(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
28 November 2024 (28.11.2024)

(10) **International Publication Number**
WO 2024/241193 A1

(51) **International Patent Classification:**
G06T 7/60 (2017.01)

(21) **International Application Number:**
PCT/IB2024/054887

(22) **International Filing Date:**
20 May 2024 (20.05.2024)

(25) **Filing Language:** Italian

(26) **Publication Language:** English

(30) **Priority Data:**
102023000010473 24 May 2023 (24.05.2023) IT

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(54) **Title:** 'SYSTEM AND METHOD FOR THE MORPHO-FUNCTIONAL ASSESSMENT OF THE THORACIC VASCULAR DISTRICT

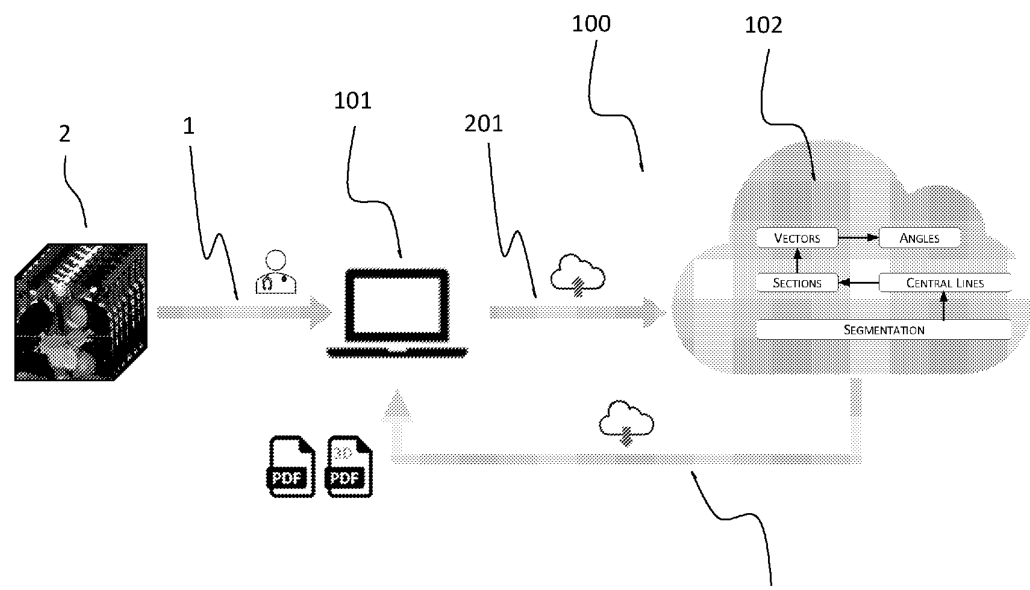

Fig.7

(57) **Abstract:** System (100) and method thereof for morpho-functional assessment of the thoracic vascular district, said system (100) comprising an arithmetic device configured to execute: processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest; segmenting of the images (2) into volumes of interest (4, 5), representing a heart valve and a section of a blood vessel; processing of a reconstruction of at least one central line (6, 6', 6", 106, 106') for each volume of interest (4, 5); processing of identifying a base section (8, 11) and a proximal section (7, 7'), the base section (8, 11) being a valve section of said at least one volume of interest (4, 5) and the proximal section (7, 7') being a section having a distance from the base section (8, 11) of less than or equal to 40 mm; calculating a first vector (10, 10') and a second vector (12, 12') tangent to the at least one central line (6, 106) and intersecting the base section (8, 11) and the proximal section (7, 7'), respectively; and calculating a proximal angle (*α, α'*), the proximal angle (*α, α'*) being between the first (10, 10') and second vector (12, 12').

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[Continued on next page]

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

'SYSTEM AND METHOD FOR THE MORPHO-FUNCTIONAL ASSESSMENT OF THE THORACIC VASCULAR DISTRICT'

DESCRIPTION

TECHNICAL FIELD OF THE INVENTION

The present invention relates to a system and related method for the morpho-functional evaluation of the thoracic vascular district which, starting from volumetric images (e.g. CT or MRI) of said district, allows to obtain a plurality of geometric parameters relating to the thoracic aorta and to the pulmonary artery and usable mainly, though not exclusively, for transcatheter aortic valve replacement (TAVR) and/or for transcatheter pulmonary valve replacement (TVPR).

STATE OF THE ART

Percutaneous cardiovascular procedures, such as TAVR and TPVR, involve the transcatheter insertion of prosthetic valves. These devices consist of biomorphic artificial valves placed inside a stent; the stent and prosthetic valve leaflets inside it are crimped into a catheter that is used to carry the device from distal access to the intracardiac implantation site. Once the implant site is reached, the catheter is retracted and the device stent is expanded into the site. In order for the device to function properly, it must first be correctly positioned in relation to the adjacent anatomical structures. For example, in the case of TAVR, the device is implanted at the native aortic valve, but must not occlude the coronary ostia that lie immediately downstream of the latter, otherwise myocardial ischaemia is induced. This requires the correct positioning of the device along the axial development of the aorta and in particular the aortic bulb. In addition, for the implant to be stable, the stent of the device must expand until it completely adheres to the wall of the implant site, generating a thrust against it and thus mechanical interference. This is the only way to prevent the device from migrating after its insertion, and to prevent the so-called 'paravalvular leakage', i.e. the backflow of blood between the prosthetic device and the wall when the prosthetic valve is closed. More specifically, mechanical interference is such that implant stability is ensured when the device is positioned 'on axis' with the implant site, its nominal size is slightly oversized in relation to the size of the implant site, and the wall of the implant site is not too yielding.

It is also important that the thrust exerted by the stent on the wall of the implant site is not excessive, i.e. that it is not such as to dilate the implant site and induce undesirable interactions with important adjacent structures. For example, in the case of TAVR, compression of the His bundle running close to the implantation site must be avoided in order to avoid generating electrical signal conduction problems in the myocardium; in the case of TPVR, on the other hand, the device must not dilate the pulmonary artery to the point where it compresses the left coronary artery running close to the implantation site in order to avoid inducing ischaemia. Finally, it is necessary that downstream of the expansion, the stent section should have as circular a configuration as possible. The presence of calcific deposits or the elliptical geometry of the implant site may, in fact, distort the geometry of the expanded device to an appreciable extent, and this may lead to an incorrect movement of the prosthetic flaps and, therefore, to their incorrect coaptation when the valve is closed and, ultimately, to a reduction in their fatigue life.

In contrast to open-chest surgery, transcatheter TAVR and TPVR procedures do not allow direct visual access to the operating field, which during the procedure can only be investigated indirectly, i.e. through two-dimensional (2D) fluoroscopy projections. For this reason, pre-operative planning is crucial in these procedures, during which the feasibility of implantation is assessed and the most appropriate valve device type and size are selected on the basis of three-dimensional (3D) X-ray images, e.g., computed tomography (CT). Currently, the planning of TAVR and TPVR procedures consists of identifying an appropriate implantation zone, i.e. one with characteristics that guarantee the stability and proper function of the prosthetic device once it is implanted. The characteristics of the implant zone are patient-specific; therefore, they are measured for each implant candidate from clinical imaging, which commonly consists of CT images. In the case of TAVR, there are established guidelines ([*Blanke P, Weir-McCall JR, Achenbach S, Delgado V, Hausleiter J, Jilaihawi H, Marwan M, Norgaard BL, Piazza N, Schoenhagen P, Leipsic JA. Computed tomography imaging in the context of transcatheter aortic valve implantation (TAVI) / transcatheter aortic valve replacement (TAVR): An expert consensus document of the Society of Cardiovascular Computed Tomography. J Cardiovasc Comput Tomogr 2019;13(1):1-20*]; [*Vahanian A, Beyersdorf F, Praz F, Milojevic M, Baldus S, Bauersachs J, Capodanno D, Conradi L, De Bonis M, De Paulis R, Delgado V, Freemantle N, Gilard M, Haugaa KH, Jeppsson A, Jüni P, Pierard L, Prendergast BD, Sádaba JR, Tribouilloy C, Wojakowski W. 2021 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 2022;43(7):561-632*], [*Perry TE, George SA, Lee B, Wahr J, Randle D, Sigurðsson G. A guide for pre-procedural imaging for transcatheter aortic valve replacement patients. Perioperative Medicine 2020;9(1):36*], according to which the measured characteristics are: maximum and minimum diameter, cross-sectional area and perimeter at the aortic valve plateau, the aortic bulb (sinuses of Valsalva) and the sino-tubular junction that distally borders the aortic bulb; distance between the coronary ostia and the aortic valve plateau; and, finally, calcium score, i.e., the total volume of calcium deposits that may be present at the implantation site. In the case of TPVR, there are no established guidelines like those available for TAVR and planning is therefore less standardised (*[Curran L, Agrawal H, Kallianos K, Kheiwa A, Lin S, Ordovas K, Mahadevan VS. Computed tomography guided sizing for transcatheter pulmonary valve replacement. IJC Heart & Vasculature 2020; 29:100523]; [Canan A, Ocazionez-Trujillo D, Vargas D, Foley TA, Cabalka AK, Rajiah PS. Pre- and Postprocedure Imaging of Transcatheter Pulmonary Valve Implantation. RadioGraphics 2022;42(4):991-1011]*). The dimensions that are, however, measured are the maximum and minimum diameter, area and perimeter of the cross-sectional area at the native valvular plane of the pulmonary artery. Any other measurements are performed in different ways, in the various centers, according to their specific practices.

However, the various measurements described above have certain limitations, of which the three described below are of particular relevance.

The measurements described are partial, i.e. they focus only on the tract of the vessel that constitutes the implant site without considering the immediately adjacent anatomy. This leads to neglecting the effect of the latter on the actual possibility of positioning the device correctly.

The measurements listed above are mainly obtained through manual procedures, which are therefore highly operator-dependent and not very repeatable. This prevents the standardization of intervention planning on a large scale.

The measurements described are static, i.e. taken at a single instant in the cardiac cycle, because there are no instruments to effectively and systematically assess the evolution of the parameters of interest during the cardiac cycle. However, the size of the implantation site may change during the cardiac cycle due to the pulsatility of blood flow within deformable structures such as arteries. In aortic valves or pulmonary conduits with very severe calcific stenosis, this size variation may have an almost negligible impact on device sizing. Conversely, in both TAVR candidates with less severe calcific stenosis and TPVR candidates with an insufficient right ventricular outflow tract (RVOT) but no calcific deposits, the variation in shape and size of the implantation zone can be significant. Neglecting it can lead to underestimating the size of the implant site by measuring it at a time that is not its maximum expansion and does not allow quantifying the compliance of the implant site wall, which is relevant to implant site stability.

OBJECTS AND SUMMARY OF THE INVENTION

An object of the present invention is, therefore, to provide a system and related method for the morpho-functional assessment of the thoracic vascular district that allows morphological indices to be obtained that take into account not only the geometry of the implant site but also the geometry of the immediately adjacent area.

To this end, the system of the present invention provides for the identification of the implantation section and the section delimiting proximally and, more or less distally, the tract of the vessel affected by the device when it is expanded, followed by the calculation of the tangent vectors to the central line of the vessel of interest at the identified sections, as well as the angles between these two vectors.

More specifically, it is an object of the present invention to provide a system for the morpho-functional assessment of the thoracic vascular district, said system comprising an arithmetic device configured to execute:

- processing of importing volumetric radiological images of the vascular district at a time instant of interest;
- segmenting the images into volumes of interest, at least one of said volumes representing at least one half-lunar heart valve and at least one tract of a blood vessel extending from said valve;
- processing of reconstructing at least one central line for each vessel represented by at least one volume of interest;
- processing of identifying a base section and a proximal section, the base section being a valve section of said at least one volume of interest and the proximal section being a section having a distance from the base section, less than or equal to 40 mm;
- calculating a first vector, the first vector intersecting the base section and being tangent to at least the central line;
- calculating a second vector, the second vector intersecting the proximal section and being tangent to at least one central line; and
- calculating a proximal angle, the proximal angle being between the first vector and the second vector.

The above-mentioned object is, moreover, achieved by the system and method of the present invention as described, in more detail, in the attached set of claims.

A second object of the present invention is to provide a system and related method for the morpho-functional assessment of the thoracic vascular district that allows a set of morphological indices to be obtained in a repeatable and standardized procedure, thus avoiding errors due to highly operator-dependent procedures.

This object is achieved thanks to the use of automatic segmentation methods (e.g. by means of a 'deep convolutional network') of the thoracic aorta and the pulmonary artery, and thanks to the fact that the identification of the vessel's central line and the quantification of the anatomy, as reconstructed, are the result of fully automatic calculations. This eliminates the arbitrariness of the operator in selecting the sections on which to take measurements and, in identifying, on the selected sections, the repere points to be used for the calculation of the parameters of interest.

A further aim of the present invention is, finally, to provide a system and method for the morpho-functional assessment of the thoracic vascular district that allows for a dynamic type of assessment, i.e. it allows the evolution of the parameters of interest during the cardiac cycle to be measured effectively and systematically.

To this end, the system of the present invention comprises an arithmetic device configured to execute, not only all of the operations listed above, but also an analysis over time for morphological or dimensional assessment of a vessel section or region, at multiple stages of the cardiac cycle, as described in more detail below with regard to the sixth embodiment of the present invention.

These and further features of the present invention will be made clearer by reading the following detailed description, relating to some preferred embodiments of the present invention, to be considered by way of a non-limiting example of the more general concepts claimed.

BRIEF DESCRIPTION OF THE DDRAWINGS

The following description refers to the attached drawings, wherein:

- Figure 1a is a representation of the thoracic aorta with its central line and its base, proximal and distal sections together with vectors perpendicular to them;
- Figure 1b is a representation of the central line of the thoracic aorta with the vectors perpendicular to the sections shown in Figure 1a, as well as a representation of the angles formed reciprocally by said vectors;

- Figure 2a is a representation of the thoracic aorta and pulmonary artery with the central line of the thoracic aorta alone and its base, proximal, intermediate and distal sections together with vectors perpendicular to them;
- Figure 2b is a representation of the central line of the thoracic aorta with the vectors perpendicular to the sections shown in Figure 2a, as well as a representation of the angles formed reciprocally by said vectors;
- Figure 3a is a representation of the pulmonary artery with its central line and its base and proximal sections together with vectors perpendicular to them;
- Figure 3b is a representation of the central line of the pulmonary artery with the vectors perpendicular to the sections shown in Figure 3a, as well as the angles formed reciprocally by said vectors;
- Figure 4a is a representation of the pulmonary artery with its central line, as well as a representation of the vectors of the pulmonary bifurcation;
- Figure 4b is a representation of the central line of the pulmonary artery, the vectors shown in Figure 4a, and the angles formed reciprocally by said vectors;
- Figure 5a is a representation of the thoracic aorta and the three branches of the aortic arch with their central lines together with the ends of said central lines;
- Figure 5b is a representation of the central line of the thoracic aorta and the central lines of the three branches of the aortic arch together with the ends of said central lines;
- Figure 6a is a representation of the pulmonary trunk, the right pulmonary artery and the left pulmonary artery, with their central lines together with the ends of said central lines;
- Figure 6b is a representation of the central lines of the pulmonary trunk, right pulmonary artery and left pulmonary artery together with the ends of said central lines; and
- Figure 7 is a schematic representation of the sixth embodiment of the system of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

With reference to Figures 1a, 1b, 2a and 2b, a first embodiment of a system (100) according to the present invention comprises an arithmetical device configured to execute:

- processing of importing (1) volumetric radiological images (2) of the thoracic vascular district at a time instant of interest;
- segmenting the images (2) into volumes of interest (4), at least one of said volumes (4) representing the aortic valve and thoracic aorta;
- processing of reconstructing a central line (6) of the thoracic aorta represented by the volume of interest (4); and
- processing of identifying a base section (8) and a proximal section (7), the base section (8) being a section of the aortic valve and the proximal section (7) being a section with a distance from the base section (8) of less than or equal to 40 mm;
- calculating a first vector (10) intersecting the base section (8) and being tangent to the central line (6);
- calculating a second vector (12) intersecting the proximal section (7) and being tangent to the central line (6); and
- calculating a proximal angle (α), the proximal angle (α) being between the first vector (10) and the second vector (12).

The processing of identifying the base section (8) comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a nadir;
- registering an atlas on the images (2), so as to obtain registered images on which each nadir is represented;
- processing of identifying the base section (8) as a section of the volume of interest (4) lying on a plane passing through all the nadirs represented in the recorded images.

The processing of identifying the proximal section, comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being an intersecting line of one of the three valve leaflets of the aortic valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on which each commissure is represented;
- processing of identifying the proximal section (7) as a section of the volume of interest (4) lying on a plane passing through all the commissures represented in the recorded images.

The processing of reconstructing the central line (6) comprises:

- processing of identifying two ends (19, 20) of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, resulting in a plurality of centers; and
- calculating the central line (6) as a line (6) passing through the two ends (19, 20) and on which said centers lie.

With reference to Figures 5a and 5b, the processing of identifying the two ends (19, 20) comprises:

- an elaboration of a discretization of the surface of at least one volume of interest representing the thoracic aorta (4), with a triangular grid;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- processing of identifying a first (19) and a second (20) ends as points of the volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values,

respectively.

With reference to Figures 1a, 1b, 2a and 2b, a second embodiment of a system (100) according to the present invention comprises an arithmetical device configured to execute:

- processing of importing (1) volumetric radiological images (2) of the thoracic vascular district at a time instant of interest;
- segmenting the images (2) into volumes of interest (4), at least one of said volumes representing the aortic valve, the thoracic aorta and its first three branches: brachiocephalic trunk, left common carotid artery and left subclavian artery;
- processing of reconstructing a first central line (6) and a second central line (6', 6''); and
- processing of identifying a base section (8) and a proximal section (7), the base section (8) being a section of the aortic valve and the proximal section (7) being a section with a distance from the base section (8) of less than or equal to 40 mm;
- processing of identifying at least one distal section (13) of the volume of interest (4);
- calculating a first vector (10), the first vector (10) intersecting the base section (8) and being tangent to the first central line (6) of the volume of interest (4), i.e. the central line (6) of the thoracic aorta;
- calculating a second vector (12), the second vector (12) intersecting the proximal section (7) and being tangent to the first central line (6) of the thoracic aorta;
- calculating a third vector (14), the third vector (14) intersecting the at least one distal section (13) being tangent to the second central line (6') of the volume of interest (4), i.e. the central line (6') of the brachiocephalic trunk;
- calculating a proximal angle (α), the proximal angle (α) being between

the first vector (10) and the second vector (12);

- calculating a first distal angle (γ), the first distal angle (γ) being between the first vector (10) and the third vector (14); and
- calculating a second distal angle (δ), the second distal angle (δ) being between the second vector (12) and the third vector (14).

The processing of identifying the base section (8) comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a nadir;
- registering an atlas on the images (2), so as to obtain registered images on which each nadir is represented;
- processing the identifying the base section (8) as a section of the volume of interest (4) lying on a plane passing through all the nadirs represented in the recorded images.

The processing of identifying the proximal section (7), comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on which each commissure is represented;
- processing of identifying the proximal section (7) as a section of the volume of interest (4) lying on a plane passing through all the commissures represented in the recorded images.

With reference to Figures 5a and 5b, the processing of reconstructing the first central line (6) of the thoracic aorta comprises:

- processing of identifying a first ends (19) and a second ends (20) of the volume of interest (4);
- a calculation of a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there

is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;

- calculating the center of each sphere of said plurality of maximum spheres, obtaining a plurality of centers; and
- calculating the first central line (6) as a line (6) passing through the first end (19) and the second end (20) and on which lie said centers.

The processing of identifying the two ends (19, 20) of the first central line (6) comprises:

- an elaboration of a discretization of the surface of at least one volume of interest (4), with a triangular grid, thus obtaining a triangulated surface;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- processing of identifying a first (19) and a second (20) ends as points of the volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values, respectively.

Also the processing of reconstructing the second central line (6') of the brachiocephalic trunk comprises:

- processing of identifying a first end (19) and a second end (18, 18' 18") of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, resulting in a plurality of centers; and
- calculating the second central line (6') as a line (6') passing through the first (19) and second end (18) and on which lie said centers.

The first end (19) of the second central line (6') coincides with the first end (19) of the first central line (6).

The processing of identifying the second end (18) of the second central line (6') comprises:

- calculating the Heat Kernel Signature descriptor for each point on the triangulated surface, said calculating consisting of solving a heat equation using the Laplace Beltrami operator;
- a recursive selection of points having a 'Heat Kernel Signature' greater than a threshold, this threshold being incremented with each recursion, and the recursive selection terminating when the number of connected regions of points having a 'Heat Kernel Signature' greater than the threshold is three;
- calculating a maximum value of the Heat Kernel Signature descriptor for at least one of the connected regions identified by the recursive selection, resulting in up to three maximum values; and
- processing of identifying the second end (18) as the point in at least one of the identified connected regions at which the Heat Kernel Signature descriptor takes on its maximum value.

The processing of identifying a distal section (13) of the at least one volume of interest (4) comprises:

- calculating an intersection point (17') between the first central line (6) and a second central line (6'); and
- processing of identifying at least one distal section (13) as a section perpendicular to the first central line (6) and the second central line (6'), and passing through the point of intersection.

Obviously, it is possible to repeat the procedure described above to also identify a second and a third distal section using the points of intersection between the central line (6) of the thoracic aorta and the central line (6'') of the left common carotid artery and between the central line (6) of the thoracic aorta and the central line (6'') of the left subclavian artery. The first ends of the central line (6'') of the left common carotid artery and the central line (6'') of the left subclavian artery will also coincide with the first end (19) of the central line of the thoracic aorta (6), while both the second end (18') of the central line (6'') of the left common carotid artery and the second end (18'') of the central line (6'') of the left subclavian artery can be calculated using the same procedures as described for the second end (18) of the central line (6'') of the brachiocephalic trunk.

With reference to figures 3a, 3b, 4a and 4b, a third embodiment of a system (100) according to the present invention comprises an arithmetical device configured to execute:

- processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest;
- segmenting the images (2) into volumes of interest (5), at least one of said volumes representing the pulmonary valve and the pulmonary artery;
- processing of reconstructing a first central line (106) and a second central line (106'); and
- processing of identifying a base section (11) and a proximal section (12), the base section (11) being a section of the pulmonary valve and the proximal section (7') being a section with a distance from the base section (11) of less than or equal to 40 mm;
- calculating a first vector (10') intersecting the base section (11) and being tangent to a first central line (106);
- calculating a second vector (12') intersecting the proximal section (7') and being tangent to the first central line (106); and
- calculating a proximal angle (α') the proximal angle (α') being between the first vector (10') and the second vector (12').

The processing of identifying the base section (11) comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the pulmonary valve and each of said insertion lines having a nadir;

- registering an atlas on the images (2), so as to obtain registered images on which each nadir is represented;
- processing of identifying the base section (11) as a section of the volume of interest (5) lying in a plane passing through all the nadirs represented in the recorded images.

The processing of identifying the proximal section (7'), comprises:

- processing of importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the pulmonary valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on which each commissure is represented;
- processing of identifying the proximal section (7') as a section of the volume of interest (5) lying on a plane passing through all the commissures represented in the recorded images.

With reference to Figures 6a and 6b, the processing of reconstructing the first central line (106) comprises:

- processing of identifying a first end (21) and a second end (22) of the volume of interest (5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (5) and such that there is no other sphere inscribed in the volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, and obtaining a plurality of centers; and
- calculating the first central line (106) as a line (106) passing through the first end (21) and the second end (22) on which said centers lie.

Similarly, processing of reconstructing the second central line (106') comprises:

- processing of identifying a first end (21) and a third end (23) of the volume of interest (5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (5) and such that there is no other sphere inscribed in the volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, resulting in a plurality of centers; and
- calculating the second central line (106') as a line (106) passing through the first end (21) and the third end (23) on which said centers lie.

The processing of identifying the three ends (21, 22, 23) comprises:

- processing of importing a reference image, three reference ends of the volume of interest being represented in the reference images (5);
- registering the reference images on the images (2) so as to obtain recorded images on which each of the three reference ends is represented; and
- processing of identifying the first (21), the second (22) and the third end (23) as the three reference ends represented on the recorded images.

The arithmetic device of the third embodiment (100) of the system of the present invention is further configured to execute:

- calculating a point of intersection (17) between the first central line (106) and the second central line (106'), as a point common to the first (106) and the second central line (106') and having a maximum distance from the first end (21), the first central line (106) being a central line (106', 106') passing through the first (21) and the second end (22) and the second central line (106') being a central line (106') passing through the first (21) and the third end (23);
- processing of subdividing the first central line (106) into a first segment between the first end (21) and the point of intersection (17), said first

segment being common to the second central line (106') and a second segment between the point of intersection (17) and the second end (22);

- processing of subdividing the second central line (106') into a third segment coinciding with the first segment and a fourth segment between the point of intersection (17) and the third end (23);
- calculating a third vector (44), the third vector (44) being a vector approximating in the least-squares sense a segment of the first segment, said segment of the first segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;
- calculating a fourth vector (44'), the fourth vector (44') being a vector approximating in the least-squares sense a segment of the second segment, said segment of the second segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;
- calculating a fifth vector (44''), the fifth vector (44'') being a vector approximating in the least-squares sense a tract of the fourth segment, said tract of the fourth segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;
- calculating a first angle (η), the first angle (η) being between the fourth vector (44') and the fifth vector (44'');
- calculating a second angle (θ_{sx}), the second angle (θ_{sx}) being between the third vector (44) and the fourth vector (44'); and
- calculating a third angle (θ_{dx}), the third angle (θ_{dx}) being between the third vector (44) and the fifth vector (44').

With reference to Figures 1a, 1b, 2a, 2b, 3a, 3b, 4a and 4b, a fourth embodiment of a system (100) according to the present invention comprises an arithmetic device configured to execute:

- processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest;
- segmenting the images (2) into a first volume of interest (4), representing

the aortic valve, a tract of the thoracic aorta extending from the aortic valve, as well as the three branches of the aortic arch: brachiocephalic trunk, left common carotid artery and left subclavian artery, and into a second volume of interest (5) representing the pulmonary valve and a tract of the pulmonary artery extending from the pulmonary valve;

- processing of reconstructing a first central line (6) and at least a second central line (6', 6'') for the first volume of interest (4) and a first central line (106) and a second central line (106') for the second volume of interest (5);
- processing of identifying a first base section (8), a second base section (11), a first proximal section (7) and a second proximal section (7'), the first base section (8) being a tract of the aortic valve i.e. the valve of the first volume of interest (4) the first proximal section (7) being a section having a distance from the first base section (8, 11) of less than or equal to 40 mm, the second base section (11) being a tract of the pulmonary valve i.e. the valve of the second volume of interest (5) and the second proximal section (7') being a section having a distance from the first base section (11) of less than or equal to 40 mm;
- processing of identifying at least one distal section (13) of the first volume of interest (4);
- processing of identifying an intermediate section (15) of the first volume of interest (4), the intermediate section (15) being located between the first proximal section (7) and the at least one distal section (13);
- calculating a first vector (10) intersecting the first base section (8) and being tangent to the first central line (6) of the first volume of interest (4);
- calculating a second vector (12) intersecting the first proximal section (7) and being tangent to the first central line (6) of the first volume of interest (4);
- calculating a third vector (14) intersecting the at least one distal section

(13) being tangent to the second central line (6', 6'') of the first volume of interest (4);

- calculating a fourth vector (16) intersecting the at least one intermediate section (15) and tangent to the first central line (6) of the volume of interest (4);
- calculating a fifth vector (10') intersecting the second base section (11) and being tangent to the first central line (106) of the second volume of interest;
- calculating a sixth vector (12') intersecting the second proximal section (7') and being tangent to the first central line (106) of the second volume of interest (5);
- calculating a first proximal angle (α), the first proximal angle (α) being between the first vector (10) and the second vector (12);
- calculating a second proximal angle (α'), the proximal angle (α') being between the fifth vector (10') and the sixth vector (12');
- calculating a first distal angle (γ), the first distal angle (γ) being between the first vector (10) and the third vector (14);
- calculating a second distal angle (δ), the second distal angle (δ) being between the second vector (12) and the third vector (14);
- calculating a third distal angle (ε), the third distal angle (ε) being between the third vector (14) and the fourth vector (16); and
- calculating an intermediate angle (β), the intermediate angle being between the first vector (10) and the fourth vector (16).

With reference to Figures 5a and 5b, 6a and 6b, processing of reconstructing the first central line (6) of the first volume of interest (4), as well as the first (106) and second central line (106) of the first volume of interest (5) comprises:

- processing of identifying a first (19) and a second (20) end of the first volume of interest (4), a first (21), a second (22) and a third (23) end of the second volume of interest (5);

- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the first volume of interest (4), in the second volume of interest (5) and such that there is no other sphere inscribed in the first volume of interest (4), or in the second volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, thus obtaining a plurality of centers; and
- calculating the first central line (6) of the first volume of interest as a line (6) passing through the first end (19) and the second end (20) of the first volume of interest (4), and on which lie said centers;
- calculating the first central line (106) of the second volume of interest (5) as a line (106) passing through the first end (21) and the second end (22) of the second volume of interest (5), and on which lie said centers; and
- calculating the second central line (106') of the second volume of interest (5) as a line (106') passing through the first end (21) and the third end (23) of the second volume of interest (5), and on which lie said centers.

The processing of reconstructing the second central line (6') of the first volume of interest (4) also comprises:

- processing of identifying a first end (19) and a second end (18) of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the first volume of interest (4) and such that there is no other sphere inscribed in the first volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, thus obtaining a plurality of centers; and
- calculating the second central line (6') as a line (6') passing through the

first (19) and second end (18) and on which lie said centers.

The processing of identifying the two ends (19, 20) of the first central line (6) of the first volume of interest (4) comprises:

- an elaboration of a discretization of the surface of the first volume of interest (4), with a triangular grid;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- processing of identifying the first (19) and second (20) end of the first volume of interest (4) as points of the first volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values, respectively.

The first end (19) of the second central line (6') of the first volume of interest (4) coincides with the first end (19) of the first central line (6) of the first volume of interest (4).

The processing of identifying the second end (18) of the second central line (6') of the first volume of interest (4) comprises:

- calculating the Heat Kernel Signature descriptor for each point on the triangulated surface, said calculating consisting of solving a heat equation using the Laplace Beltrami operator;
- a recursive selection of points having a 'Heat Kernel Signature' greater than a threshold, this threshold being incremented with each recursion, and the recursive selection terminating when the number of connected regions of points having a 'Heat Kernel Signature' greater than the threshold is three;
- calculating a maximum value of the Heat Kernel Signature descriptor for at least one of the connected regions identified by the recursive selection, resulting in up to three maximum values; and
- processing of identifying the second end (18) of the second central line

(6') of the first volume of interest (4), as the point of at least one of the identified connected regions at which the Heat Kernel Signature descriptor takes on its maximum value.

The processing of identifying the three ends (21, 22, 23) of the first central line (106) of the second volume of interest (5) and the second central line (106') of the second volume of interest (5) comprises:

- processing of importing a reference image, three reference ends of the second volume of interest being represented in the reference images (5);
- registering the reference images on the images (2) so as to obtain recorded images on which each of the three reference ends is represented; and
- processing of identifying the first (21), second (22) and third (23) ends of the second volume of interest (5) as the three reference ends represented on the recorded images.

The processing of identifying at least one distal section (13) of the first volume of interest (4) comprises:

- calculating a point of intersection (17') between the first central line (6) and the second central line (6') of the first volume of interest (4); and
- processing of identifying the at least one distal section (13) as a section perpendicular to the first central line (6) and second central line (6') of the first volume of interest (4), and passing through the point of intersection (17') between the first central line (6) and a second central line (6') of the first volume of interest (4).

The processing of identifying the middle section (15) of the first volume of interest (5) comprises:

- calculating a point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) as a point common to the first (106) and second central line (106') and having a maximum distance from the first end (21) of the first central line

(106), or of the second central line (106'), of the second volume of interest (5); and

- processing of identifying the intermediate section (15) of the first volume of interest (4) as a section perpendicular to the first central line (106) of the second volume of interest (5) and passing through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5).

Finally, the arithmetic device of the fourth embodiment of the system (100) of the present invention is further configured to execute:

- processing of subdividing the first central line (106) of the second volume of interest (5) into a first segment between the first end (21) of the first central line (106) of the second volume of interest (5) and the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) said first segment being common to the second central line (106') of the second volume of interest (5) and a second segment between the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) and the second end (22) of the first central line (106) of the second volume of interest (5);
- processing of subdividing the second central line (106') of the second volume of interest (5) into a third segment coinciding with the first segment and a fourth segment between the point of intersection (17) between the first central line (106') and the second central line (106') of the second volume of interest (5) and the third end (23) of the second central line (106') of the second volume of interest (5);
- calculating a seventh vector (44), the seventh vector (44) being a vector approximating in the sense of least squares a tract of the first segment, said tract of the first segment being passing through the point of intersection (17) between the first central line (106) and the second central

line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;

- calculating an eighth vector (44'), the eighth vector (44') being a vector approximating in the sense of least squares a tract of the second segment, said tract of the second segment being passing through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;
- calculating a ninth vector (44''), the ninth vector (44'') being a vector approximating in the least-squares sense a tract of the fourth segment, said tract of the fourth segment being passing through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;
- calculating a first angle (η), the first angle (η) being between the eighth vector (44') and the ninth vector (44'');
- calculating a second angle (θ_{sx}), the second angle (θ_{sx}) being between the seventh vector (44) and the eighth vector (44'); and
- calculating a third angle (θ_{dx}), the third angle (θ_{dx}) being between the seventh vector (44) and the ninth vector (44'').

A fifth embodiment of a system according to the present invention comprises an arithmetic device configured to execute all of the operations listed in the description relating to any of the preceding embodiments and, in addition thereto, an analysis over time for morphological or dimensional assessment of a vessel section or region for one or more phases of the cardiac cycle.

More specifically, the arithmetic device of the fifth embodiment of the system of the present invention is configured for importing input data representative of whether a single transverse plane or a larger region of the vessel represented by the volume of interest (4, 5) in question is to be analysed along its central line. These input data are set by the user.

In the event that the user chooses to perform the analysis of a single transverse plane, the arithmetic device is configured to process an automatic definition of said plane, at the point on the vessel centerline represented by the volume of interest (4, 5). The arithmetic device is then configured to process the following operations:

- calculating the planar profile of the vessel lumen, at the initial instant of analysis (stage 0), as the intersection of the plane with the surface grid of the vessel;
- definition of two longitudinal planes, perpendicular to the plane of interest and mutually perpendicular to each other by means of a consistent orthogonal curvilinear reference system; and
- Quantification of the longitudinal displacement of the transverse plane along the vessel centerline of the volume of interest between the initial instant (phase 0) and the subsequent instant (phase 1), using an algorithm based on the optical flow (OF) method.

At the end of these operations, the arithmetic device updates the position of the transverse plane and the image data is automatically interpolated within the volume of interest. The displacement range of the lumen profile points is then calculated using an OF algorithm and the planar coordinates of these points are updated from the previous instant. The operation is then repeated for all available phases and at the end of the operations the device arithmetically outputs the time-dependent curves of area, perimeter, equivalent diameters and eccentricity of the vessel section for the entire duration of the multiphase sequence.

In the case of dynamic analysis of a larger region of the vessel, on the other hand, the arithmetic device is configured to receive as input data user-defined limits of the region to be considered, such as a start position and an end position defined on the central line.

The arithmetic device is then configured to process the following operations:

- definition of an ennuple N of equally spaced points, with odd N (3, 5, 7, etc.) and a spacing of 1÷2 mm, along the central line of interest;

- carrying out the operations described above in relation to the analysis of the individual transverse plane for each individual transverse plane identified along the central line.

At each stage, the new spatial coordinates of the N points are updated on the image plane by means of OF algorithms and the new perimeter of the lumen section is finally regularised. For each stage, both the position and orientation of each point profile are referred to a single curvilinear reference system, orthogonal to the vessel centerline. The resulting configuration of nodes is used to generate a numerical grid of 9-node biquadratic quadrangular elements; the corresponding displacement field in the image volume is extracted for each grid point. Subsequently, the displacement field U(t) is interpolated for all nodes in the region of interest using shape functions for 9-node elements from the displacement field calculated for the nodes in the numerical grid. This results in a time-dependent displacement map for the entire region of interest defined on the vessel surface, which is provided to the user by the arithmetic device.

A sixth embodiment of a system according to the present invention concerns a system comprising:

- a client device (101) including an arithmetic device configured to execute:
  - processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest;
  - processing of a dispatch (201) of images (2) to a server device; and
- a server device (102) comprising an arithmetic device configured to execute:
  - all the processing, segmenting and calculating operations performed by the arithmetic device described in connection with the first to fifth embodiments of the system of the present invention; and
  - processing of sending (202) of the values of the proximal angle

(α), or of the first vector (10) or of the second vector (11) to the client device (101), said client device (101) being further configured for displaying and/or storing said values.

With reference to Figures 1a, 1b, 2a and 2b, a first embodiment of a method for the morpho-functional assessment of the thoracic vascular district, according to the present invention, concerns a method comprising the steps of:

- acquiring volumetric radiological images (2) of the thoracic vascular district at a time instant of interest;
- segmenting, by means of a processor, the images (2) into volumes of interest (4), at least one of said volumes (4) representing the aortic valve and thoracic aorta;
- reconstructing, by means of a processor, a central line (6) of the thoracic aorta represented by the volume of interest (4); and
- identifying, by means of a processor, a base section (8) and a proximal section (7), the base section (8) being a section of the aortic valve and the proximal section (7) being a section with a distance from the base section (8) of less than or equal to 40 mm;
- calculatint, by means of a processor, a first vector (10) intersecting the base section (8) and tangent to the central line (6);
- calculating, by means of a processor, the second vector (12) intersecting the proximal section (7) and tangent to the central line (6); and
- calculating, by means of a processor, a proximal angle (α), the proximal angle (α) being between the first vector (10) and the second vector (12).

The step of identifying the base section (8) comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a nadir;
- registering the atlas on the images (2), so as to obtain recorded images on which each nadir is represented;

- identifying the base section (8) as the section of the volume of interest (4) lying on a plane passing through all the nadirs represented in the recorded images.

The step of identifying the proximal section (7) comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on which each commissure is represented;
- identifying the proximal section (7) as the section of the volume of interest (4) lying in a plane passing through all the commissures shown in the recorded images.

The step of reconstructing the central line (6) comprises:

- identifying two ends (19, 20) of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of the said plurality of maximum spheres, obtaining a plurality of centers; and
- calculating the central line (6) as a line (6) passing through the two ends (19, 20) and on which lie said centers.

With reference to Figures 5a and 5b, the step of identifying the two ends (19, 20) comprises:

- discretizing the surface of at least one volume of interest representing the thoracic aorta (4), with a triangular grid;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and

- identifying a first (19) and a second (20) end as points of the volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values, respectively.

With reference to Figures 1a, 1b, 2a and 2b, a second embodiment of the method according to the present invention comprises the steps of:

- acquiring volumetric radiological images (2) of the thoracic vascular district at a time instant of interest;
- segmenting, by means of a processor, the images (2) into volumes of interest (4), at least one of said volumes representing the aortic valve, the thoracic aorta and its first three branches: brachiocephalic trunk, left common carotid artery and left subclavian artery;
- reconstructing, using a processor, a first central line (6) and a second central line (6', 6''); and
- identifying, by means of a processor, a base section (8) and a proximal section (7), the base section (8) being a section of the aortic valve and the proximal section (7) being a section with a distance from the base section (8) of less than or equal to 40 mm;
- identifying, by means of a processor, a distal section (13) of the volume of interest (4);
- calculating, by means of a processor, a first vector (10) intersecting the base section (8) and tangent to the first central line (6) of the volume of interest (4), i.e. the central line (69) of the thoracic aorta;
- calculating, by means of a processor, a second vector (12) intersecting the proximal section (7) and being tangent to the first central line (6) of the thoracic aorta;
- calculating, by means of a processor, a third vector (14) intersecting the at least one distal section (13) being tangent to the second central line (6') of the volume of interest (4), i.e. the central line (6') of the brachiocephalic trunk;

- calculating, by means of a processor, a proximal angle (α), the proximal angle (α) being between the first vector (10) and the second vector (12);
- calculating, by means of a processor, a first distal angle (γ), the first distal angle (γ) being between the first vector (10) and the third vector (14); and
- calculating, by means of a processor, a second distal angle (δ), the second distal angle (δ) being between the second vector (12) and the third vector (14).

The step of identifying the base section (8) comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a nadir;
- registering the atlas on the images (2), so as to obtain recorded images on which each nadir is represented;
- identifying the base section (8) as the section of the volume of interest (4) lying on a plane passing through all the nadirs represented in the recorded images.

The step of identifying the proximal section (7), comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the aortic valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on which each commissure is represented;
- identifying the proximal section (7) as the section of the volume of interest (4) lying in a plane passing through all the commissures shown in the recorded images.

With reference to Figures 5a and 5b, the step of reconstructing the first central line (6) of the thoracic aorta comprises:

- identifying a first end (19) and a second end (20) of the volume of interest (4);

- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating a center of each sphere of said plurality of maximum spheres, obtaining a plurality of centers; and
- calculating the first central line (6) as a line (6) passing through the first end (19) and the second end (20) and on which lie said centers.

The step of identifying the two ends (19, 20) of the first central line (6) comprises:

- discretizing the surface of at least one volume of interest (4) with a triangular grid, thus obtaining a triangulated surface;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- identifying a first (19) and a second (20) end as points of the volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values, respectively.

The step of reconstructing the second central line (6') of the brachiocephalic trunk also comprises:

- identifying a first end (19) and a second end (18, 18' 18") of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4) and such that there is no other sphere inscribed in the volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, obtaining a plurality of centers; and
- calculating the second central line (6') as a line (6') passing through the first (19) and second end (18) and on which lie said centers.

The first end (19) of the second central line (6') coincides with the first end (19) of the first central line (6).

The step of identifying the second end (18) of the second central line (6') comprises:

- calculating the Heat Kernel Signature descriptor for each point on the triangulated surface, this calculation consisting of solving a heat equation using the Laplace Beltrami operator;
- recursive selecting points having a 'Heat Kernel Signature' greater than a threshold, this threshold being incremented with each recursion, and recursively selecting terminating when the number of connected regions of points having a 'Heat Kernel Signature' greater than the threshold is three;
- calculating a maximum value of the Heat Kernel Signature descriptor for at least one of the connected regions identified by recursively selecting, thus obtaining up to three maximum values; and
- identifying the second end (18) as the point in at least one of the identified connected regions at which the Heat Kernel Signature descriptor takes on its maximum value.

The step of identifying a distal section (13) of the at least one volume of interest (4) comprises:

- calculating a point of intersection (17') between the first central line (6) and a second central line (6'); and
- identifying the at least one distal section (13) as a section perpendicular to the first central line (6) and the second central line (6'), and passing through the point of intersection.

With reference to Figures 3a, 3b, 4a and 4b, a third embodiment of a method according to the present invention comprises the steps of:

- acquiring volumetric radiological images (2) of the vascular district at a time instant of interest;
- segmenting, by means of a processor, the images (2) into volumes of

interest (5), at least one of said volumes representing the pulmonary valve and the pulmonary artery;

- reconstructing, by means of a processor, a first central line (106) and a second central line (106'); and
- identifying, by means of a processor, a base section (11) and a proximal section (12), the base section (11) being a section of the pulmonary valve and the proximal section (7') being a section with a distance from the base section (11) of less than or equal to 40 mm;
- calculating, by means of a processor, a first vector (10') intersecting the base section (11) and tangent to a first central line (106);
- calculating, by means of a processor, a second vector (12') intersecting the proximal section (7') and being tangent to the first central line (106); and
- calculating, by means of a processor, a proximal angle (α') the proximal angle (α') being between the first vector (10') and the second vector (12').

The step of identifying the base section (11) comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the pulmonary valve and each of said insertion lines having a nadir;
- registering the atlas on the images (2), so as to obtain recorded images on which each nadir is represented;
- identifying the base section (11) as the section of the volume of interest (5) lying on a plane passing through all the nadirs represented in the recorded images.

The step of identifying the proximal section (7') comprises:

- importing an atlas depicting three insertion lines, each of said lines being a line of intersection of one of the three valve leaflets of the pulmonary valve and each of said insertion lines having a commissure;
- registering the atlas on the images (2), so as to obtain recorded images on

which each commissure is represented;

- identifying the proximal section (7') as the section of the volume of interest (5) lying on a plane passing through all the commissures represented in the recorded images.

With reference to Figures 6a and 6b, the step of reconstructing the first central line (106) comprises:

- identifying a first end (21) and a second end (22) of the volume of interest (5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (5) and such that there is no other sphere inscribed in the volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, and obtaining a plurality of centers; and
- calculating the first central line (106) as a line (106) passing through the first end (21) and the second end (22) on which said centers lie.

Similarly, the step of reconstructing the second central line (106') comprises:

- identifying a first end (21) and a third end (23) of the volume of interest (5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (5) and such that there is no other sphere inscribed in the volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of the said plurality of maximum spheres, obtaining a plurality of centers; and
- calculating the second central line (106') as a line (106) passing through the first end (21) and the third end (23) on which said centers lie.

The step of identifying the three ends (21, 22, 23) comprises:

- importing reference images, three reference ends of the volume of interest being represented in the reference images (5);

- registering reference images on images (2) so as to obtain recorded images on which each of the three reference ends is represented; and
- identifying the first (21), second (22) and third end (23) as the three reference ends represented on the recorded images.

The third embodiment of the method of the present invention further comprises the steps of:

- calculating, by means of a processor, a point of intersection (17) between the first central line (106) and the second central line (106'), as a point common to the first (106) and the second central line (106') and having a maximum distance from the first end (21), the first central line (106) being a central line (106', 106') passing through the first (21) and second end (22) and the second central line (106') being a central line (106') passing through the first (21) and third end (23);
- subdividing, by means of a processor, the first central line (106) into a first segment between the first end (21) and the point of intersection (17), said first segment being common to the second central line (106') and a second segment between the point of intersection (17) and the second end (22);
- subdividing, by means of a processor, the second central line (106') into a third segment coinciding with the first segment and a fourth segment between the point of intersection (17) and the third end (23);
- calculating, by means of a processor, a third vector (44), the third vector (44) being a vector approximating in the sense of least squares a tract of the first segment, said tract of the first segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;
- calculating, by means of a processor, a fourth vector (44'), the fourth vector (44') being a vector approximating in the least-squares sense a tract of the second segment, said tract of the second segment being through

the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;

- calculating, by means of a processor, a fifth vector (44''), the fifth vector (44'') being a vector approximating in the least-squares sense a tract of the fourth segment, said tract of the fourth segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm;
- calculating, by means of a processor, a first angle (η), the first angle (η) being between the fourth vector (44') and the fifth vector (44'');
- calculating, by means of a processor, a second angle (θ_{sx}), the second angle (θ_{sx}) being between the third vector (44) and the fourth vector (44'); and
- calculating, by means of a processor, a third angle (θ_{dx}), the third angle (θ_{dx}) being between the third vector (44) and the fifth vector (44').

With reference to figures 1a, 1b, 2a, 2b, 3a, 3b, 4a and 4b, a fourth embodiment of the method according to the present invention comprises the steps of

- acquiring volumetric radiological images (2) of the vascular district at a time instant of interest;
- segmenting, by means of a processor, the images (2) into a first volume of interest (4) representing the aortic valve, a tract of the thoracic aorta extending from the aortic valve, and the three branches of the aortic arch: brachiocephalic trunk, left common carotid artery and left subclavian artery, and into a second volume of interest (5) representing the pulmonary valve and a tract of the pulmonary artery extending from the pulmonary valve;
- reconstructing, by means of a processor, a first central line (6) and at least a second central line (6', 6'') for the first volume of interest (4) and a first central line (106) and a second central line (106') for the second volume of interest (5);
- identifying, by means of a processor, a first base section (8), a second base

section (11), a first proximal section (7) and a second proximal section (7'), the first base section (8) being a section of the aortic valve i.e. the valve of the first volume of interest (4), the first proximal section (7) being a section having a distance from the first base section (8 11) of less than or equal to 40 mm, the second base section (11) being a section of the pulmonary valve i.e. the valve of the second volume of interest (5) and the second proximal section (7') being a section having a distance from the first base section (11) of less than or equal to 40 mm;

- identifying, by means of a processor, at least one distal section (13) of the first volume of interest (4);
- identifying, by means of a processor, an intermediate section (15) of the first volume of interest (4), the intermediate section (15) being located between the first proximal section (7) and the at least one distal section (13);
- calculating, by means of a processor, a first vector (10) intersecting the first base section (8) and tangent to the first central line (6) of the first volume of interest (4);
- calculating, by means of a processor, a second vector (12) intersecting the first proximal section (7) and tangent to the first central line (6) of the first volume of interest (4);
- calculating, by means of a processor, a third vector (14) intersecting the at least one distal section (13) being tangent to the second central line (6', 6'') of the first volume of interest (4);
- calculating, by means of a processor, a fourth vector (16) intersecting the at least one intermediate section (15) and tangent to the first central line (6) of the volume of interest (4);
- calculating, by means of a processor, a fifth vector (10') intersecting the second base section (11) and tangent to the first central line (106) of the second volume of interest;

- calculating, by means of a processor, a sixth vector (12') intersecting the second proximal section (7') and tangent to the first central line (106) of the second volume of interest (5);
- calculating, by means of a processor, a first proximal angle (α), the first proximal angle (α) being between the first vector (10) and the second vector (12);
- calculating, by means of a processor, a second proximal angle (α'), the proximal angle (α') being between the fifth vector (10') and the sixth vector (12');
- calculating, by means of a processor, a first distal angle (γ), the first distal angle (γ) being between the first vector (10) and the third vector (14);
- calculating, by means of a processor, a second distal angle (δ), the second distal angle (δ) being between the second vector (12) and the third vector (14);
- calculating, by means of a processor, a third distal angle (ε), the third distal angle (ε) being between the third vector (14) and the fourth vector (16); and
- calculating, by means of a processor, an intermediate angle (β), the intermediate angle being between the first vector (10) and the fourth vector (16).

With reference to Figures 5a and 5b, 6a and 6b, the step of reconstructing the first central line (6) of the first volume of interest (4), as well as the first (106) and second central line (106) of the first volume of interest (5) comprises:

- identifying a first (19) and a second (20) end of the first volume of interest (4), a first (21), a second (22) and a third (23) end of the second volume of interest (5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the first volume of interest (4), or in the second volume of interest (5) and such that there is no other sphere inscribed in

the first volume of interest (4), or in the second volume of interest (5) and having the same center as said maximal sphere, which contains said maximal sphere;

- calculating the center of each sphere of said plurality of maximum spheres, thus obtaining a plurality of centers; and
- calculating the first central line (6) of the first volume of interest as a line (6) passing through the first end (19) and the second end (20) of the first volume of interest (4), and on which lie said centers;
- calculating the first central line (106) of the second volume of interest (5) as a line (106) passing through the first end (21) and the second end (22) of the second volume of interest (5), and on which lie said centers; and
- calculating the second central line (106') of the second volume of interest (5) as a line (106') passing through the first end (21) and the third end (23) of the second volume of interest (5), and on which lie said centers.

The step of reconstructing the second central line (6') of the first volume of interest (4) also comprises:

- identifying a first end (19) and a second end (18) of the volume of interest (4);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the first volume of interest (4) and such that there is no other sphere inscribed in the first volume of interest (4) and having the same center as said maximal sphere, which contains said maximal sphere;
- calculating the center of each sphere of said plurality of maximum spheres, thus obtaining a plurality of centers; and
- calculating the second central line (6') as a line (6') passing through the first (19) and second end (18) and on which lie said centers.

The step of identifying the two ends (19, 20) of the first central line (6) of the first volume of interest (4) comprises:

- discretising the surface of the first volume of interest (4) with a triangular grid;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- identifying the first (19) and second (20) end of the first volume of interest (4) as points of the first volume of interest (4) at which the eigenvector of the Laplace Beltrami operator takes on said maximum and minimum values, respectively.

The first end (19) of the second central line (6') of the first volume of interest (4) coincides with the first end (19) of the first central line (6) of the first volume of interest (4).

The step of identifying the second end (18) of the second central line (6') of the first volume of interest (4) comprises:

- calculating the Heat Kernel Signature descriptor for each point on the triangulated surface, this calculation consisting of solving a heat equation using the Laplace Beltrami operator;
- recursively selecting points having a 'Heat Kernel Signature' greater than a threshold, this threshold being incremented with each recursion, and recursively selecting terminating when the number of connected regions of points having a 'Heat Kernel Signature' greater than the threshold is three;
- calculating a maximum value of the Heat Kernel Signature descriptor for at least one of the connected regions identified by recursively selecting, thus obtaining up to three maximum values; and
- identifying the second end (18) of the second central line (6') of the first volume of interest (4) as the point on at least one of the identified connected regions at which the Heat Kernel Signature descriptor takes on its maximum value.

The step of identifying the three ends (21, 22, 23) of the first central line (106) of the second volume of interest (5) and the second central line (106') of the second volume of interest (5) comprises:

- importing reference images, three reference ends of the second volume of interest being represented in the reference images (5);
- registering reference images on images (2) so as to obtain recorded images on which each of the three reference ends is represented; and
- identifying the first (21), second (22) and third ends (23) of the second volume of interest (5) as the three reference ends represented on the recorded images.

The step of identifying the at least one distal section (13) of the first volume of interest (4) comprises:

- calculating a point of intersection (17') between the first central line (6) and the second central line (6') of the first volume of interest (4); and
- identifying the at least one distal section (13) as a section perpendicular to the first central line (6) and the second central line (6') of the first volume of interest (4), and passing through the point of intersection (17') between the first central line (6) and a second central line (6') of the first volume of interest (4).

The step of identifying the intermediate section (15) of the first volume of interest (5) comprises:

- calculating a point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) as a point common to the first (106) and second central line (106') and having a maximum distance from the first end (21) of the first central line (106), or of the second central line (106'), of the second volume of interest (5); and
- identifying the intermediate section (15) of the first volume of interest (4) as a section perpendicular to the first central line (106) of the second

volume of interest (5) and passing through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5).

Finally, the method of the present invention further comprises the steps of:

- subdividing, by means of a processor, the first central line (106) of the second volume of interest (5) into a first segment comprised between the first end (21) of the first central line (106) of the second volume of interest (5) and the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), said first segment being common to the second central line (106') of the second volume of interest (5), and in a second segment comprised between the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) and the second end (22) of the first central line (106) of the second volume of interest (5);
- subdividing, by means of a processor, the second central line (106') of the second volume of interest (5) into a third segment coinciding with the first segment and a fourth segment between the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5) and the third end (23) of the second central line (106') of the second volume of interest (5);
- calculating, by means of a processor, a seventh vector (44), the seventh vector (44) being a vector approximating in the sense of least squares a tract of the first segment, said tract of the first segment being passed through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;
- calculating, by means of a processor, an eighth vector (44'), the eighth vector (44') being a vector approximating in the least-squares sense a tract

of the second segment, said tract of the second segment being passed through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;

- calculating, by means of a processor, a ninth vector (44''), the ninth vector (44'') being a vector approximating in the sense of least squares a line of the fourth segment, said line of the fourth segment being passed through the point of intersection (17) between the first central line (106) and the second central line (106') of the second volume of interest (5), and having a length between 0.5 cm and 1.5 cm;
- calculating, by means of a processor, a first angle (η), the first angle (η) being between the eighth vector (44') and the ninth vector (44'');
- calculating, using a processor, a second angle (θ_{sx}), the second angle (θ_{sx}) being between the seventh vector (44) and the eighth vector (44'); and
- calculating, by means of a processor, a third angle (θ_{dx}), the third angle (θ_{dx}) being between the seventh vector (44) and the ninth vector (44'').

A fifth embodiment of a method according to the present invention comprises all the operations listed in the description relating to any of the preceding embodiments and, in addition to these, an analysis over time for morphological or dimensional assessment of a section or region of the vessel for one or more phases of the cardiac cycle.

More particularly, the sixth embodiment of the method of the present invention comprises the step of importing input data representative of whether one wishes to analyse a single transverse plane or a larger region of the vessel represented by the volume of interest (4, 5) in question, along its central line. Such input data is set by the user.

In the event that the user chooses to perform the analysis of a single transverse plane, the method comprises the step of automatically defining said plane, at the point of the central line of the vessel represented by the volume of interest (4, 5). The sixth embodiment of the method of the present invention, further comprising the steps of:

- calculating the planar profile of the vessel lumen, at the initial instant of analysis (stage 0), as the intersection of the plane with the vessel surface grid;
- defining two longitudinal planes, perpendicular to the plane of interest and mutually perpendicular to each other by means of a consistent orthogonal curvilinear reference system; and
- quantifying the longitudinal displacement of the transverse plane along the vessel centerline of the volume of interest between the initial instant (phase 0) and the subsequent instant (phase 1), using an algorithm based on the optical flow (OF) method.

At the end of these operations, the position of the transverse plane is updated and the image data automatically interpolated within the volume of interest. The displacement range of the lumen profile points is then calculated using an OF algorithm and the planar coordinates of these points are updated from the previous instant. The operation is then repeated for all available phases and at the end of the operations, the time-dependent curves of area, perimeter, equivalent diameters and eccentricity of the vessel section for the entire duration of the multiphase sequence are provided as output.

In the case of dynamic analysis of a larger region of the vessel, on the other hand, the method comprises the step of receiving, as input data, user-defined limits of the region to be considered, such as a start position and an end position defined on the central line.

The method then comprises the following steps:

- defining an ennuple N of equally spaced points, with odd N (3, 5, 7, etc.) and a spacing of 1÷2 mm, along the central line of interest; and
- carrying out, by means of a processor, the operations described above in relation to the analysis of the individual transverse plane for each individual transverse plane identified along the central line.

At each stage, the new spatial coordinates of the N points are updated on the image plane using OF algorithms and the new perimeter of the lumen section is finally regularized. For each stage, both the position and orientation of each point profile are referred to a single curvilinear reference system, orthogonal to the vessel centerline. The resulting configuration of nodes is used to generate a numerical grid of 9-node biquadratic quadrangular elements; the corresponding displacement field in the image volume is extracted for each grid point. Subsequently, the displacement field U(t) is interpolated for all nodes in the region of interest using shape functions for 9-node elements from the displacement field calculated for the nodes in the numerical grid. This results in a time-dependent displacement map for the entire region of interest defined on the vessel surface, which is provided to the user as output.

CLAIMS

1. A system (100) for morpho-functional assessment of the thoracic vascular district, said system (100) comprising an arithmetic device configured to execute:

- processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest;
- segmenting the images (2) into volumes of interest (4, 5), at least one of said volumes (4, 5) representing at least one semilunar heart valve and at least one section of a blood vessel extending from said valve;
- processing of a reconstructing at least a central line (6, 6′, 6′′, 106, 106′) for each vessel represented by the at least one volume of interest (4, 5); and

characterized by the fact that the arithmetic device is further configured to execute:

- processing of identifying a base section (8, 11) and a proximal section (7, 7′), the base section (8, 11) being a valve section of said at least one volume of interest (4, 5) and the proximal section (7, 7′) being a section having a distance from the base section (8, 11) less than or equal to 40 mm;
- calculating a first vector (10, 10′) intersecting the base section (8, 11) and being tangent to the at least central line (6, 106);
- calculating a second vector (12, 12′), the second vector (12, 12′) intersecting the proximal section (7, 7′) and being tangent to the at least one central line (6, 106); and
- calculating a proximal angle (α, α′), the proximal angle (α, α′) being between the first vector (10, 10′) and the second vector (12, 12′).

2. System (1) according to the preceding claim wherein the processing of identifying the base section (8, 11) and the proximal section (7, 7') comprising:

- processing of importing an atlas depicting three insertion lines, each of said lines being an intersection line of one of said three valve leaflets and each of said insertion lines having a nadir and a commmisura;

- registering an atlas on the images (2), so as to obtain registered images on which each nadir and each commissure is represented;
- processing of identifying the base section (8, 11) as a section of the volume of interest (4, 5) lying in a plane passing through all the nadirs represented in the recorded images; and
- processing of identifying the proximal section (7, 7') as a section of the volume of interest (4, 5) lying on a plane passing through all the commissures represented in the recorded images.

3. System (1) according to claim 1, wherein the processing of reconstructing the at least one central line (6, 6', 6'', 106, 106') comprises:

- processing of identifying the at least two ends (18, 18', 18'', 19, 20, 21, 22, 23) of each volume of interest (4, 5);
- calculating a plurality of maximal spheres, each maximal sphere being a sphere inscribed in the volume of interest (4, 5) and such that there is no other sphere inscribed in the volume of interest (4, 5) and having the same centre as said maximal sphere, which contains said maximal sphere;
- calculating the centre of each sphere of said plurality of maximum spheres, obtaining a plurality of centres; and
- calculating the at least one central line (6, 6', 6'', 106, 106') as a line (6) passing through said at least two ends (18, 18', 18'', 19, 20, 21, 22, 23) and on which said centres lie.

4. System (1) according to the preceding claim, wherein the processing of identifying at least two ends (21, 22, 23) comprises:

- processing of importing reference images, in the reference images being represented three reference ends of the volume of interest (5);

- registering the reference images on the images (2) so as to obtain registered images on which each of the three reference ends is represented; and
- processing of identifying a first (21), a second (22) and a third end (23) as the three reference ends represented on the recorded images.

5. System (1) according to the preceding claim, wherein the arithmetic device is further configured to execute:

- calculating an intersection point (17) between a first central line (106) and a second central line (106'), as a point common to the first (106) and the second central line (106') and having a maximum distance from the first end (21), the first central line (106) being a central line (106, 106', 106') passing through the first (21) and the second end (22) and the second central line (106') being a central line (106') passing through the first (21) and the third end (23);
- processing of subdividing the first central line (106) into a first segment between the first end (21) and the point of intersection (17), said first segment being common to the second central line (106') and a second segment between the point of intersection (17) and the second end (22)
- processing of subdividing the second central line (106') into a third segment coinciding with the first segment and a fourth segment comprised between the point of intersection (17) and the third end (23);
- calculating a third vector (44), the third vector (44) being a vector approximating in the least-squares sense a tract of the first segment, said tract of the first segment being passed through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm
- calculating a fourth vector (44'), the fourth vector (44') being a vector approximating in the least-squares direction a tract of the second

segment, said tract of the second segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm; and

- calculating a fifth vector (44''), the fifth vector (44'') being a vector approximating in the least-squares direction a segment of the fourth segment, said segment of the fourth segment being through the point of intersection (17) and having a length between 0.5 cm and 1.5 cm.

6. System (1) according to the preceding claim wherein the arithmetic device is further configured to execute:

- calculating a first angle (η), the first angle (η) being between the fourth vector (44') and the fifth vector (44'');
- calculating a second angle (θ_{sx}), the second angle (θ_{sx}) being between the third vector (44) and the fourth vector (44')
- calculating a third angle (θ_{dx}), the third angle (θ_{dx}) being between the third vector (44) and the fifth vector (44').

7. System (1) according to claim 3 wherein the processing of identifying at least two ends (19, 20) comprises:

- processing of discretizing the surface of the at least one volume of interest (4), with a triangular grid, thereby obtaining a triangulated surface;
- calculating the Laplace Beltrami operator of the triangulated surface;
- calculating the maximum and minimum of an eigenvector of the Laplace Beltrami operator; and
- processing of identifying a first (19) and a second (20) end as points of the volume of interest (4) at which the eigenvector of the Laplace Beltrami operator assumes said maximum and minimum values, respectively.

8. System (1) according to the preceding claim, wherein the processing of

identifying at least two ends (18, 18′, 18′′) further comprises:

- calculating the Heat Kernel Signature descriptor for each point of the triangulated surface, said calculation comprising solving a heat equation using the Laplace Beltrami operator;
- processing of recursive selecting points having a “Heat Kernel Signature” greater than a threshold, said threshold being incremented with each recursion, and the recursive selecting terminating when the number of connected regions of points having a “Heat Kernel Signature” greater than the threshold is three;
- calculating a maximum value of the Heat Kernel Signature descriptor for each of the connected regions identified by the recursive selecting, resulting in three maximum values; and
- processing of identifying a third (18), a fourth (18′) and a fifth (18′′) ends as points of the connected regions at which the ‘Heat Kernel Signature’ descriptor takes on said three maximum values.

9. System (1) according to claim 8, wherein the arithmetic device is further configured to execute:

- processing of identifying the at least one distal section (13) of the at least one volume of interest (4);
- calculating a third vector (14), the third vector (14) intersecting the at least one distal section (13) and being tangent to the at least one central line (6, 6, 6', 6") of the at least one volume of interest (4);
- calculating a first distal angle (γ), the first distal angle (γ) being between the first vector (10) and the third vector (14); and
- calculating a second distal angle (δ), the second distal angle (δ) being between the second vector (12) and the third vector (14).

10. System (1) according to claim 9, wherein the processing of identifying a

distal section (13) of the at least one volume of interest (4) comprises:

- calculating an intersection point (17′) between a first central line (6) and a second central line (6′), the first central line (6) being a central line (6) passing through the first (19) and the second end (20) and the second central line (6′) being a central line (6′) passing through the first (19) and the third end (18); and
- processing of identifying the at least one distal section (13) as a section perpendicular to the first central line (6) and the second central line (6′), and passing through the point of intersection (17′).

11. System (1) according to claim 10 wherein, the arithmetic device is further configured to execute:

- processing of identifying an intermediate section (15) of the at least one volume of interest (4), the intermediate section (15) being located between the proximal section (7) and the distal section (13);
- calculating a fourth vector (16), the fourth vector (16) intersecting the at least one intermediate section (15) and being tangent to the at least one central line (6) of the at least one volume of interest (4);
- calculating a third distal angle (ε), the third distal angle (ε) being between the third vector (14) and the fourth vector (16)
- calculating an intermediate angle (β), the intermediate angle being between the first vector (10) and the fourth vector (16).

12. System (1) according to claim 11, wherein the processing of identifying an intermediate section (15) of the at least one volume of interest (4, 5) comprises:

- segmenting (3) the images (2) into at least a first volume of interest (4), representing a section of thoracic aorta extending from the aortic valve, and a second volume of interest (5), representing a section of pulmonary artery extending from the pulmonary valve;

- classifying the first (4) and second (5) volume of interest into the classes: thoracic aorta and pulmonary artery, respectively;
- processing of importing reference images, in the reference images being represented three ends of the volume of interest (5) representing the pulmonary artery tract;
- registering the reference images on the images (2) so as to obtain registered images on which each of the three ends is represented; and
- processing of identifying a sixth (21), a seventh (22) and an eighth end (23) as the three ends represented on the recorded images;
- calculating a third central line (106) as a central line (6, 6', 6'', 106, 106') passing through the sixth (21) and the seventh end (22)
- calculating a fourth central line (106') as a central line (6, 6'', 6'', 106, 106') passing through the sixth (21) and eighth end (23);
- calculating a point of intersection (17) between the third central line (106) and the fourth central line (106') as a point common to the third (106) and fourth central lines (106') and having a maximum distance from the sixth end (21); and
- processing of identifying the intermediate section (15) of the first volume of interest (4) as a section perpendicular to the third central line (106) and passing through the point of intersection (17) between the third central line (106) and the fourth central line (106').

13. A system (100) for morpho-functional assessment of the thoracic vascular district, comprising:

- a client device (101) comprising an arithmetic device configured to execute:
  - processing of importing (1) volumetric radiological images (2) of the vascular district at a time instant of interest;
  - processing of sending (201) the images (2) to a server device; and

- a server device (102) comprising an arithmetic device configured to execute:
  - processing of recepting the images (2) sent by the server device;
  - segmenting the images (2) into volumes of interest (4, 5), at least one of said volumes representing at least one semilunar heart valve and at least one section of a blood vessel extending from said valve;
  - processing of reconstructing at least one central line (6, 6′, 6′′, 106, 106′) for each vessel represented by the at least one volume of interest (4, 5);
  - processing of identifying a base section (8, 11) and a proximal section (7, 7′), the base section (8, 11) being a section of the valve of said at least one volume of interest (4, 5) and the proximal section (7, 7′) being a section having a distance from the base section (8, 11) of less than or equal to 40 mm (8, 11)
  - calculating a first vector (10, 10′), the first vector (10, 10′) intersecting the valve section (8, 11) and being tangent to the at least central line (6, 106);
  - calculating a second vector (12, 12′), the second vector (12, 12′) intersecting the proximal section (7, 7′) and being tangent to the at least one central line (6, 106);
  - calculating a proximal angle (α, α′), the proximal angle (α, α′) being between the first vector (10, 10′) and the second vector (12, 12′); and
  - processing of sending (202) the values of the proximal angle (α, α′), either of the first vector (10, 10′) or of the second vector (12, 12′) to the client device (101), said client device (101) being further configured for displaying and/or storing said values.

14. Method for the morpho-functional assessment of the thoracic vascular

district, comprising:

- acquiring volumetric X-ray images (2) of the vascular district at a time instant of interest;
- segmenting, by means of a processor, the images (2) into volumes of interest (4, 5), at least one of said volumes representing at least one half-lunar cardiac valve and at least one section of a blood vessel extending from said valve; and
- reconstructing, by means of a processor, at least one central line (6, 6', 6'', 106, 106') for each vessel represented by the at least one volume of interest (4, 5);

characterized by further comprising, for each of the volumes of interest (4, 5):

- identifying, by means of a processor, a base section (8, 11) of the at least one volume of interest (4, 5), the base section (8, 11) being a valve section of said at least one volume of interest (4, 5);
- identifying, by means of a processor, a proximal section (7, 7') of the at least one volume of interest (4, 5), the proximal section (7, 7') being a section having a distance from the base section (8, 11) of less than or equal to 40 mm;
- calculating, by means of a processor, a first vector (10, 10') intersecting the valve section (8, 11) and being tangent to the at least central line (6, 106);
- calculating, by means of a processor, a second vector (12, 12') intersecting the proximal section (7, 7') and being tangent to the at least one central line (6, 106); and
- calculating, by means of a processor, a proximal angle (α, α'), the proximal angle (α, α') being between the first vector (10, 10') and the second vector (12, 12').

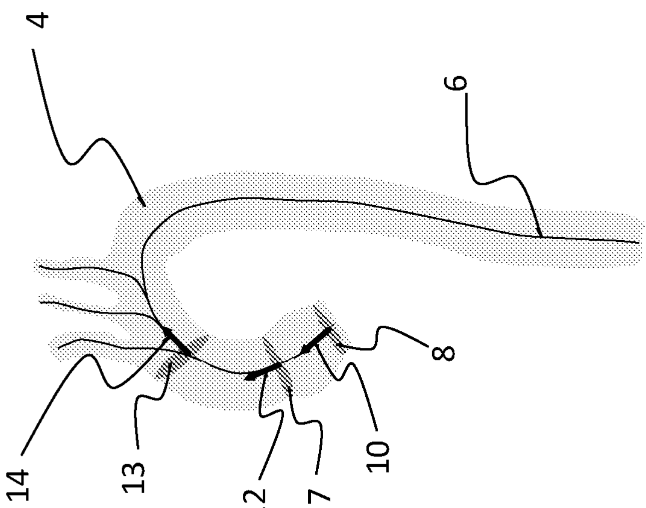

Fig.1a

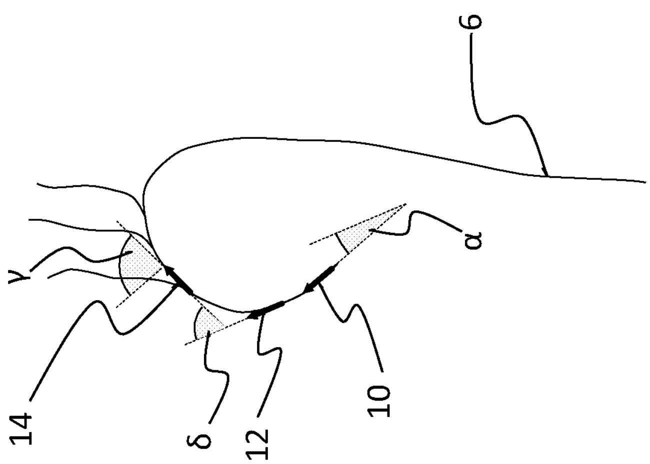

Fig.1b

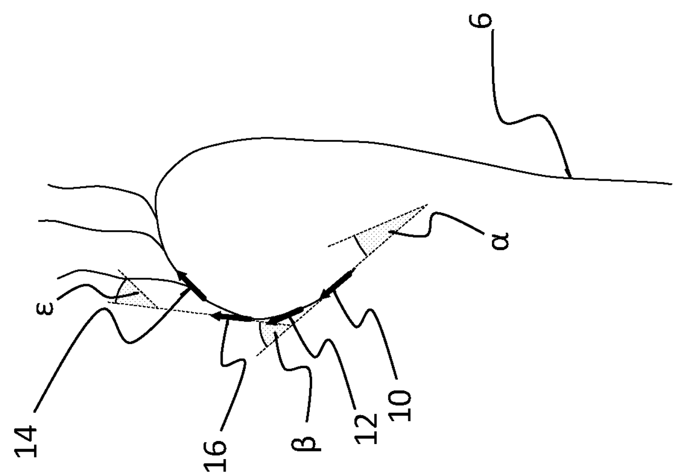

Fig.2b

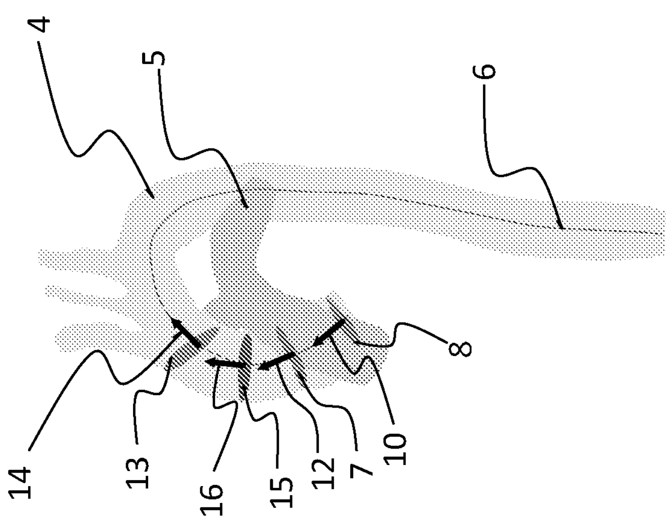

Fig.2a

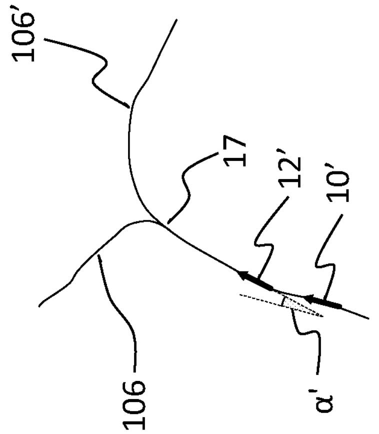

Fig.3b

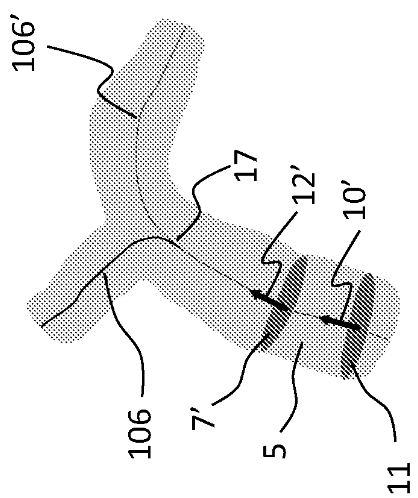

Fig.3a

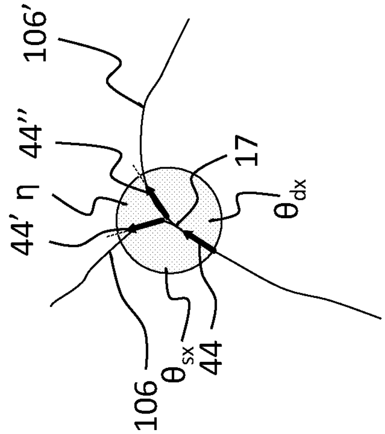

Fig.4b

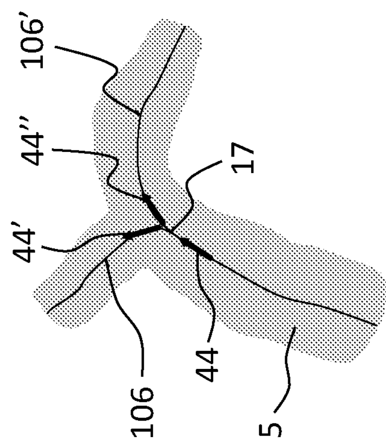

Fig.4a

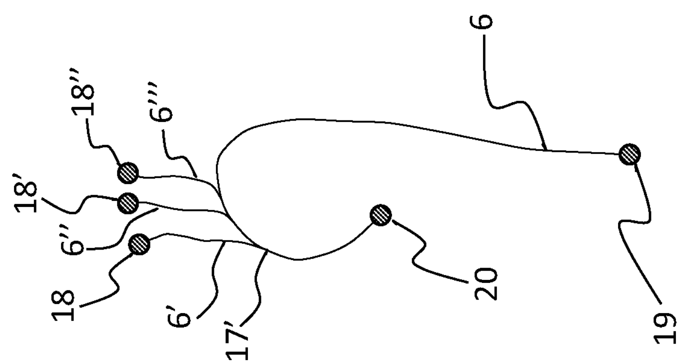

Fig.5b

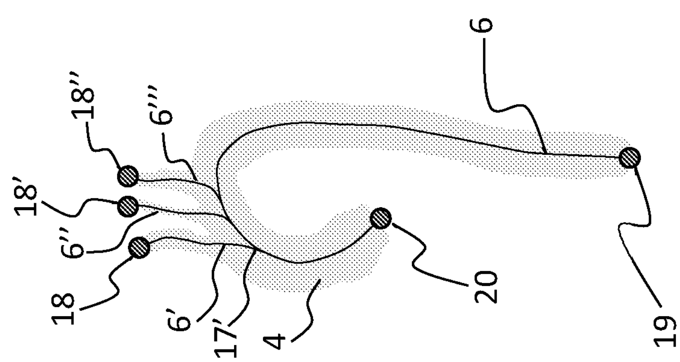

Fig.5a

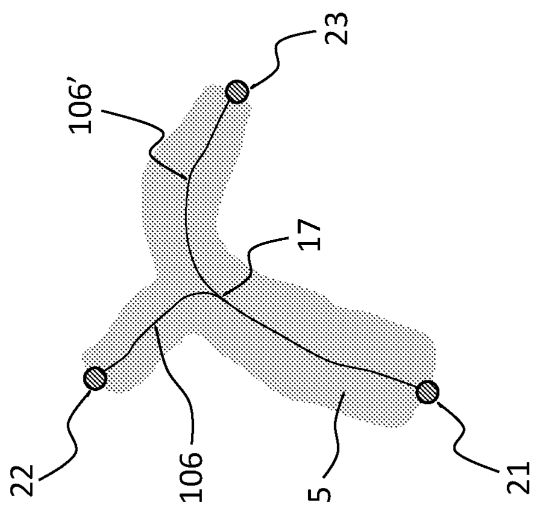

Fig.6a

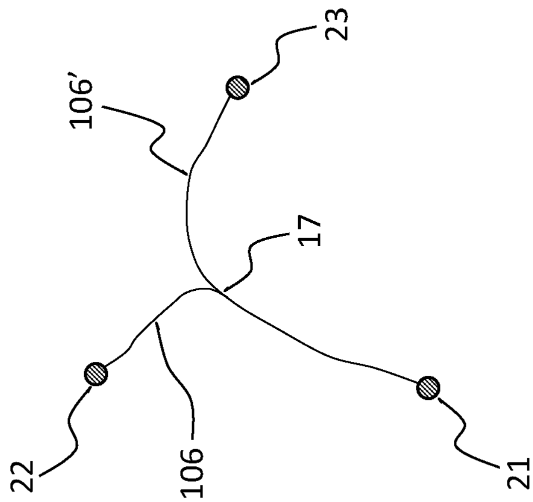

Fig.6b

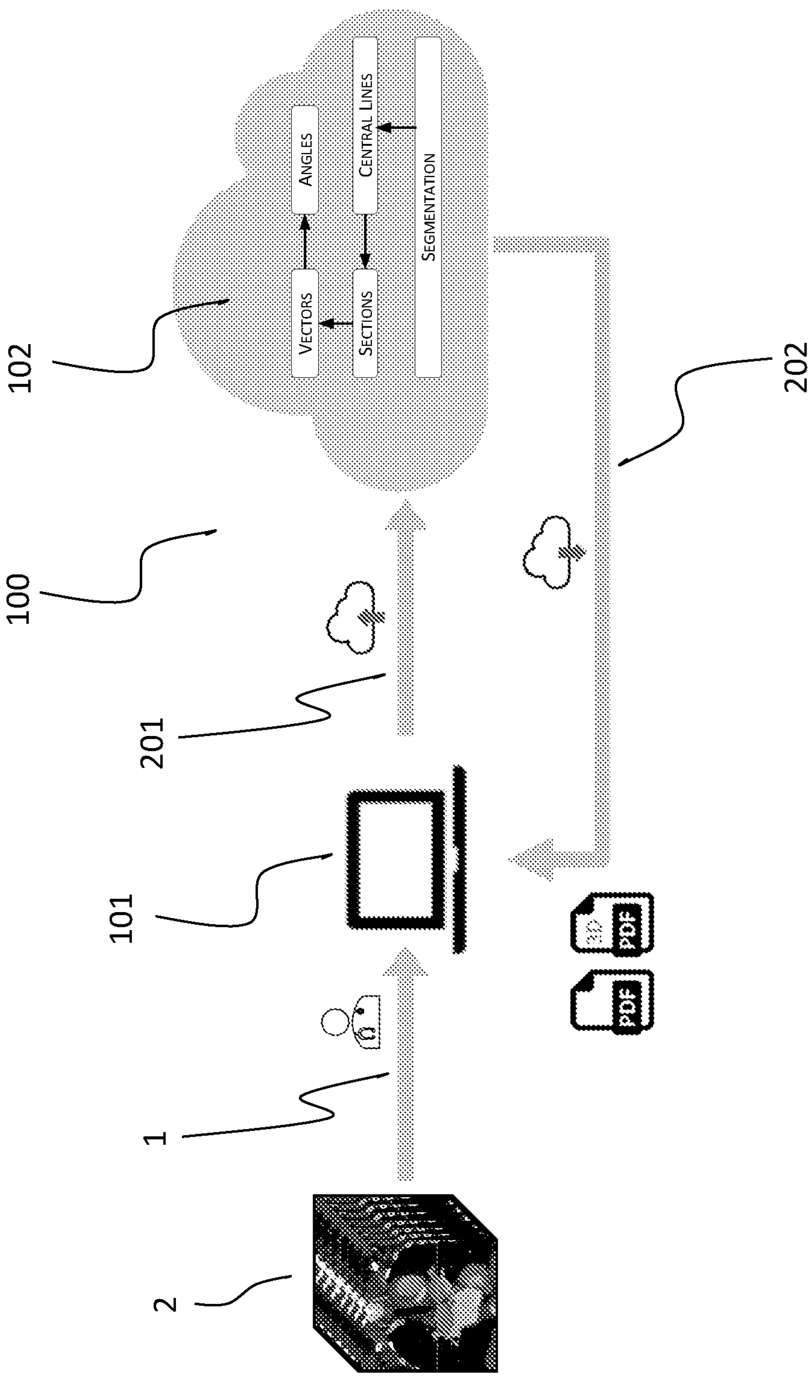
ANGLES
CENTRAL LINES
VECTORS
SECTIONS
SEGMENTATION
102
100
201
101
1
2
202
PDF
3D PDF

Fig.7

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2024/054887

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06T7/60
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	YEFENG ZHENG ET AL: "Automatic Aorta Segmentation and Valve Landmark Detection in C-Arm CT for Transcatheter Aortic Valve Implantation", IEEE TRANSACTIONS ON MEDICAL IMAGING, IEEE, USA, vol. 31, no. 12, 1 December 2012 (2012-12-01), pages 2307-2321, XP011491188, ISSN: 0278-0062, DOI: 10.1109/TMI.2012.2216541 abstract figure 3 Section III.; figures 5,8 Section IV., first paragraph Section V.; figure 12 -----	1-14

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 August 2024	04/09/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Salvador, Elena

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GOOLEY ROBERT P ET AL: "Quantification of normative ranges and baseline predictors of aortoventricular interface dimensions using multi-detector computed tomographic imaging in patients without aortic valve disease", EUROPEAN JOURNAL OF RADIOLOGY, ELSEVIER SCIENCE, NL, vol. 84, no. 9, 5 June 2015 (2015-06-05), pages 1737-1744, XP029260115, ISSN: 0720-048X, DOI: 10.1016/J.EJRAD.2015.05.029 abstract Section 2.4.; figure 1 -----	1-14
A	CALLAGHAN FRASER M. ET AL: "Age-related changes of shape and flow dynamics in healthy adult aortas: A 4D flow MRI study", JOURNAL OF MAGNETIC RESONANCE IMAGING , vol. 49, no. 1 13 January 2019 (2019-01-13), pages 90-100, XP093109217, US ISSN: 1053-1807, DOI: 10.1002/jmri.26210 Retrieved from the Internet: URL:https://api.wiley.com/onlinelibrary/tdm/v1/articles/10.1002%2Fjmri.26210 abstract Section Parameterization of Aortic Geometry and Flow; page 92 - page 93; figure 1 -----	1-14
A	SAITTA SIMONE ET AL: "A Deep Learning-Based and Fully Automated Pipeline for Thoracic Aorta Geometric Analysis and Planning for Endovascular Repair from Computed Tomography", JOURNAL OF DIGITAL IMAGING, SPRINGER INTERNATIONAL PUBLISHING, CHAM, vol. 35, no. 2, 26 January 2022 (2022-01-26), pages 226-239, XP037716174, ISSN: 0897-1889, DOI: 10.1007/S10278-021-00535-1 [retrieved on 2022-01-26] abstract Section Pipeline Implementation; figures 1,2 Section Parameter Computation; figure 3 -----	1-14

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INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2024/054887

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 113 974 667 A (UNIV NORTHEASTERN; FIRST HOSPITAL CHINA MEDICAL UNIV) 28 January 2022 (2022-01-28) the whole document -----	1-14
A	ELATTAR MUSTAFA ET AL: "Automatic aortic root landmark detection in CTA images for preprocedural planning of transcatheter aortic valve implantation", INTERNATIONAL JOURNAL OF CARDIOVASCULAR IMAGING, KLUWER ACADEMIC PUBLISHERS, DORDRECHT, NL, vol. 32, no. 3, 23 October 2015 (2015-10-23), pages 501-511, XP035902925, ISSN: 1569-5794, DOI: 10.1007/S10554-015-0793-9 [retrieved on 2015-10-23] abstract Section Methods; figures 1,3 Section Parameter Computation; figure 3 -----	1-14
A	SUN XIAOLIN ET AL: "Straightened Segmentation in 4D Cardiac CT: A Practical Method for Multiparametric Characterization of the Landing Zone for Transcatheter Pulmonary Valve Replacement", APPLIED SCIENCES, vol. 12, no. 24, 15 December 2022 (2022-12-15), page 12912, XP093110492, ISSN: 2076-3417, DOI: 10.3390/app122412912 the whole document -----	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2024/054887

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
CN 113974667	A	28-01-2022	NONE	