related simulations, the AV geometry and the ventricle volumes can automatically be obtained by model-based segmentation. In a first step the blood cavity is segmented in a CT image. From the surface mesh, a volumetric mesh for CFD simulations can be generated. Model-based segmentation may be used to extract the volume change over time. A flow profile across the outflow tract and its temporal behavior are then defined. The result of the CFD simulation can be analyzed to estimate physiological parameters (e.g. the pressure drop etc.) across the aortic valve. The results of the flow simulation can also be visualized and “Virtual Doppler Ultrasound” images may be generated to allow a physician assessing the result.

[0032] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive. The invention is not limited to the disclosed embodiment.

[0033] Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

[0034] The foregoing description details certain embodiments of the invention. It will be appreciated, however, that no matter how detailed the foregoing appears in text, the invention may be practiced in many ways, and is therefore not limited to the embodiments disclosed. It should be noted that the use of particular terminology when describing certain features or aspects of the invention should not be taken to imply that the terminology is being re-defined herein to be restricted to include any specific characteristics of the features or aspects of the invention with which that terminology is associated.

1. An apparatus for simulating blood flow through a cardiovascular structure close to the heart of a patient, said apparatus comprising:

an estimation circuit for estimating a cardiac ejection output per heart stroke based on a volume of at least one heart chamber of said patient in different filling states at two or more points in time, and for deriving at least one patient-specific boundary condition for the flow through said cardiovascular structure from the cardiac ejection output per heart stroke; and

a simulation circuit for simulating a blood flow through a volumetric mesh of said cardiovascular structure under consideration of said patient-specific boundary conditions, to visualize said blood flow or to derive at least one physiological parameter of said patient.

2. The apparatus according to claim **1**, further comprising a modeling circuit for generating said volumetric mesh of said cardiovascular structure based on partitioned segmented digital image of said cardiovascular structure.

3. The apparatus according to claim **1**, wherein said digital image is a computed tomography image or a magnetic resonance image or an ultrasonic image.

4. The apparatus according to claim **1**, wherein said apparatus is adapted to derive from said simulated blood flow at one or more of a pressure drop, an average blood residence time, a flow rate, a wall shear stress and a blood swirl in said cardiovascular structure.

5. A method of simulating blood flow through a cardiovascular structure close to the heart of a patient, said method comprising:

estimating a cardiac ejection output per heart stroke based on a volume of at least one heart chamber of said patient in different filling states at two or more points in time;

deriving at least one patient-specific boundary condition for the flow through said cardiovascular structure from the cardiac ejection output per heart stroke; and

simulating a blood flow through a volumetric mesh of said cardiovascular structure under consideration of said patient-specific boundary conditions, to visualize said blood flow or to derive at least one physiological parameter of said patient.

6. The method according to claim 5, further comprising partitioning said digital image by using a model-based segmentation to obtain a surface mesh of said cardiovascular structure.

7. The method according to claim 5, wherein said simulation is a computational fluid dynamics simulation or a fluid-solid interaction simulation.

8. The method according to claim 5, further comprising estimating said cardiac ejection output per heart stroke based on electrocardiography gated digital images.

9. The method according to claim 5, further comprising estimating said cardiac ejection output per heart stroke based on digital images of said at least one heart chamber in a maximum filling state and a minimum filling state.

10. The method according to claim 5, further comprising using said estimated cardiac ejection output per heart stroke to define a blood flow from a ventricular outflow tract to said cardiovascular structure.

11. The method according to claim 10, further comprising deriving said at least one patient-specific boundary condition by estimating a flow profile across said ventricular outflow tract and its temporal behavior.

12. The method according to claim 11, further comprising estimating said flow profile by defining a quadratic profile or a velocity profile of a pulsatile flow.

13. The method according to claim 5, further comprising estimating said cardiac ejection output per heart stroke based on volumes of said at least one heart chamber of said patient at an end of systole and at an end of a diastole.

14. The method according to claim 5, further comprising generating virtual Doppler ultrasound images based on said simulated blood flow.

15. A computer program product comprising code means for producing the steps of claim 5 when run on a computing device.

* * * * *

专利名称(译)	用于在从估计的心脏射血输出导出的患者特定边界条件下模拟血流的方法和装置		
公开(公告)号	US20150317429A1	公开(公告)日	2015-11-05
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[标]申请(专利权)人(译)	飞利浦DEUT 飞利浦灯具控股公司		
申请(专利权)人(译)	飞利浦DEUTSCHLAND GMBH KONINKLIJKE PHILLIPS N.V.		
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发明人	PETERS, JOCHEN WEESE, JUERGEN SCHMITT, HOLGER		
IPC分类号	G06F19/12 A61B5/00 A61B8/06 A61B5/026 A61B6/03		
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优先权	61/738562 2012-12-18 US		
外部链接	Espacenet USPTO		

摘要(译)

本发明涉及一种用于模拟通过心血管结构的血流的方法和装置，例如，血液腔，如左心室流出道，主动脉根包括AV，加升主动脉，心室容积，主动脉或血液流过的任何其他腔，在患者特定的边界条件下，每个心脏射血输出心脏中风。可以在两个或更多个不同时间点以不同填充状态从患者心腔的体积估计心脏射血输出。流动模拟的结果可以用于导出至少一个生理参数或者可以是可视化的，并且可以生成虚拟多普勒超声图像以允许医生评估结果。

