Three-Dimensional Reconstruction of Stenosed Coronary Arteries from Biplane Angiograms and its Importance to Computer Simulation Studies of Blood Flow

H. Mühlthaler [a] and B. Quatember [b]

[a] *Department of Vascular Surgery, University Clinic of Surgery, University of Innsbruck, Austria (h.muehlthaler@archiatros.com)*

[b] *Department of Computer Science, University of Innsbruck, Austria (bernhard.quatember@uibk.ac.at)*

Abstract: In the entire field of coronary artery disease, the normal diagnostic assessment of the degree of stenosis severity is at present a simple visual inspection of biplane angiograms, which only allows a rough qualitative assessment. Only occasionally do cardiologists perform the so-called "Quantitative Coronary Angiography (QCA)". This, however, is also a rather imperfect method, since the quantitative analysis refers exclusively to the two projections of the flow domain. Hence, the QCA allows no genuine quantitative assessment of the reductions of the cross-sectional lumenal areas in the regions of stenoses. Really meaningful assessments would require a three-dimensional reconstruction of the flow domain. The contemporary methods for such a three-dimensional reconstruction are not accurate enough to allow reliable diagnoses and are not used in clinical practice. We have developed an advanced and remarkably accurate method for the three-dimensional reconstruction of the coronary arteries. This method comprises the segmentation of the biplane angiograms and the construction of a wire frame model, the first stage of which consists of a family of ellipses. On the perimeter of each ellipse of the family, four points - located at the ends of the major and minor axes - are then defined, and four NURBS curves are constructed, connecting each defined point on the perimeter of each ellipse with the adjacent points on the successor and/or predecessor ellipse. This wire frame model is used for a fair quantitative assessment of the stenosis geometry. However, this knowledge of the complex three-dimensional geometry is still insufficient, since cardiologists primarily need a reliable knowledge of the hemodynamic relevance of the stenosis. Thus, computer simulations of the coronary hemodynamics are essential. In the companion paper, such computer simulations are described. They are carried out by using the finite element method. In particular we will show that the aforementioned wire frame model of the flow domain is well suited for the generation of the mesh that is a prerequisite for carrying out this numerical method.

Keywords: Three-dimensional reconstruction; Biplane angiograms; Coronary arteries; Stenoses

1. INTRODUCTION

The diagnosis and planning of therapy in the entire field of cardiovascular diseases should be based on a fair knowledge of the patient's hemodynamic state. This is particularly true of coronary artery disease where stenoses in the epicardial arteries are important pathological changes which may have serious consequences. Stenoses may reduce the flow of blood to the myocardium. The disturbed flow in the region of a stenosis accelerates the progression of pathophysiological changes and may cause the formation and development of thrombi. To assess these adverse effects, it is important to know the three-dimensional flow patterns. However, measurements of the coronary hemodynamics are difficult to carry out. Their scope and the available results do not reliably assess the disturbed flow in stenosed arterial sections. We are therefore dependent on computer simulations to determine the three-dimensional flow patterns. An important prerequisite for these simulation studies is a fair knowledge of the geometry of the flow domain within the epicardial arteries.

The simulation methodology of the coronary hemodynamics will be described in the companion paper [Quatember and Mühlthaler, 2001b].

We will focus here on the acquisition of the patient-specific geometry of the three-dimensional flow domain in the patient's coronary arteries. Among all medical imaging modalities, the biplane angiography is still regarded as the "gold standard" in the field of coronary artery disease.

We will describe the development of an advanced method for the three-dimensional reconstruction of the coronary arteries from biplane angiograms.

Several reconstruction methods of this kind have already been developed in the past two decades. Reiber [1996] and Bao [1991] employed densitometric methods. However, the accuracy of densitometric approaches can be rather limited. This is particularly true if there is an imperfect mixing of the contrast agent in the flow domain of the coronary arteries. A few years after the introduction of the densitometric approaches, several articles introducing so-called geometric approaches appeared [Coppini et al., 1991; Guggenheim et al., 1991; Wahle et al., 1995]. Their authors proved the superiority of such geometric approaches to densitometric methods. However, the accuracy of the known geometric methods still does not suffice to carry out meaningful three-dimensional simulation studies of the blood flow in the coronary arteries, especially in stenosed sections.

Our three-dimensional reconstruction method has a remarkably high degree of accuracy. The geometric models obtained with our method have already been used for meaningful simulation studies of coronary hemodynamics [Quatember and Mühlthaler, 2000, 2001a, b and c].

2. MEDICAL IMAGING IN THE FIELD OF CORONARY ARTERY DISEASE

In comparison to other sections of the cardiovascular system, the acquisition of the geometry of the coronary arteries is much more difficult because the coronary arteries are moving rapidly.

2. 1 Imaging Modalities of the Coronary Arteries

In the past, coronary angiography (biplane angiography) was the only modality available to provide images of the coronary anatomy. In recent years, however, medical science has made considerable advances in coronary imaging. Currently, the following additional modalities for the acquisition of geometric data of the epicardial arteries are available:

- spiral CT imaging,
- electron beam computed tomography (EBCT), and
- magnetic resonance imaging (MRI).

These advanced imaging modalities provide physicians with three-dimensional images, but they cannot fulfil all the requirements for meaningful hemodynamic simulations. In particular, they cannot provide cardiologists with sufficiently accurate, reliable and consistent geometrical data. The imaging of the coronary arteries remains a very difficult task due to the motion of the coronary arteries, their relatively small size and their tortuous shape.

At present, only biplane angiography systems can produce medical images with a sufficiently high resolution – thus their status as the "gold standard" for diagnosing and planning therapy [Baim and Grossman, 1996].

There are other advanced imaging modalities in the field of coronary artery disease, such as intracoronary ultrasound and angioscopy. However, these imaging modalities are used not primarily for the acquisition of geometric data, but for the detection of pathological changes relevant to coronary artery disease which are not visible on an angiogram. These include angiographically "silent" signs of arteriosclerosis at the inner arterial walls and impaired perfusion zones of the myocardium.

2. 2 Cardiac Catheterization and Biplane Coronary Angiography: The Diagnostic Standard in the Field of Coronary Artery Disease

Cardiologists take biplane angiograms in catheterization laboratories by means of biplane angiography systems [Baim and Grossman, 1996]. A biplane angiography system is depicted in Figure 1. It consists of two image chains, each of which comprises an X-ray tube and an image intensifier. After injection of a contrast agent, the X-ray tube of each image chain casts the shadow of the network of the coronary arteries on the image intensifier.

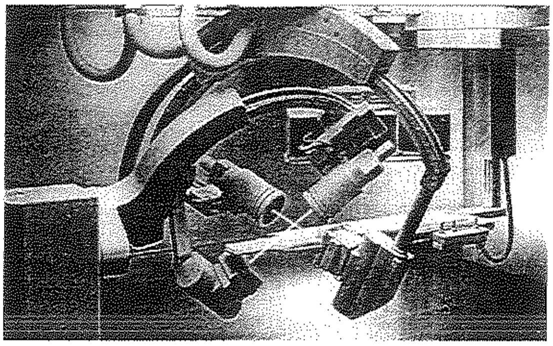

Figure 1. Biplane angiography system.

As can be seen in Figure 2, the image-forming system is based on two central projections.

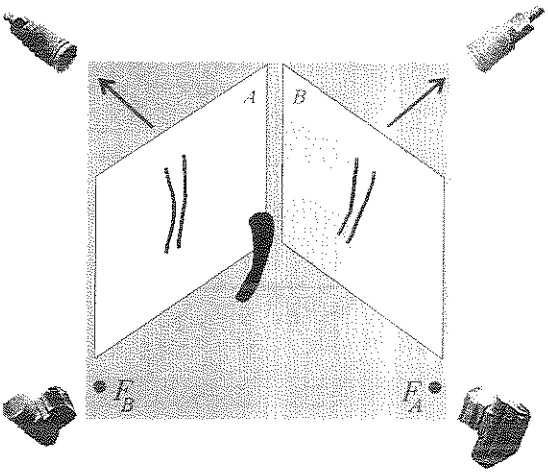

Figure 2. Production of biplane angiograms: central projection.

The focus of each X-ray tube forms the centre of projection; the input windows of each image intensifier constitutes the plane of projection. The images recorded with the image intensifiers are called biplane angiograms.

In current clinical practice, cardiologists usually confine themselves to:

- a simple visual inspection of the biplane angiograms and, only occasionally,
- the determination of quantitative data obtained by the so-called "Quantitative Coronary Angiography (QCA)".

However, they only refer to the projection of a coronary artery and not directly to its shape in the three-dimensional space. Cardiologists would benefit from systems that provide them with

- a three-dimensional representation of the flow domain within the epicardial arteries and, based on this representation, with
- patient-specific simulation studies of the coronary hemodynamics.

Although, as previously mentioned, a few methods for the three-dimensional reconstruction of the coronary arteries (flow domain) have already been developed [Coppini et al., 1991; Guggenheim et al., 1991; Wahle et al., 1995], they were not introduced into clinical practice due to their insufficient accuracy.

We have developed an advanced method for the three-dimensional reconstruction of the coronary arteries [Mühlthaler, 1999; Mühlthaler and Quatember, 2000] which will be described in the next paragraph. The companion paper [Quatember and Mühlthaler, 2001b] deals with simulation studies of the coronary hemodynamics that are based on the three-dimensional representation of the coronary arteries obtained with this new reconstruction method [Quatember and Mühlthaler, 2000, 2001a and c].

3. DEVELOPMENT OF AN ADVANCED METHOD FOR THE THREE-DIMENSIONAL RECONSTRUCTION OF THE CORONARY ARTERIES FROM BIPLANE ANGIOGRAMS

There is no unique solution for the problem of a three-dimensional reconstruction of the coronary arteries from two central projections; it is thus a so-called ill-posed inverse problem. We decided to overcome this non-uniqueness:

- by making the simplifying assumption that the cross-sectional lumenal areas are ellipses and
- by defining specific image processing procedures and reconstruction algorithms.

However, in several cases of markedly eccentric stenoses, our assumption of cross-sectional lumenal areas may be regarded as an over-simplification.

3. 1 Segmentation of the Biplane Angiograms

Our long-term goal is a fully automatic edge detection procedure. However, that will require the development of special-purpose software, since, at least at present, standard image processing software packages do not suffice. We have postponed this difficult development task until a later stage of our project. At present, we confine ourselves to the segmentation of the biplane angiograms by a manual edge detection. This will be carried out by an expert with a fair knowledge of anatomy who will be able to detect the edges even if the image quality is poor, especially in the case of angiograms with so-called "weak spots." Degradations of this kind are mainly caused by insufficient mixing of the contrast agent within the flow domain of the coronary arteries.

As can be seen in Figure 3, the expert detects the edges by setting a sequences of points along each border of the X-ray shadow. In regions with markedly weak spots, he sets the points by relying solely on his anatomical knowledge.

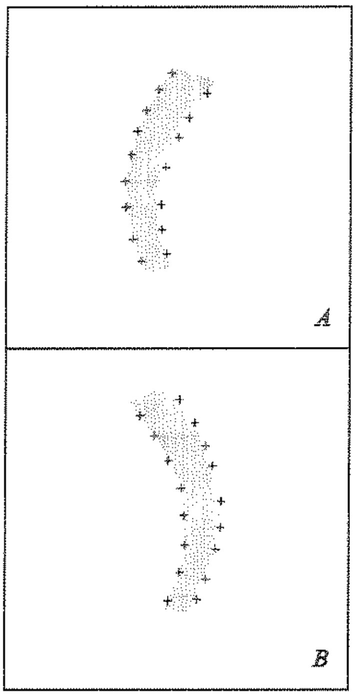

Figure 3. Manual edge detection.

The four edges are then automatically determined by defining four interpolating cubic spline curves, each of which passes through one of the four sequences of points along the individual borders of the X-ray shadows.

3.2 Automatic Calculation of the Centreline in Both Projections

The computer programme automatically carries out an equidistant subdivision of the four edges. In each projection plane, it connects opposite points with straight lines and defines the bisection points of these lines. It then determines the centrelines c_A and c_B in both projections A and B as two interpolating spline curves that pass through these two sequences of bisection points.

3.3 Automatic Calculation of the Centreline in the Three-Dimensional Space

Our construction of the centreline in the three-dimensional space is founded on pairs of so-called corresponding points which lie on the centreline c_A and c_B in both projections and are subject to epipolar constraints. The computer programme automatically draws back projection rays through all pairs of corresponding points. Due to the epipolar constraints, the back projection rays of each pair of corresponding points are intersecting lines. The points of intersection belong to the centreline c^{3D} in the three-dimensional space. The centreline is then defined as an interpolating spline curve (space curve) that passes through these points of intersection (cf. Figure 4).

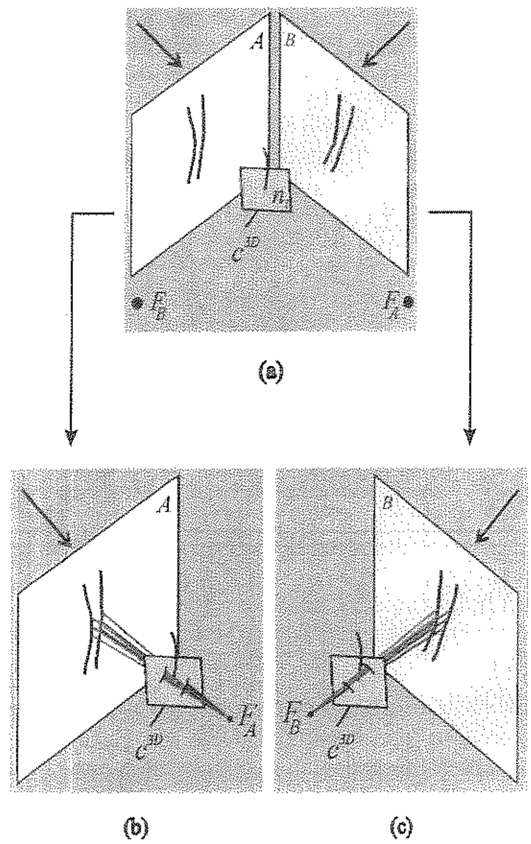

Figure 4. (a)-(c) Three-dimensional reconstruction; intersection of back projection rays with a normal plane.

3.4 Automatic Construction of Normal Planes of the Centreline and the Best Approximate Ellipses for the Lumenal Cross Sectional Areas

As mentioned above, our aim is a three-dimensional geometric model of the flow domain of the coronary arteries that consists of a family of ellipses. In each of the aforementioned points of intersection belonging to the centreline c^{3D} in three-dimensional space, we define normal planes n_i, $i=1...N$. Figure 4 shows such a normal plane.

We now combine:

- a pair of corresponding points with its two back projection rays,
- their point of intersection, and
- their normal plane

to form a group. As can be seen in Figure 4(b) and (c), we determine for each group in both projections several points lying on the edges which are in the vicinity of the aforementioned pair of corresponding points. From these selected points, we draw back projection rays and determine their points of intersection with the normal plane. We thus obtain four sequences of intersection points. As depicted in Figure 5, we define four interpolating spline curves c_{ij}, $j=1...4$, that pass through these four sequences of intersection points in the normal plane. We will call these spline curves intersection curves. As depicted in Figure 5, we then compute the best approximate ellipse in the normal plane by minimising the sum of the squares of the distances $d(-,-)$ between the intersection curves c_{ij} and the ellipse $ell_i(a_i,b_i,\alpha_i)$. The computation of this minimum is based on the numerical method of Hooke and Jeeves [Allen, 1971].

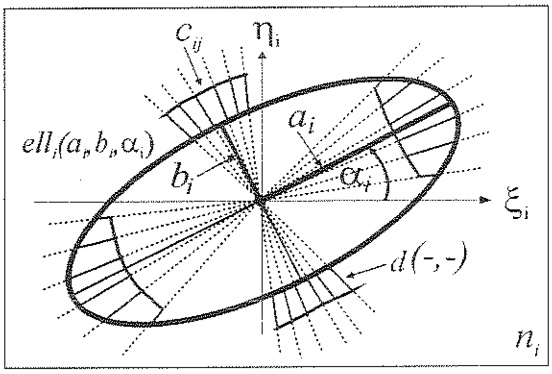

Figure 5. Calculation of the best approximate ellipse based on the principle of least squares.

3.5 Geometric Model of the Inner Surface of the Coronary Artery

We thus obtain a family of ellipses located on the normal planes of the three-dimensional centreline as an initial representation of the geometry of the inner surface of the section of the coronary artery represented (cf. Figure 6). This initial representation of the geometry is then extended by performing the following steps:

- On the perimeter of each ellipse of the family, we define four points that are located at the ends of the major and minor axes
- We construct four cubic interpolating spline curves that connect each defined point on the perimeter of each ellipse with the adjacent points on the successor and/or predecessor ellipse.

The combination of the aforementioned family of ellipses and these four interpolating spline curves constitutes our geometric model of the arterial section.

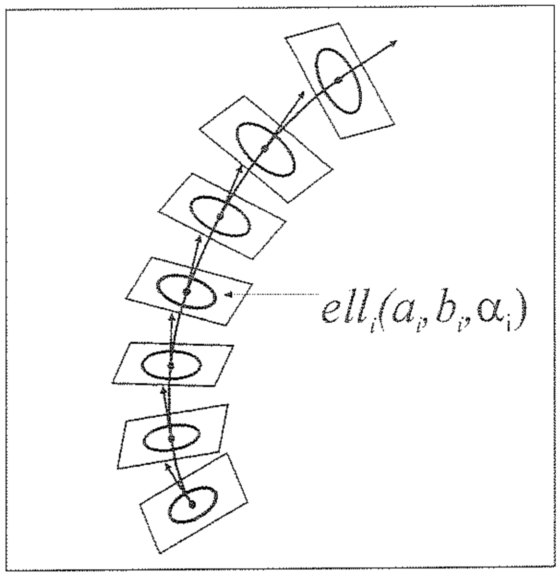

Figure 6. Initial geometric representation of the flow domain.

This geometric model serves:

- as the basis for the visualisation of the geometry of the coronary arteries by performing a triangulation and a rendering (cf. Figure 7) and
- as the basis for the simulation studies described in the companion paper [Quatember and Mühlthaler, 2001b].

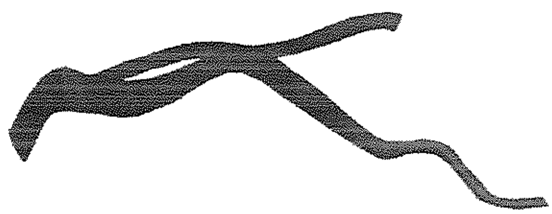

Figure 7. Visualisation of the geometric model.

4. IMPORTANCE OF THE NEWLY DEVELOPED RECONSTRUCTION METHOD TO COMPUTER SIMULATIONS OF THE CORONARY BLOOD FLOW

Our three-dimensional representation of the coronary arteries is necessary for patient-specific simulation studies of the three-dimensional flow of blood. We carry out simulations of this kind the finite element method and thus a mesh in the flow domain of the epicardial arteries. Our geometric model comprises a family of ellipses and is ideally suited to the generation of a high-quality mesh using the multi-block approach. The details of the mesh generation procedures and the simulation studies can be found in the companion paper [Quatember and Mühlthaler, 2001b].

5. CONCLUSIONS

In this paper, we dealt with an advanced method for the three-dimensional reconstruction of the epicardial arteries from biplane angiograms. Analyses of the results show that in terms of accuracy of the reconstruction procedures, our method is superior to other known methods for the three-dimensional reconstruction of the coronary arteries. The accuracy of our method is sufficiently high to permit clinically relevant patient-specific simulation studies of the three-dimensional blood flow, even in regions of the coronary arteries with disturbed flow. The wire frame model of geometry of the flow domain we obtain with our reconstruction method is well suited for the generation of the mesh that is a prerequisite for carrying out simulation studies of the coronary hemodynamics with the finite element method.

6. REFERENCES

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