Three-dimensional reconstruction of the coronary arteries using *a priori* knowledge

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Abstract—*A method for 3D reconstruction of the coronary arteries from two radiographic images is presented. A novel technique for matching image structures is the main contribution of the work. After a comprehensive study of the knowledge required to approach this problem, an automatic method, which includes both numeric and symbolic procedures to solve geometric ambiguities, is developed. In the proposed method, all possible (virtual) reconstructions are first obtained. Their validity is evaluated by means of a priori knowledge about the 3D object and its projections. From the set of chosen possible solutions, the most likely solution is selected. The method is tested using real images and is implemented in a platform that allows further clinical validation.*

Keywords—*Digital angiography, Biplane, 3D reconstruction, Coronary arteries*

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1 Introduction

1.1 *Coronary arteries*

THE CORONARY arteries, which are directly connected to the base of the aorta, are responsible for the perfusion of all myocardial tissues. The coronary system is composed of two main arteries, the right one, which is responsible for blood flow to the right side of the heart (atrial and ventricular), and the left one, which irrigates the left side. Although the general aspect of these arteries varies from person to person (an example is shown in Fig. 1), some structural and spatial relationship make classification of the different ramifications possible (see Fig. 2).

The main branches of the left artery are: the left anterior descending (LAD) artery, which travels along the anterior view of the heart close to the inter-ventricular boundary, and the circumflex (CX) artery, located close to the atrial–ventricular border. LAD branches going over the left ventricle are called diagonal branches (in some cases latero-diagonals), and those that irrigate the inter-ventricular wall are called septal branches. Conversely, the ventricular branches of the right coronary and CX arteries go towards the apex and they are known as lateral branches. Both right coronary and CX branches going towards the atrium are known as atrial branches.

1.2 *Pathologies*

The main pathology that affects the coronary arteries is reduction in their internal diameter, known as stenosis. This anomaly brings about a reduction in blood perfusion to the myocardial tissue and, consequently, a reduction in the required oxygenation level that could lead to necrosis of the tissue (acute infarct). Stenosis is produced by the accumulation of lipids in the internal wall of the arteries, leading, in some particular cases, to total occlusion. Depending upon their size and location, these deposits can be eliminated with drug therapy, interventionist procedures such as balloon dilatation, or surgery to place 'by-pass' branches.

1.3 *Cardiac imaging techniques*

Coronary artery stenosis can be recognised from clinical manifestations. However, its localisation and quantification are only possible through visual analysis. Radiological methods are still the preferred imaging modality to study the coronary arteries. Use of recent approaches such as magnetic resonance imaging or computed tomography is limited owing to a number of factors, such as low resolution, length of examination, noise level and poor image contrast.

Radiology is based upon the differences in the X-ray absorption coefficient of the different materials in the heart. Visualisation of the coronary artery tree by itself is difficult, as its absorption coefficient is similar to that of the surrounding tissue; a radio-opaque contrast agent is therefore injected into the blood stream by means of a catheter. This procedure results in higher-quality images of the arteries. This method is known as angio- cardiography or angiography and is nowadays a routine procedure performed in haemodynamic rooms. Dynamic observation of the images in a real-time display of the whole procedure is commonly used.

1.4 *Reasons for 3D reconstruction*

Many different problems prevent coronary angiography reaching maximum efficiency as a clinical examination.

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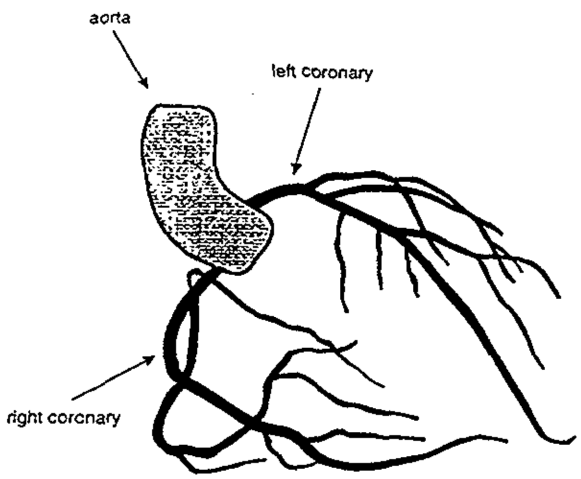

Fig. 1 *Pictorical view of coronary arteries*

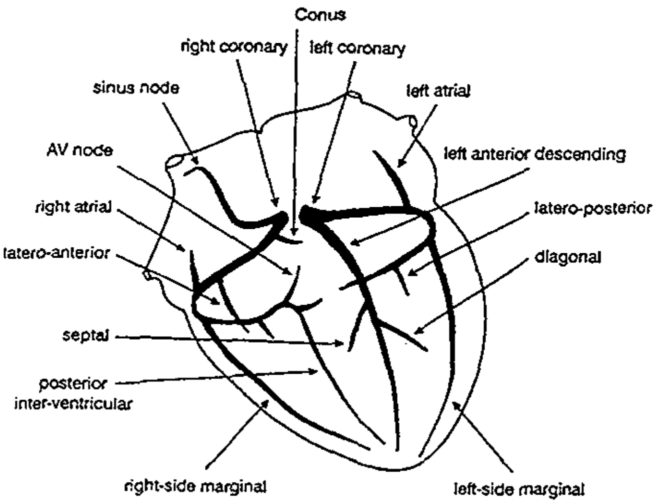

Fig. 2 *Coronary arteries and their branches*

First, there are inherent projection deformations. The more perpendicular a structure in relation to the projection plane, the more deformed its image. Secondly, the interpretation of angiographic images deals with the inevitable superposition of structures. These two factors impair the detection and evaluation of lesions and make multiple acquisitions necessary, increasing patient exposure to radiation.

Using 3D reconstruction of the coronary arteries, it is possible to select the optimum incidence, reducing the number of test X-ray illuminations and the total examination length and thus reducing the need for X-ray screening. Also, 3D reconstruction makes simulation of surgical procedures in the coronary arteries possible. This is particularly important in surgery to correct congenital defects in infants and in helping in local examinations, such as endoscopy and intravascular echography.

2 Three-dimensional reconstruction

2.1 *Background*

Three-dimensional reconstruction of the coronary arteries has been a topic of great interest to researchers over the past ten years. The first attempts (SMITH and STARMER, 1976; SAYRE and RUBIN, 1979; VIGNAUD and RABISCHONG, 1979) led to heavily interactive systems. Semi-automatic systems followed later (PARKER *et al.*, 1986; DUMAY *et al.*, 1988). Subsequently, use of knowledge for labelling segmented arteries within the images was employed and tested (TSUJI and NAKARO, 1981; RITCHINGS *et al.*, 1985; ANAKÖK *et al.*, 1987; CATROS and MISCHLER, 1988).

Fig. 3 *3D reconstruction stages*

Some interesting propositions concerning knowledge-based matching procedures have also been published (YACHIDA *et al.*, 1984; GARREAU, 1988; SUN, 1990; BARTH *et al.*, 1990; COPPINI *et al.*, 1991; RAKE, 1991), although it must be pointed out that none was robust enough or completely operator independent. The difficulties led to a loss of interest in this problem. Nevertheless, the availability of biplane systems and images in digital format facilitate advanced research work into an improved solution to 3D reconstruction of the arterial tree.

2.2 *Reconstruction process*

Fig. 3 presents the general approach to 3D reconstruction from a limited number of projections. Image formation includes aspects such as mathematical normalisation of projections, image acquisition, distortion correction, pre-processing etc. Segmentation deals with the separation of the image into zones, which, in this case, refers to the determination of the arterial segments in the angiogram. When the image has been segmented, the projection of the different structures must be identified; this part of the approach is known as matching reconstruction, which in turn entails estimation of the position of the object in the 3D space, obtained from its projections. This procedure is performed using simple mathematical manipulation. Once reconstructed, the object can be displayed using classical scene visualisation methods (shades, perspectives etc.) for further analysis and interpretation.

Reconstruction of the coronary arteries requires particular attention with regard to heart movement, patient movement, contrast medium diffusion and X-ray detection quality.

2.3 *Structure matching*

Three-dimensional reconstruction from two projections is a problem that can have multiple solutions. In fact, several 3D objects can have the same pair of projections. This can be observed in Fig. 4, where seven different objects have the

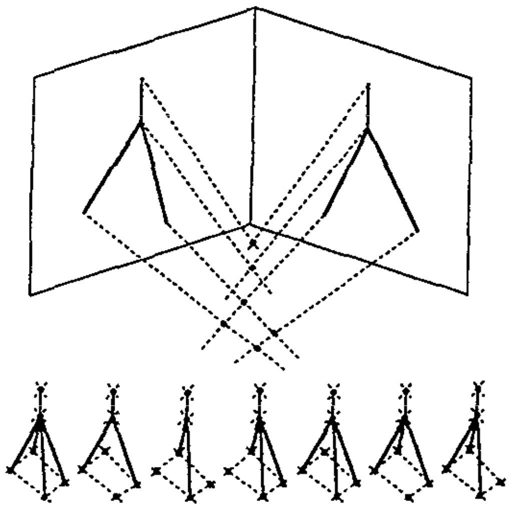

Fig. 4 *Ambiguities in reconstruction from two projections*

same appearance once projected. Without *a priori* knowledge about the object, it is impossible to identify the correct solution. In the Fig. 4 example, this knowledge could state that the only kind of branching allowed is bifurcation, in which case the number of possible solutions is two.

In general, the difference in appearance between projections increases with the angular difference between them, but at the same time the numerical values of the 3D co-ordinates obtained are more precise. In this work, precision is important, and thus a reconstruction process from two quasi-orthogonal views is attempted. The problem here is to identify and model relevant knowledge that allows the solution of ambiguities in the matching of vascular structures from biplane orthogonal angiographic images.

3 Knowledge acquisition and modelling

3.1 *Required knowledge characteristics*

The required knowledge must be specific to the problem in hand to produce an optimum solution. In this research, our interest lies mainly in high-level knowledge, that is, the modelling of the object itself, and not lower-level tasks, such as image-processing algorithms. Even though empirical or shallow knowledge is frequently used in knowledge based systems, its usefulness is very limited in this problem. Therefore, in this work, a deep knowledge-based system was preferred. Although numerical descriptions of the coronary arteries have been attempted (DODGE *et al.*, 1988), a qualitative description was preferred, owing to the limitations of numerical descriptions.

Knowledge is restricted in this case to the 3D and 2D spaces, although it is known that the coronary arteries are a 3D object with two temporal components (the propagation of the radio-opaque contrast agent and the movements of the heart). If it is assumed that both biplane images are taken fast enough for the temporal delay to be considered negligible, and only one set of two images is considered each time, the knowledge space is reduced accordingly.

3.2 *Knowledge sources*

Knowledge was obtained from different sources, including anatomy reference books (MCALPINE, 1975; CHRISTIDÈS and CABROL, 1976); a sequence of programmed interviews with a consultant cardiologist; observation of numerous angiographic images from a data bank; and a previous 3D reconstruction of real images performed using a biplane system.*

3.3 *Studied properties*

Studied properties can be classified as follows:

3.3.1 *Properties independent of the model space:* These properties are related to the structure of the coronary arteries, that is, relationship's such as 'branch from' or 'gives rise to', and the number of occurrences of each type of artery (diagonals, septals, lateral, atrial). These properties are very stable. However, their capacity to detect matching errors is quite low. In addition, owing to the number of superpositions and crosses observed in the images, these properties, in most cases, are not useful. In some cases, the diameter of the arteries can be useful for identification purposes. Nevertheless, pathologies and projection effects make their use difficult and subject to the attenuation laws (see Section 3.4).

3.3.2 *Space dimension dependent properties:* These properties include form, size and absolute or relative position of the arteries. Their form, expressed in terms of curved, irregular or variable, is a very difficult property to model. Besides, it does not provide clear differentiation between the form of a real artery or that of a 'ghost' resulting from a mismatch. Also, they are difficult to use to discriminate between different arteries. Finally, strong form deformations due to the projection effects make this property ineffective. On the other hand, the size of arteries, perhaps the most unstable property, is difficult to use. It varies and, in many cases, does not follow the diameter/length relationship. In fact, small-diameter arteries can, in some cases, be longer than those of large diameter. The length of an artery cannot be considered a discriminant property in almost any context. By the same token, position is not useful as it requires a reference system. A fixed reference system is not always useful owing to anatomical differences between patients. A reference system defined from the object itself has not been identified yet. If, in addition to these problems, the presence of ghost arteries with similar positions is considered, the position property loses all utility in the modelling process.

In 2D space, the situation is rather different, owing to the fact that many reference systems can be defined from different sections of the image. However, using this approach, the positions are still not discriminant enough, with the exception of the LAD and CX arteries under standard right anterior oblique (RAO) and left anterior oblique (LAO) views. As Fig. 5 illustrates, the positions of these arteries are complementary between both images. This property become less valid closer to the apex or the origin of the coronary arteries, as the relationship described becomes too sensitive to the position of the principal axis of the ventricle.

Finally, the angular relationship between new branches and main branches, or between any two arteries, has a drawback owing to the need for specific points for its measurement, making this property unstable. Besides, these angular relationships are similar between real and ghost arteries.

From the previous analysis, it can be concluded that these properties are not useful in modelling the arterial tree owing to their limited power to discriminate between real and ghost arteries in the reconstruction process. In the case of the coronary arteries, two important properties can be derived. The first is the path of the arteries on the surface of the ventricle, the form of which is close to an ellipsoid. It is thus possible to ensure that the arteries wrap an ellipsoidal space. This is probably the most important of the modelling properties identified thus far. From this property, other properties can be derived, such as the restriction in the length of a superposition (two curves in an ellipsoidal surface can superimpose only under particular conditions) and the impossibility of a

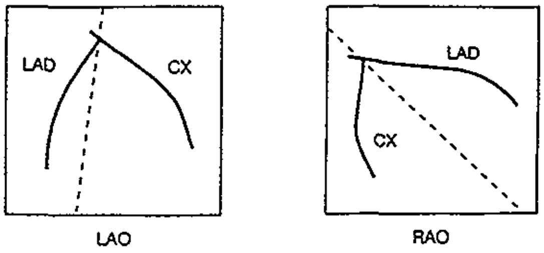

Fig. 5 *Positions of LAD and CX arteries in relation to ventricular axis under standard views. (— — —) Ventricular axis*

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* General Electric, Milwaukee, USA.

triple superposition (the superposition of three curves implies their belonging to another surface). The second property is the path the arteries take without touching or crossing each other.

The preceding study of the general appearance of the coronary arterial tree led to the identification of the following stable properties:

(*a*) bi-dimensional properties:
- complementary position of LAD and CX arteries in standard RAO and LAO views
- difference in artery diameter among arteries

(*b*) three-dimensional properties:
- arteries wrap an ellipsoidal space
- arteries do not cross each other.

3.4 *Modelling of identified properties*

Modelling of the identified properties must take into account their nature: they are geometrical, qualitative and global. The shape of the ventricle (geometrical property) requires an analytic normalisation that takes into consideration all the errors of such an approach. Not having an estimation of the ventricular surface before the vascular reconstruction makes things harder. The inhomogeneous distribution of the arteries on the ventricular surface precludes the use of a numerical parametrisation technique.

The surface is estimated using the properties derived from the intersection of an ellipsoid with a series of parallel planes that gives rise to a series of ellipses (Fig. 6). This intersection is estimated from the intersection of the arteries with the cutting planes. The direction of the normal to these planes is determined by two characteristic points: the origin of the virtual solution and its baricentric point. This procedure allows the extraction of the following properties (Fig. 7):

(i) The curve defined by the sequence of characteristic points (b), or any other equivalent perimetric sequence of points, must have a form that can be approximated by an elliptic segment.
(ii) The set of points of the intersection of a cutting plane with the coronary tree must allow the interpolation of a partially or totally elliptic curve.
(iii) The artery position with respect to the faces of the ventricle (anterior/back or right/left) must be the same in all cuts.
(iv) The relative position between the different arteries must be the same from one plane to another.

These properties make a meta-rule that establishes the strategy of validation of each virtual position, after the numerical procedures have been completed. Verification of each property becomes possible by means of a set of rules applied to the numerical results.

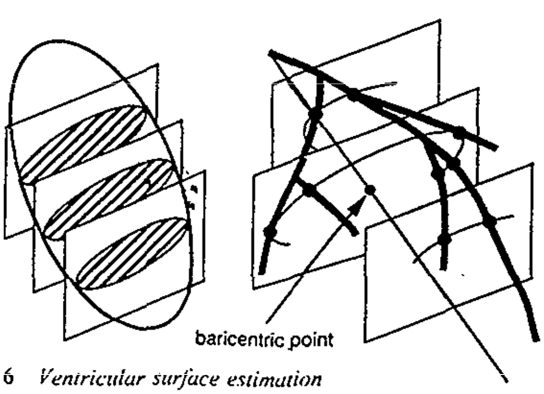


Fig. 6 *Ventricular surface estimation*

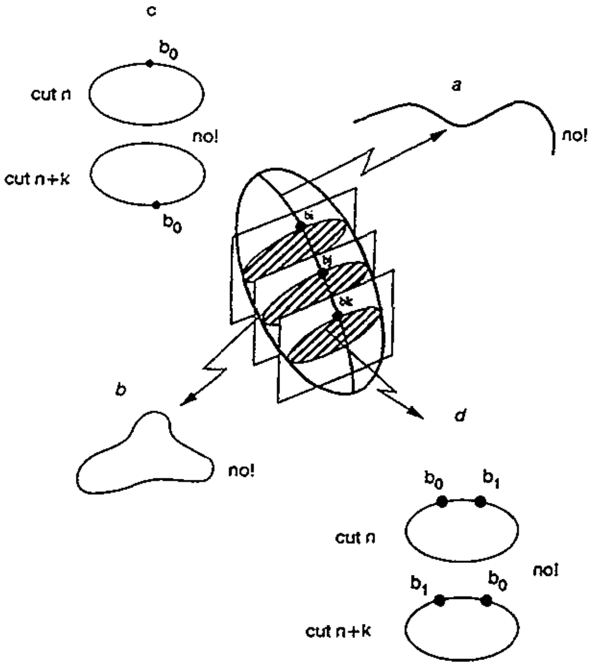


Fig. 7 *Criteria for virtual solution validation: (a) criterion 1: elliptical contour; (b) criterion 2: elliptical cuts; (c) criterion 3: without ventricular crossing; (d) criterion 4: no crossings among arteries*

As mentioned earlier, other properties can be derived from the shape of the ventricle, such as the maximum superposition between segments and the impossibility of triple superposition. These properties were also coded in rules, giving rise in each case to a main rule and a set of rules that allow their application (condition evaluation). Similarly, the knowledge about the structural properties was coded (usually bifurcations, occasionally trifurcations). The latter set of rules is used to guide the assembly of virtual solutions.

Owing to the frequent presence of stenosis on the images, the calibre of arteries must be redefined based on grey levels. According to X-ray attenuation laws, the diameter is defined as the closed integral of the grey-level natural logarithm inside an arterial segment. This integral represents the projected 'mass'. The correctness of this definition depends on the precise delimitation of the arterial segment boundaries. The calibre property becomes less useful in the presence of superposition.

The position relationship between the LAD and CX arteries was represented by means of an analytic function, defined as the product of two independent functions $A(x)$ and $B(x)$ that, respectively, weight the orthogonal distance of the image points with respect to the ventricular axis (principal axis) and the longitudinal distance with respect to the ventricle centre.

The shape of these functions and the normalisation constants k_1 and k_2 (Fig. 8) were established in an empirical way. The first is a signed quadratic function centred at the midpoint of the ventricular axis. The second is a quadratic exponential function, with the ordinate and abscissa axes interchanged with respect to the previous function (this function is antisymmetric under inversion of the x-abscissa). In Fig. 8, x represents both the distance from the ventricular axis and the distance from the ventricular centre. The sub-index denotes the image number. Note that all these functions are tilted towards the ventricular axis.

Regarding RAO images, the last of these functions was defined as $f(-x)$, such that the points belonging to the LAD/CX arteries generate negative/positive values in both images.

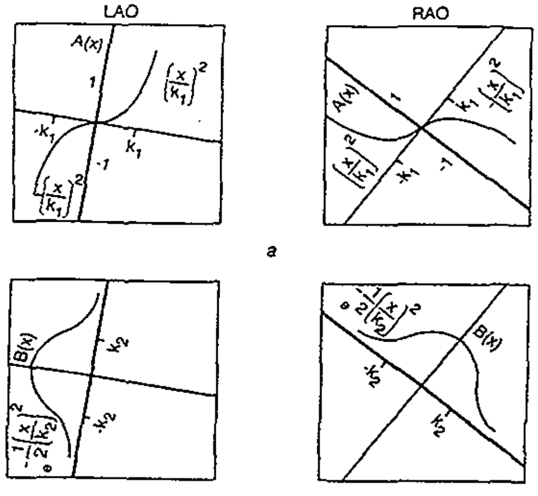


Fig. 8 *Matching function definition. (a) Function A. (b) Function B.* $M = A_iB_iA_jB_j$

The reliability of the matching of two points belonging to corresponding epipolar lines (see Section 4) is defined as the product of values in the applied function to each one of these points. When both of them belong to the LAD or CX artery, the product is a large positive value; otherwise it is large negative. This function is applied plane by plane. For a point in an image, we calculate the magnetism with respect to all points on the other image, discarding branches that contain points below an established threshold.

This property leads to the definition of a set of rules to be invoked before the assembly of virtual solutions.

4 Proposed method

Our objective, as stated earlier, is the 3D reconstruction of the coronary tree from two projections using *a priori* knowledge. As matching of the structures is the central problem to be solved for an adequate reconstruction procedure, the following technical decisions were made:

(*a*) The central lines of the arteries were selected as matching primitives, with the diameter as one of the attributes. Therefore the input images for the reconstruction process were simplified into filar segments.

(*b*) Epipolar geometry was used extensively as a tool to reduce the search space during the matching. According to epipolar geometry (Fig. 9), the projection sources S_0, S_1, together with any spatial point P, define a plane π called the epipolar plane. The intersection (L_0, L_1) of this plane with each one of the projection planes (I_0, I_1) is known as the epipolar line. E_0 and E_1 are called epipoles. Knowing the position of the sources and the projection of a point on one of the images, the other projection should be found on the corresponding epipolar line. In this way, the search space of the equivalent of a point in the other image is limited to a straight line, leading to a considerable reduction in the number of possibilities.

(*c*) The method was oriented, basically, towards the reconstruction of the left coronary artery.

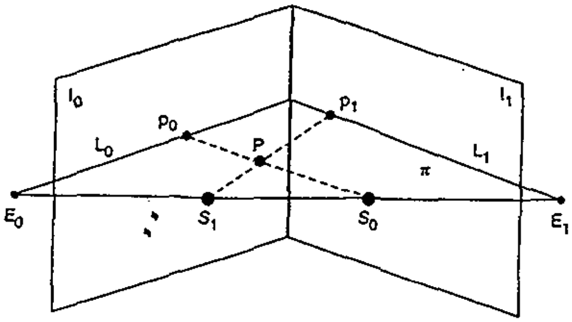


Fig. 9 *Epipolar geometry*

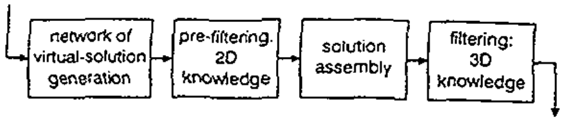


Fig. 10 *Proposed methodology*

The proposed method is based on the following premises:

- limited user intervention
- maximum separation between algorithmic and symbolic procedures
- decision based on the exploration of various alternatives
- extensive use of the global properties.

The following four stages constitute the core of the implemented method (see Fig. 10):

Stage 1 Generation of all virtual arterial segments: This stage generates all possible reconstructions using the set of combinations allowed by matching primitives from both images. The result is a 3D net, where the right solution is found from numerous incorrect virtual solutions (ghost solutions).

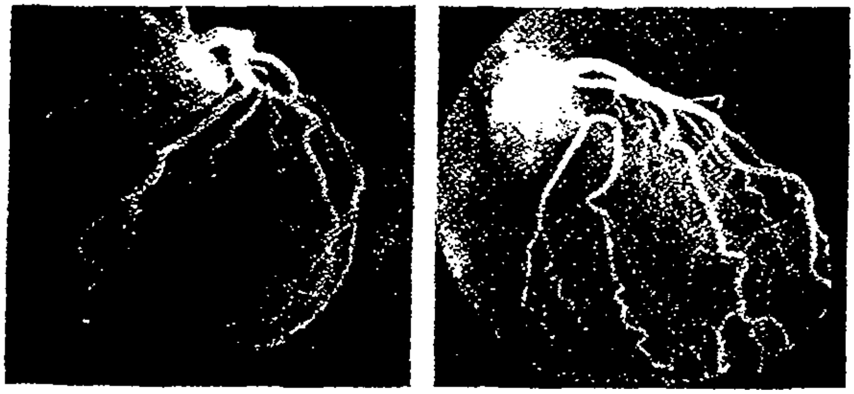
Stage 2 Pre-filtering: Pre-filtering is basically the reduction of the search space by elimination of all virtual segments that, according to 2D knowledge, can be considered as impossible or strongly improbable. Remember that 2D knowledge includes the relationship between the LAD and CX positions, as well as artery diameter information.

Stage 3 Assembly of virtual solutions: This consists of extracting, from the net of virtual reconstructions, coherent subsets with the appearance of the coronary arteries (tree-like structures). It is mainly a problem of graph tracking, in which a path is searched from a specific point (net origin) towards a goal (a virtual segment, the end of which lacks connection), where neither the goal nor the number of points is known *a priori*. In this process, the decisions taken in each 3D point, where several 3D segments start, depend upon a series of criteria that encompass part of the structural and geometrical knowledge of the coronary arteries.

Stage 4 Filtering: Filtering identifies the virtual solutions that comply with the geometrical properties that model the 3D knowledge relating to the coronary arteries. In the ideal case, filtering should lead to a single solution: the correct one. Nevertheless, this situation seems exceptional, as the difference between a correct solution and a ghost could be only a short segment. The final task of this stage is to select the best solution, from among all the virtual solutions that pass the filtering process.

5 Implementation

The first implementation of the method used two programming languages: C and Prolog. The assembly of solutions (see



a

b

Fig. 11 *Biplane images corresponding to left coronary artery. (a) $LAO = 60$; (b) $RAO = 30$*

preceding Section) was totally implemented in Prolog. By taking advantage of Prolog's backtracking mechanisms and natural recursion, it was possible to produce quite a short program (200 lines). However, this implementation is not optimum owing to the time required, particularly for clinical applications. The optimisation at the predicates, clauses and data structure level is not sufficient, and therefore a faster language, programming technique or specialised hardware might be necessary.

The remainder of the procedures were implemented in C Language, and run on a SUN SparcStation I. For this particular machine, the network of virtual solutions is generated in 30 s, and the validation of each solution takes 5 s.

6 Results

A pair of biplane images from the left coronary artery, under standard acquisition angles ($RAO = 30°$ and $LAO = 60°$) were used to test the outlined procedure (Fig. 11). Segmentation was performed by manually detecting the centre lines and borders of the arterial segments. The five most identifiable arteries in the images (LAD, CX, latero-diagonal and laterals) were selected. Next, 25 segments for the LAO image and 13 segments for the RAO image were delineated. A total of 285 ambiguous 3D points were then reconstructed, and 329 virtual segments were identified. For a selected maximum error of 0.001° in epipolar planes, we obtained precisely reconstructed shapes. According to our tests, even with an error of 2°, we obtained precisely reconstructed shapes.

Pre-filtering allowed the reduction of virtual segments from 329 to 245 (35% reduction), using a threshold of -0.15 in the coherence function for the magnetism property, and a calibre property reduction from 329 to 290 (15%). Both properties considered together allow a total reduction of 42%. A further study (WINDYGA *et al.*, 1996) has demonstrated that the number of solutions discarded is not very sensitive to the selected threshold and the other parameters involved; for example, a 50% variation in the threshold could yield a zero variation in the magnetism function performance.

From the 3D network, a set of 24 solutions was manually extracted, to test the performance of the 3D properties. This was done to study the effect of significant matching errors in the generation of a valid global solution. The application of the matching algorithm to the full 3D network is not necessary because it will generate many solutions that are very similar.

The impossibility of artery crossing allowed us to discard 12 of the 24 solutions, by setting the maximum number of crosses to 2. It may seem compromising to set the threshold of crosses to 2, when, according to the statements in Section 3.3, it should be 0. This is owing to the fact that some arteries, at the branching level, have configurations that can geometrically be described as crossings. However, in the current implementation, these local configurations are not identified and are just considered in a global manner.

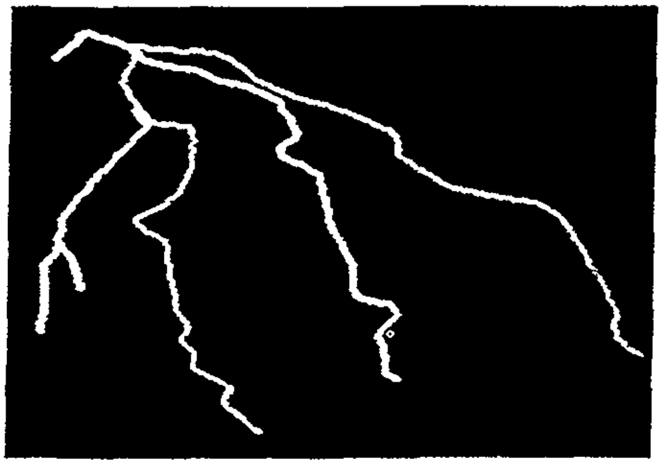


Fig. 12 *Reconstructed coronary artery*

Using the ventricular cavity and the elliptical shape of the cuts leads to 20 out of the 24 virtual solutions being discarded. Finally, the ellipsoidal contour adjustment points gave six possible virtual solutions. By combining all the properties, only two solutions are kept, and the one that has a better performance in all the tests is retained as the correct solution (Fig. 12).

7 Conclusions and future directions

This work has demonstrated the feasibility of using physiological and geometrical knowledge to solve the problem of reconstruction of the arterial tree from two orthogonal projections. The weaknesses of relying on purely quantitative or local properties to identify correct solutions, due to variability among patients, have been shown. In addition, the difficulties in defining reference systems and in identifying the representative anatomical elements have been discussed. Finally, the similarities between correct and ghost solutions have also been discussed. It has been argued that the useful properties for knowledge modelling are coronary branching characteristics and their relationships to the quasi-ellipsoidal shape of the ventricle

The implementation was made in a general form in which numerical and symbolic procedures are separated. Although results from a set of two images have been presented, the procedures developed can be applied to most images. A reduction in computation time by means of a more efficient implementation will allow application to a larger database, and a parallel-computational technique is currently under development.

To reduce computation time, the procedure for virtual-solution assembly, which takes more memory and execution time, deserves special attention,. The addition of other constraints or fine tuning of the current algorithm will certainly aid in the optimisation. Also, evaluation of the elliptic shape must be done in a more sophisticated way. Approximation by means of B-splines or Bezier functions could be explored.

A more precise definition and application of the artery diameter as a knowledge element is a task that must be completed. Also, the robustness of properties such as no arteries crossing and not crossing the ventricular cavity have to be increased to prevent local confusing configurations. By the same token, the relative position LAD/CX could be redefined to increase the efficacy of pre-filtering. The best-solution mechanism of selection must be tuned up according to the results of the tests performed on a large set of images.

Co-ordination between this type of 3D reconstruction, 3D reconstruction of the ventricles, and studies of cardiac dynamics along the cardiac cycle seems to be a natural follow up for this project. The results presented were obtained for the left coronary artery at telediastole. It would be quite appropriate to obtain the reconstruction for both left and right arteries, at different instants of the cardiac cycle, and study the dynamics of the blood flow in a 3D space.

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Author's biography

Piotr S. Windyga was born in Merida, Venezuela, in 1962. He received a Systems Engineering degree from the University of Los Andes, Merida, Venezuela, in 1985, and the Magister in Electronics and Doctor in Image Processing degrees from Simon Bolivar University, Caracas, Venezuela and the University of Rennes I, France, in 1989 and in 1994, respectively. A former consultant of Venezuelan Oil Companies, for the past seven years Dr. Windyga has conducted projects related to the automatic interpretation of coronary angiographic images and developed software tools for high-level image understanding and 3D reconstruction of medical images.