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Cardiac Workstation and Dynamic Model to Assist in Coronary Tree Analysis

A dissertation submitted by **Ricardo Toledo Morales** at Universitat Autònoma de Barcelona to fulfil the degree of **Doctor en Informática**.

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Bellaterra, Barcelona
April 27, 2001.

Ricardo Toledo

Abstract

This thesis explores the issues involved in automatic coronary vessel analysis using deformable models and estimation algorithms. The work is carried out as a consequence of a previous international research and development project on multimedia and teleworking in medicine (radiology imaging). After developing and validating a multimedia workstation from a user perspective, the experience obtained showed the convenience to incorporate new computer vision tools to assist the physicians during the image assessment in the diagnostic process. The work presented is a part of a computer assisted diagnosis system within a telemedicine system.

Focusing on cardiac imaging, the first step is to adapt the workstation to such image modality, then the goal is to build a computerized coronary tree model, able to incorporate $3D$ static (anatomical) and dynamic (vessel movements) data. Such a model is useful to increase the knowledge necessary when dealing with a difficult image modality in computer vision, like coronary angiography. To build the model, many computer vision problems have to be addressed. From low level tasks as vessel detection up to high level ones like image understanding are necessarily covered. Mainly, deformable models (snakes) and estimation techniques are discussed and used with innovative ideas through the model building process. Ought to the tight dependence of the deformable models on the low level image feature detectors, new methods to learn the vessels based on statistical analysis and fine tune the detector are proposed increasing the segmentation confidence. A new statistical potential map is developed within a new energy minimizing scheme. Snakes are also applied in the $3D$ reconstruction process. A graph is designed and used to hold the knowledge of the complete model. The novel approach for vessel analysis and the final model were validated and the results are very encouraging.

Contents

Chapter 1

Introduction

This chapter consists of an introduction to the main subjects treated in this thesis. It starts with a description of the coronary heart disease, following by a survey of the computer technologies related to cardiac imaging and ends with a summary of the global objectives of the thesis.

1.1 Coronary heart disease

Coronary heart disease is one of the more extended and growing diseases in developed countries. The coronary arteries provide blood to the heart muscle (myocardium). Anatomically speaking, the arteries begin in the aorta and branch in two systems, the left and right coronary tree. When one or more segments are obstructed (total or partially) the blood is not able to flow and a portion of the myocardium is not correctly irrigated (fed). This is the beginning of a myocardium infarct. Figure 1.1 depicts a normal artery, a partially obstructed and a total blockage one. A powerful technique to help the assessment and treatment of the narrowing or stenosis is to image the coronary arteries with x-rays (figure 1.2). This technique has become indispensable nowadays as a tool in the coronary heart disease diagnosis and treatment. The coronary artery disease (stenosis) is, usually, assessed visually by the cardiologist. However, the increasing power of computers has provided a background to develop powerful, objective, accurate and reproducible techniques to measure the vessel lesions. Such tools are very important since it is widely known that inter and intraobserver variations of 15% or more are not exceptions among experts, resulting in serious limitation for long term expert evaluation of vessel lesions [90].

1.2 Computer technologies

The use of computers in medical imaging is becoming standard. All developments have occurred in the past 4 decades. In the $60s$, nuclear medicine was the first branch

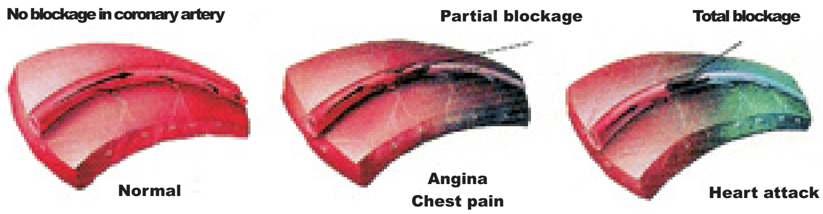

Figure 1.1: Obstruction in coronary arteries.

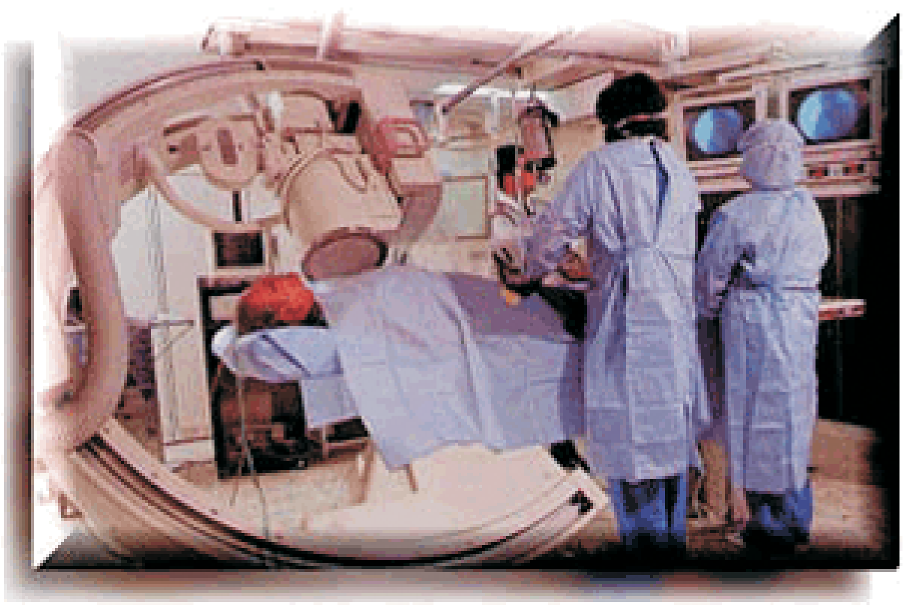

Figure 1.2: Angiographic system.

of radiology to use a computer to generate time-activity curves from a set of dynamic images. Computer Tomography (CT) and Digital Subtraction Angiography (DSA) were developed at the late 1960*s* and early 1970*s*. DSA was developed to improve angiograms by subtraction of the surrounding soft-tissue and bone information; computers were necessary to perform this operation. Initially, in DSA, an external computer was used to process images. The X-ray unit could be used without the computer. The basis of the CT unit, was the computer; without it, the CT unit could not be used. Single photon emission computed tomography was introduced in the late 1970*s* followed by magnetic resonance, both of which required a computer to control the equipment and reconstruct images.

In the 1970*s*, researchers started to attempt to transmit images to remote location for display. In the early 1980*s* a project based on the IBM 8086 family of PCs at the University of Kansas demonstrated that digital CT and ultrasound scans (US) could be [47]:

1. archived to disk or tape,
2. displayed, and
3. transmitted over ethernet.

The words Picture Archiving and Communication Systems (PACS) were presented in November 1981 by Samuel Dwyer III [47] as a seminar title addressed to graduated students in biomedical engineering in Iowa. This is the beginning of PACS research, coincident with an increasing introduction of digital imaging equipment into the hospital radiology departments.

Many works have been done in Europe and USA around the use of computer in medical imaging departments [58, 57]. PACS have evolved to solve common problems in the conventional medical image management systems. The new paradigm has a strong impact in the daily routine of any imaging department and, hence, its organizational impact is also subject of research.

For example, a PACS increases the availability of the images and has the potentiality to keep track of medical protocols in a clever way assuring a global better quality in the patient attention, that otherwise (without the computer) is very difficult to achieve.

Potential benefits, like an increasing time available for diagnostic activities has been demonstrated. From a technological point of view, there are enough to manage a whole digital image department. The bottleneck of digital images has been overcome. There is a leverage in price/performance convenient for the system development.

This market was relatively new, and in the competitive environment, equipment manufacturers were reluctant to disclose information about their data formats or to provide access to digital data. It soon became apparent that standards were needed to facilitate the connection of equipment from different manufacturers for acquisition, storage, processing and printing of digital image data.

Nowadays, computer and communication technologies are growing at incredible speed, increasing performance with parallel decreasing in prices. Information technology has rapidly increased in its presence and impact on our daily lives. The increasing capabilities of digital computers, the expansion of larger and faster computer networks, and the decreasing cost of these technologies, have brought many consequences.

The number of people with access to information resources has increased exponentially, applications such as teleworking, e-commerce, and the ease of electronic communication have had a significant impact throughout the world. There is a serious promise of improving our working and living environments, and changing the way we communicate and interact. New research fields that few years ago should have been only of theoretical scope have today clear application feasibility.

Recognising the potential for growth and the strategic importance of this industry, in 1994 the European Commission embarked on the Fourth Framework Programme for Research and Technological Development (RTD). This initiative was designed to encourage the development of technologies, which help both to improve the quality of life in Europe and to increase her industrial competitiveness. Among the activities of this programme there are specific actions aimed at information and communication technologies applied to biomedicine and healthcare. Within this sector, work aims to enable the entire sector to benefit from access to telematics services. Focusing on computers and radiology, the technology is able to provide important advantages. Using the computer as a mean to organize image and patient information improves the systematic treatment necessary when dealing with the increasing complexity of the diagnostic means available nowadays.

Covering fields such as:

- the multimedia patient record, with particular emphasis on medical images.
- the development of telematics applications that increase the resources available to medical practitioners for purposes of diagnosis, treatment and health service management.
- telemedicine, with the objective of providing isolated patients with adequate care.
- the provision of information to health workers and citizens concerning the prevention and identification of the major serious diseases.

The expected results, among others, are [57, 47]:

- avoiding the lost of images and data;
- speeding up the availability of images;
- minimizing the need of repeating the study minimizing the radiation of the patient;
- improved storage and management of patient records;
- availability of experts everywhere.

1.2.1 Telecardiology

Using computers to exchange medical images and related data through a communication network and related tasks is globally known as TeleRadiology. When the image modality is coronary angiography, we speak, more specifically, about TeleCardiology.

An added value of telemedicine systems is the potential computer assisted diagnosis capability. To this aim, there is an increasing development of computer image processing and analysis techniques applied to medical images. Such techniques try to help assisting the physicians in the image interpretation tasks.

1.3 Objectives

Addressing the goals of the healthcare telematics applications framework, this thesis presents both a telemedicine contribution and a computer vision contribution.

- Telemedicine: the software design and implementation of a medical image handling system for remote communication of x-ray angiographic images and,
- Computer vision: an approach for building a $3D$ model of the coronary tree, part of a computer assisted diagnostic tool, for the medical imaging system.

1.3.1 Telemedicine contribution. Cardiac Workstation

Our workstation provides facilities for electronically transferring diagnostic images and related identifying and administrative data between two hospitals together with an advanced computer assisted diagnostic tool able to help the cardiologist in their diagnostic and therapy planning tasks. This scenario is applicable to many situations where patients are referred from one hospital where diagnostic images have been obtained, to a second institution where therapeutic interventions or surgery are to be performed. Communication facilities may also be used in response to a patient referral, where post-interventional images may be transferred back to the referring physician who is ultimately responsible for the follow-up and ongoing patient care (meanwhile, the computer vision tool is aimed to assist in the image assessment step). To support this type of electronic image referral, an analysis of the telematics needs of clinical angiographic imaging applications was performed, and a software design and implementation was carried out. The first objective of this development is to provide a mechanism that cardiologists may use to facilitate patient referrals, and to validate this software system in a clinical environment. The workstation has to be an open system. The current standard in digital imaging and communication in medicine (DICOM) is assumed and supported. An object-oriented approach is used to build the workstation software, leading to a very flexible and easy to extend architecture. The intrinsic architecture of the software was designed to be open for the future development and incorporation of computer assisted diagnosis modules.

The workstation was developed and validated under the umbrella of the TeleRegions SUN project. This work has been carried out with the co-operation of two hospitals in our region and with the technical assistance of two research groups - one in our region and the second one in the region of Lombardy, Italy.

The project entitled TeleRegions SUN was funded by the European Commission within the Fourth Framework. The development of this system was carried out as part of the contribution of the Computer Vision Centre as a partner. Meanwhile another project was started to develop a new PC based workstation funded by the EU and called TeleRegions SUN2 - TeleApplications for European Regions (IA 1010 (UR)).

This process brought evidence about the needs of tools to assist the cardiologist in the image diagnostic task.

Once the system was validated, the second goal was defined as a consequence of the validation by experts: need of computer-assisted diagnostic tools was detected. In order to provide a computer assisted diagnostic module a computer model of the coronary arteries was considered necessary. The main reason for building a coronary model arises from the complexity of the image modality regarding computer anaysis. Developing and integrating tools for computer assisted diagnosis in angiography image sequences have a lot of expected benefits. The $3D$ model is considered a base to built such tools. Knowledge of the $3D$ structure and geometry of the tree could be used to increment the reliability of the vessel detection algorithms. Choosing the best frame for quantitative analysis from a sequence is very time consuming for a cardiologist; a Computer Assisted Diagnosis (CAD) tool could do this automatically. After the automatic detection of the best frame, it is easy to develop a data compression schema where the frames with the most relevant diagnostic data is lossless compressed while the rest of the sequence is lossy compressed. This would result in a high rate of compression keeping the diagnostic relevant data intact. Moreover, the model could offer an optimal estimation for projection parameters of the image acquisition system.

1.3.2 Computer Vision contribution. Coronary Tree Model

The main research effort is directed toward the automatic assessment of the coronary tree from an angiography image sequence. A $3D$ model of the coronary arteries is formulated as the main component at the base of the computer assisted diagnostic tool. The model is aimed to facilitate the automation of the angiography image analysis. A generic $3D$ model of the coronary tree includes static and dynamic features. Such a model shall be like a semantic network (graph), able to hold both, anatomical and dynamic knowledge about an average generic coronary tree. The model (network) must keep adaptive characteristics both in anatomical structures and dynamic features.

The combination of computer vision techniques, motion estimation algorithms and deformable models make possible to build a complete adaptive model of the coronary tree. The model allows to help in the computer assisted analysis of coronary angiography sequences.

Dynamics characteristics of the coronary tree can be systematically assessed bringing more possibilities of clinical research. For example, one can measure velocity, acceleration either as a time function or regarding the shape of an artery branch and compare between normal arteries and stenotic ones.

Any Computer Assisted Diagnostic tool involving computer image analysis need to solve many different problems. From low level image processing up to high level tasks regarding global image understanding. A CAD can be considered as a complex system. On the other hand, modeling is an old discipline used successfully to cope with complex systems. Models help in the solution in many different ways. In the case of computer analysis of angiographic image sequences, a model is necessary to cope with the inherent complexity and difficulties commented in 1.1.

The remainder of this thesis is organized as follows: chapter 2 gives a background about digital cardiac imaging and deals with the state of the art of computer vision algorithms applied to angiography imaging. Chapter 3 focuses on the methods we have used as a starting base for the vessel reconstruction, tracking and modeling using angiography image sequences. Chapter 4 offers a careful explanation of the telemedicine contribution: the analysis, design and implementation of a cardiac workstation within a telecardiology environment. We focus mainly on the intrinsic features of cardiac imaging and the current standards, because the workstation is obtained through a customization of a workstation already developed by the author for general radiology imaging. Chapter 5 is devoted to our computer vision contribution: the building of the coronary model. Using deformable models as a global framework, new methods for vessel segmentation, $3D$ reconstruction and tracking are discussed followed by the description of the graph data structure holding the coronary model data. Chapter 6 describes the validation of our approach for angiography analysis results. Finally the conclusions and future work is formulated in chapter 7.

1.4 Summary

This chapter has offered a brief summary of the coronary heart disease and introduced the role of computer technologies. Then, the objectives of the thesis has been enumerated. The chapter ends with a brief description of the following chapters of the thesis.

Chapter 2

Computer vision applied to angiography imaging: State of the art

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The chapter begins with a section dedicated to a background on coronary arteries and digital angiography, emphasizing the advantages of digital imaging (against the older analog equipment). The section continues with a brief description of research activities related to computer analysis applied to angiography imaging. Then, the state of the art in typical computer vision systems applied to coronary angiography is surveyed. This section follows a bottom-up approach from low-level image processing up to higher levels of image understanding techniques.

2.1 Background Cardiac Imaging

2.1.1 Coronary arteries

Coronary arteries are a vascular system irrigating the myocardium. The system is named, globally as coronary arteries and is split in two parts, right coronary artery and left coronary arteries according to their location in the heart (fig. 2.1). The left coronary artery is further split in three subsystems known as left main, anterior descending and circumflex. The names refer to main branches, but all of them have a set of minor branches, like septals and diagonals in the anterior descendant. The anatomy of the coronary arteries has some variations. One can distinguish three main anatomies, depending on the relationship between the circumflex and the right coronary artery regarding the irrigation of the posterior part of the heart. This is called the dominance. Therefore, there are:

- right dominance (RCA dominant) when the posterior part of the heart is fed by the right coronary artery and its minor branches (figure 2.1(a)),

- left dominance (LCA dominant) when the irrigation is covered by the circumflex (figure 2.1(b)), and
- balanced when both the circumflex and the right coronary arteries share the responsibility (figure 2.1(c)).

Figure 2.1 depicts besides the nomenclature as proposed by Dodge et al. in [32, 33]. The coronary tree model proposed in this thesis uses this nomenclature and supports the anatomies proposed by Dodge.

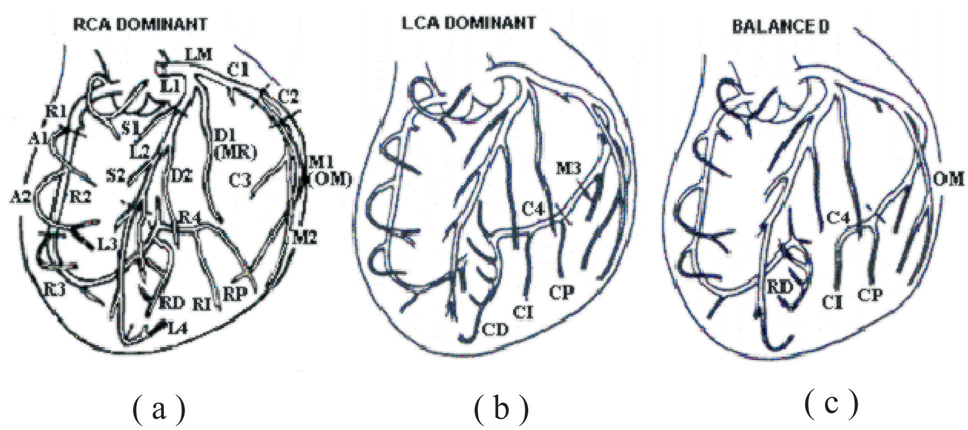


Figure 2.1: Dominance and nomenclature. LAD comprises L1, L2, L3 and L4. For the RCA dominant case LCx comprises C1, C2, C3 while RCA comprises R1, R2, R3, R4, RD, RI and RP.

The four major branches of the coronary arteries are:

1. Left main artery (LM).
2. Left anterior descendent artery (LAD).
3. Left circumflex artery (LCx).
4. Right coronary artery (RCA).

Although coronary anatomy tends to be somewhat more variable than Figure 2.1 suggests, it is possible in every case to specify segments that corresponded approximately to these standard ones.

In most cases, these segments are easy to locate, and this is extended to all cases for any major branch. The left main artery (LM) has a single segment. The left anterior descending coronary artery (LAD) is separated into four segments (Figure 2.1) defined by its origin from the LM, the first septal perforator artery (SI), the third septal perforator artery (S3, not labeled in Figure 2.1), the cardiac apex, and its terminal point on the inferior wall. S3 commonly arises near the bend of the LAD in Right Anterior Oblique (RAO) views and often is near the origin of the second diagonal. These landmarks may serve as alternative markers. If none of these is identified, the L2-L3 transition is defined as halfway from SI to the cardiac apex. Branches of the LAD included the three largest septal branches (SI-S3) and the three largest diagonal branches (DI- D3). A median ramus (MR) branch could be present as an anatomic variant arising at the trifurcation of the LM. Due to the variable nature of the branches that originate at or very near the bifurcation of the LM, the angiographer must decide whether a given case is best classified as a first diagonal (DI), first marginal (M 1) or, if intermediate between the two, as an MR. The left circumflex artery (LCx), with a right dominant anatomy, is divided into three parts (C1- C3) by the first and second marginal branches (MI and M2). In this case, the atrioventricular groove continuation of the LCx (C3) is usually small. With a balanced anatomic distribution, the LCx has a fourth segment (C4) distal to the origin of the posterior wall branch (CP) and gives rise to an inferior wall branch (C1). With a left dominant anatomy, the LCx also gives rise to the posterior descending artery (CD). In five cases, a large obtuse marginal branch (OM) served as a variant of MI and M2. A third marginal (M3) is usually small and is often absent. The right coronary artery, with a right dominant anatomy, is divided into four parts between its origin, the first acute marginal branch (Al), the third acute marginal branch (A3), the posterior descending branch (RD), and the origin of the posterior wall branch (RP). An inferior wall branch (R1) is also specified. In the case of a balanced anatomy, only the RD arises from the RCA to supply the inferior septum of the LV. With a left dominant anatomy, the inferior wall vessels arise from the LCx, as describes above.

Digital Cardiac Angiographic Imaging

Cardiac angiography is a type of angiographic imaging in which a contrast dye is injected through a hollow catheter directly into the coronary arteries (coronary arteriography), or into one of the lower heart chambers (ventriculography) (figure 2.2(a)). Since x-ray absorption by blood is low, it is necessary to inject an iodine contrast dye to enhance the contrast of the vessels. Therefore, images of this type are produced by injecting an x-ray absorbing dye into a target vessel, while simultaneously acquiring a sequence of x-ray images.

Regarding acquisition devices, detailed studies have been done related to geometric distortion correction and calibration by Reiber et al. [87]. In this thesis the projection geometry, contrast, temporal medium, temporal sampling and data synchronization during the image acquisition are considered fixed.

A brief description of acquisition devices is surveyed focusing on the projection angles in this chapter and on the communication interface to the computer (in chapter 4). Any other view of such devices is out of the scope of this thesis.

Figure 2.2 (b) shows the angiography image formation components. It explains the determinants of intensity fluctuations or image noise observed in a pixel of a digital image. A region of the camera target corresponding to a pixel receives a number of X-ray quanta that increases with tube voltage and current, the pulse width of the X-ray pulse, the conversion factor of the image intensifier, and the f-stop (iris) of the optical system. The f-stop is the only variable parameter in this chain. It can be used to vary the proportion between the mean brightness and the standard deviation (SD) of the

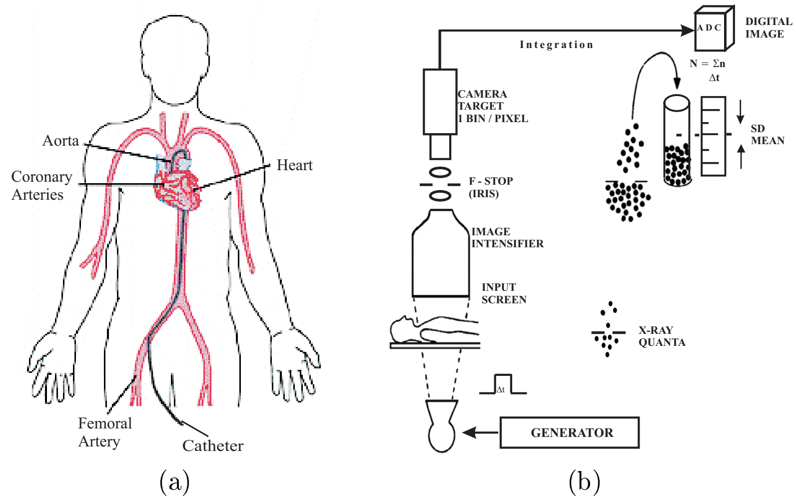
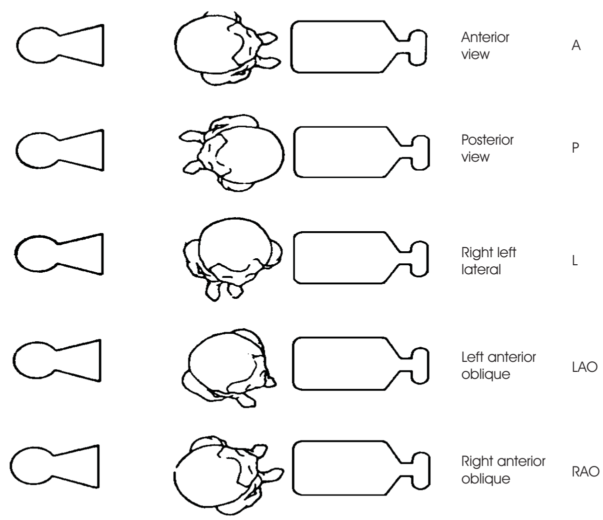


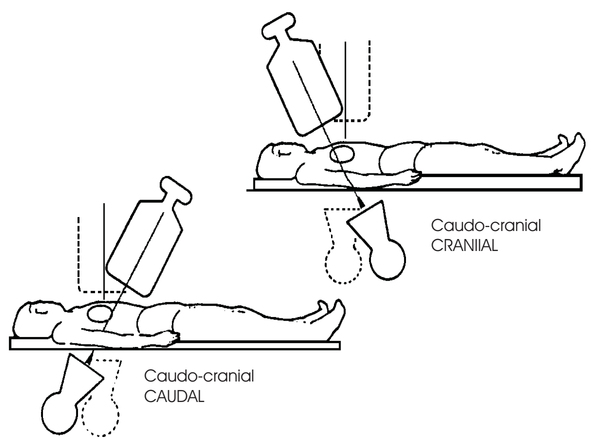
Figure 2.2: Catheter path (a) and Angiographic system components (b).

mean (i.e., the image noise). Angiography, like fluoroscopy, differs from conventional x-ray imaging techniques due to the fact that the x-ray absorbing material is in motion while the images are being acquired. In a conventional x-ray image, the body part being examined may be immobilised - a patient may be asked to hold still or to stop breathing, but requesting that a patient stop his or her heart is usually met with considerable resistance. These techniques pose additional complications to image visualisation, since the vessel structure itself is in motion as the contrast dye is being injected. Cardiovascular imaging therefore poses a significant technical challenge to the acquisition of x-ray images of sufficiently high resolution to visualise the coronary arteries, at a frame rate fast enough to capture the motion of the heart. Fortunately, the recent advances in information technology, which have been evolving in the computer industry, have also had a significant impact on cardiovascular image acquisition systems. These technologies have made digital acquisition, processing and archival image storage a reality. In the field of cardiac catheterisation, this has led to the feasibility of real-time digital acquisition of x-ray angiographic image sequences, on-line analytical image processing features, and immediate review of acquired image runs. In the rush toward digital cardiac angiography however, several compatibility issues were raised.

Figures 2.3 and 2.4 explain the nomenclature for radiographic projections. The small block arrowheads show the direction of the x-ray beam. Figure 2.3(a), shows anterior, posterior, lateral and oblique projections. If the intensifier is tilted toward the feet of the patient, a caudal view is produced. If the intensifier is tilted toward the head of the patient, a cranial view is produced (figure 2.3 (b)). Figure 2.4(c) shows cranial and caudal oblique views together with the angles conventions.

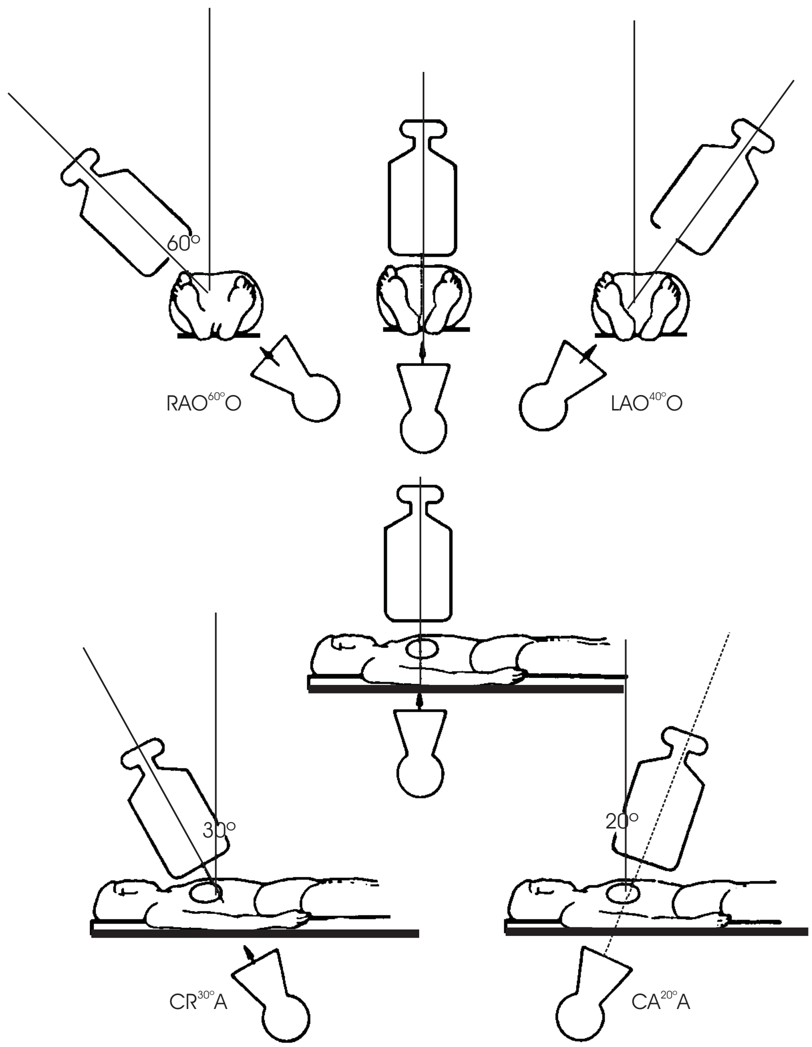


(a)



(b)

Figure 2.3: Nomenclature for angiography: rotation (a), angulation (b).



(c)

Figure 2.4: Nomenclature for angiography: angles reference system.

Figures 2.5 to 2.11 depicts the usual projection parameters and the expected artery views. Figures 2.5 to 2.9, left coronary artery. Figures 2.10 and 2.11, right coronary artery [53].

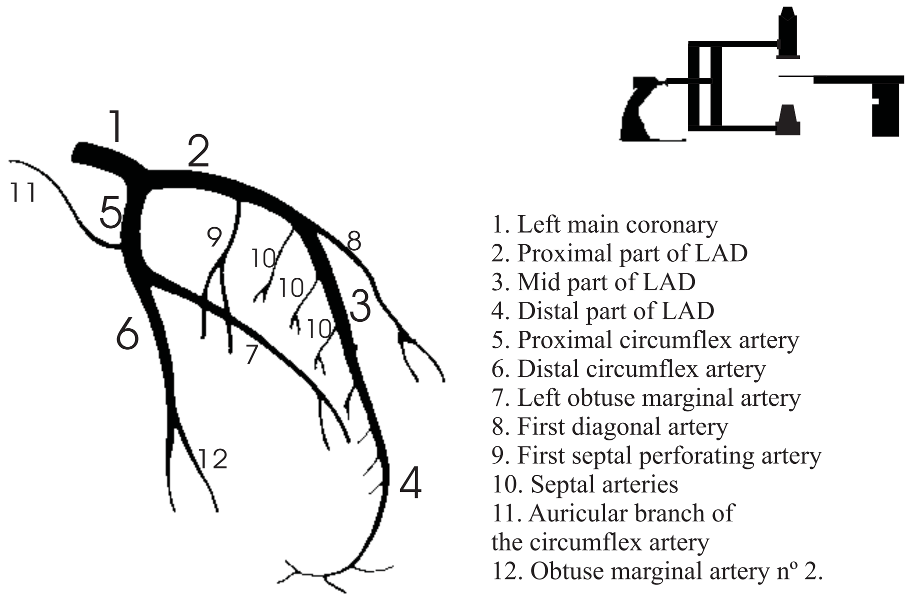


Figure 2.5: Anteroposterior projection (A-P). The A-P projection allows a good visualization of the left main coronary artery.

Digital versus analog angiography

Prior to the introduction of digital cardiac angiographic systems, the standard practice in this field was to record acquired images onto videotape for review during the catheterisation procedure and onto 35-mm cinefilm for subsequent off-line diagnosis. The image quality of the video tape recordings, however, was not sufficient for diagnosis, and only served to ensure that the acquired images had been recorded with adequate content and framing. In the early $1980^{'}$s, technological solutions became available to develop the first digital-acquisition systems for cardiac x-ray angiography. These systems introduced an analogue to digital conversion process to digitise the video signal, which had previously been used by the video tape recorder for in-room viewing. To permit digital acquisition, a system must be able to handle a massive amount of incoming data. A typical exam, consisting of 3000 image frames digitised to a matrix size of 512 x 512 pixels of 8 bits (256 grey levels) at a frame rate of 30 frames per second, requires a storage capacity of 750 megabytes (MB), and a transfer rate of 7.5 MB/s. When these digital acquisition systems were first introduced, large, high-speed hard disks were available which were capable of storing a sufficient amount of information to contain a single patient study. However, until recently, the massive data capacity required to store angiographic image data for long-term archival

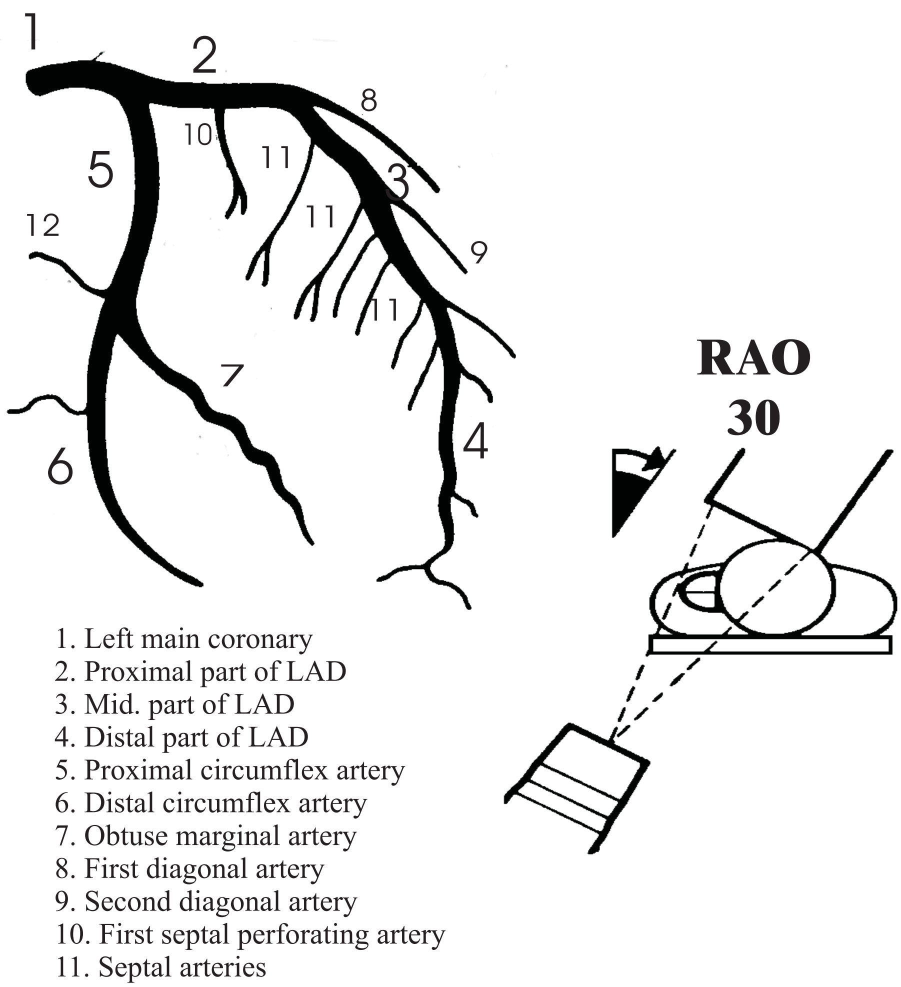


Figure 2.6: Right Anterior Oblique projection at 30° (R.A.O.30°). The RAO projection at 30° permits the entire circumflex system to be studied, as well as the first centimetres of the anterior interventricular artery.

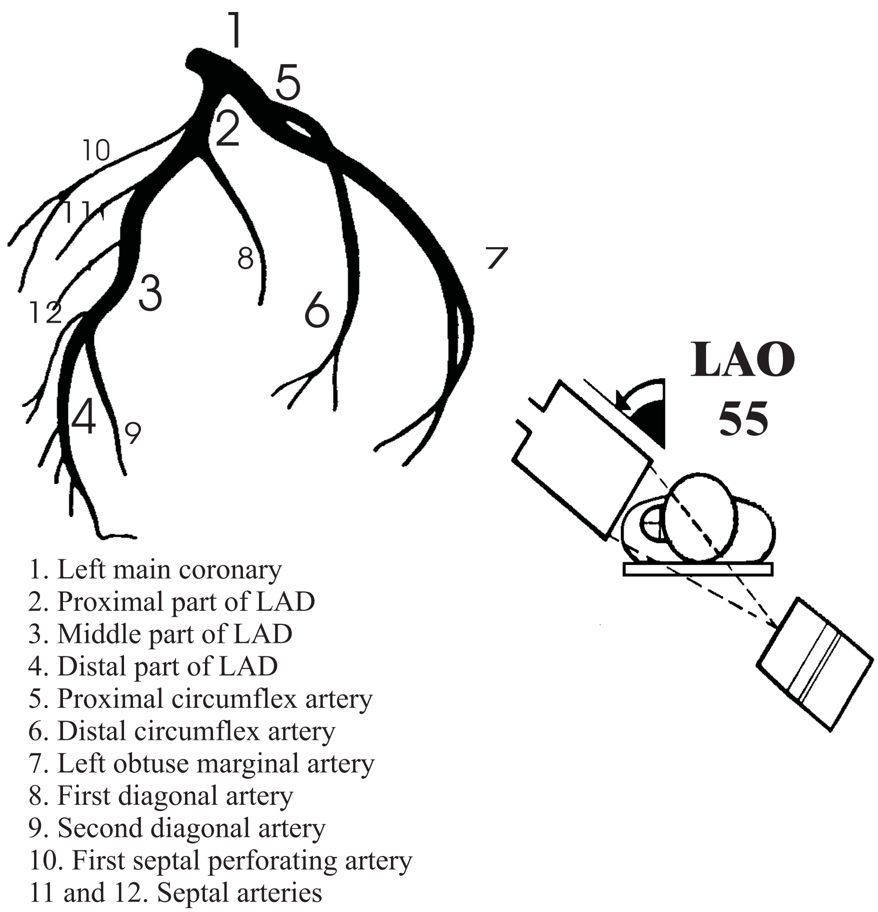


Figure 2.7: Left Anterior Oblique projection at 55°/60° (L.A.O. 55°/60°). The LAO projection at 55°/60° mainly studies the diagonal arteries and the mid and distal part of the LAD. On the other hand, the circumflex system is not well defined.

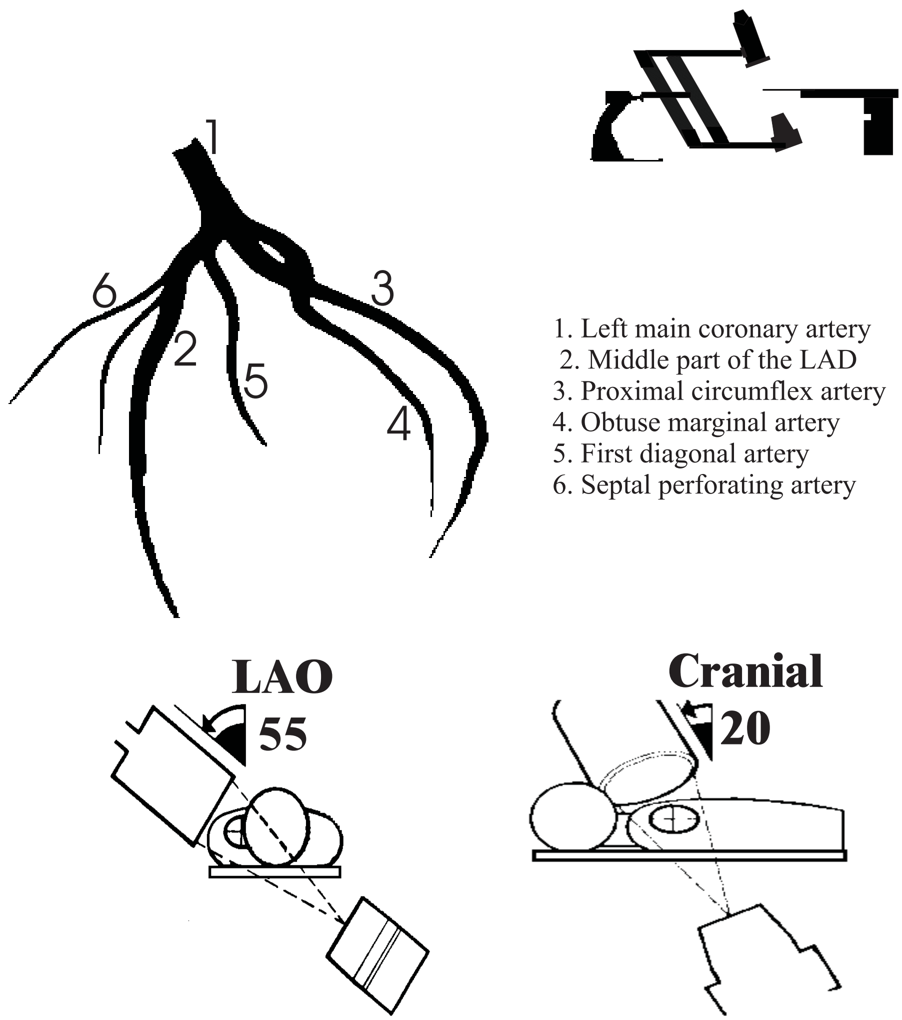
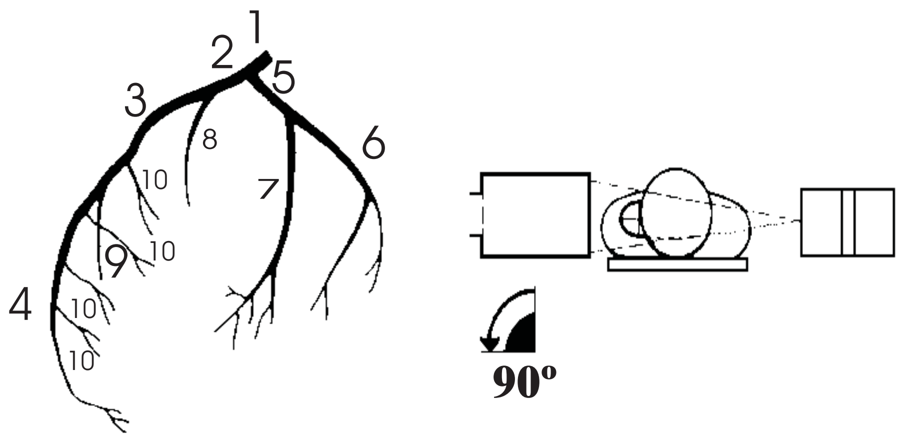
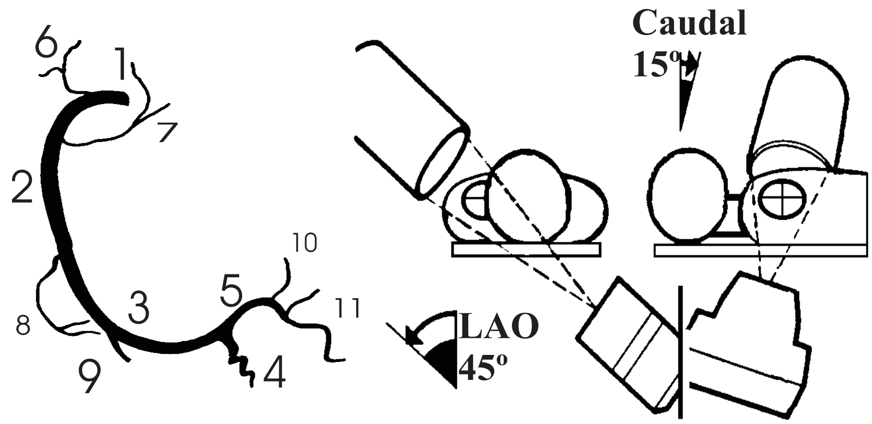


Figure 2.8: Left Anterior Oblique projection at 55° combined with a Cranial Angulation of 20°. The cranial angulation of 20° combined with the LAO projection at 55°/60° is especially useful to study the left main coronary artery.



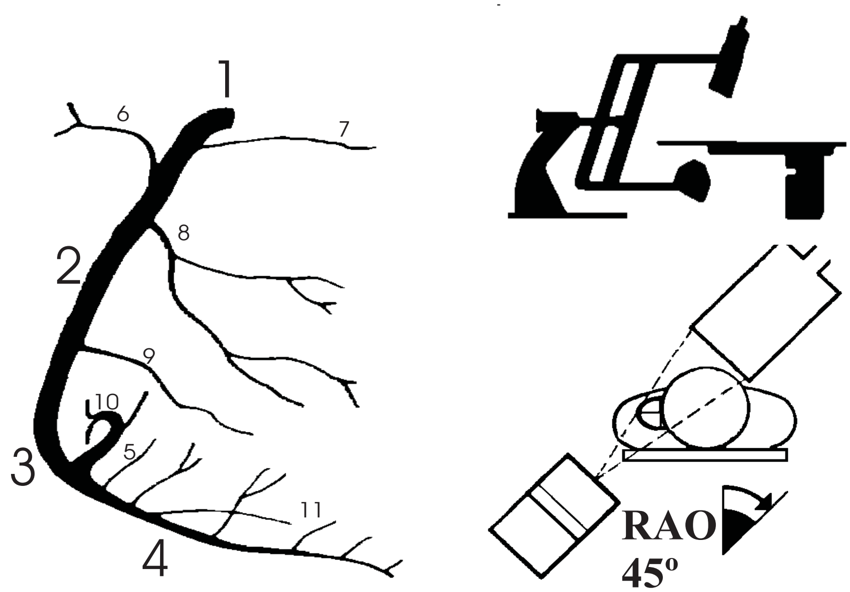
1. Left main coronary artery
2. Proximal part of LAD
3. Middle part of LAD
4. Distal part of LAD
5. Proximal circumflex artery
6. Distal circumflex artery
7. Obtuse marginal artery
8. First diagonal artery
9. Second diagonal artery
10. Septal arteries
11. Obtuse marginal artery no 2.

Figure 2.9: Left Lateral projection. The left lateral projection, allows the study of the different segments of the anterior interventricular artery, the first diagonal artery and the left marginal artery.



1. First (horizontal) segment of the right coronary artery
2. Second (vertical) segment of the right coronary artery
3. Third (horizontal) segment of the right coronary artery
4. Posterior interventricular
5. Retroventricular artery
6. Conus branch
7. Artery of the sinus, node
8. Right ventricular artery
9. Right marginal artery
10. Artery of the A-V node
11. Diaphragmatic artery

Figure 2.10: Left Anterior Oblique projection at 45° combined with a Caudal Angulation of 15°. This projection allows the whole study of the RCA and, specially, clearly defines the region of the crux of the heart.



1. First (horizontal) segment of the right coronary artery
2. Second (vertical) segment of the right coronary artery
3. Third (horizontal) segment of the right coronary artery
4. Posterior interventricular artery
5. Retroventricular artery
6. Conus branch
7. Artery of the sinus node
8. Right ventricular artery
9. Right rnarginal artery
10. Artery of the A-V node
11. Inferior septal arteries

Figure 2.11: Right Aanterior Oblique projection at 45°. The RAO projection at 45° permits the survey of the second (vertical) segment of the right coronary artery, the posterior interventricular artery and the collateral branches (right ventricular and right marginal arteries). On the other hand, the first segment and the third segment as well as the retroventricular artery are not clearly defined. This projection also allows the visualization of the retrograde reopacification of the distal part of the LAD proximally occluded.