INTRAOPERATIVE CORONARY BLOOD FLOW AND MYOCARDIAL PERFUSION IMAGING METHOD BY MEANS OF THERMAL IMAGE PROCESSING

by

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ABSTRACT

INTRAOPERATIVE CORONARY BLOOD FLOW AND MYOCARDIAL PERFUSION IMAGING METHOD BY MEANS OF THERMAL IMAGE PROCESSING

One of the most popular surgical operations is coronary artery by-pass grafting (CABG) operation, since coronary arterial disease is one of the leading causes of death and the main surgical treatment modality for this disease is the CABG operation. The main complication of the CABG operation is graft failure in either an early or late manner. While late graft failure is usually due to progression of the underlying disease, early graft failure can be caused by technical mistakes during manipulation of the heart and at the level of anastomoses. The evaluation of the graft flow and perfusion by means of thermal image processing may be a method to detect the graft failures during the operation. The method is based on the small temperature gradient that is produced by the inflow of blood into the graft and can be detected using an infrared scanner. This method is a non-invasive method that requires no catheter insertion, ionizing radiation or contrast material usage. It allows demonstrate graft patency of venous and arterial grafts and allows evaluation of perfusion after revascularization. It is also helpful detect distal stenoses in native coronary arteries. In summary, this method may be a valuable tool for intraoperative quality control in coronary artery bypass graft procedures and helps to minimize the risk of postoperative complications following myocardial revascularization.

Keywords: Angiography, Coronary, Imaging, Thermal, Infrared.

ÖZET

TERMAL GÖRÜNTÜLEME KULLANILARAK İNTRAOPERATİF KORONER KAN AKIMI VE MİYOKARDİAL PERFÜZYON GÖRÜNTÜLEME YÖNTEMİ

Günümüzde, en sık ölüm nedenlerinden birinin koroner arter hastalığı olması ve bu hastalığı önde gelen cerrahi tedavisinin koroner arter by-pass (CABG) ameliyatı olması sebebiyle bu ameliyat en sık uygulanan ameliyatlardan biridir. CABG ameliyatının en önemli komplikasyonlarından biri greft yetmezliğidir. Greft yetmezliği, erken ve geç olmak üzere iki şekilde olabilir. Geç greft yetmezligi çoğunlukla koroner arter hastalığının nüks ederek yeniden ilerlemesi ile olurken, erken greft yetmezliği çogunlukla anastomoz tekniğindeki veya ameliyattaki manipülasyona bağlı diğer hatalar nedeniyle meydana gelmektedir. Greftin sağladığı kan akımını ve perfüzyonu termal görüntü işleme yöntemi ile saptayarak greft yetmezliği tespit edilebilir. Burada yöntem, greftin kan taşıması beklenen myokard bölgesi ile greftten verilen sıvının sıcaklıkları arasındaki farktan dolayı oluşan görüntüyü termal kamera ile gözlemleyerek bu görüntünün işlenmesi prensibine dayanmaktadır. Yöntem, hastaya ekstra bir kateter uygulanması, kontrast madde verilmesi ve iyonize edici radyasyon uygulanmasını gerektirmemesi sebebiyle non-invazif (hastaya zarar vermeyen) bir yöntemdir. Yöntem ile, venöz ve arteriyel greftlerin yeterliliği, sağladıkları akım ve perfüzyon değerlendirilebilir. Ayrıca, koroner damarların uzantılarındaki darlıklar da belirlenebilir. Özetle, bu metod, CABG ameliyatı yordamının kalitesini değerlendirmek ve ameliyat sonrası komplikasyon oluşma riskini en aza indirmek için değerli bir yöntem olarak belirtilebilir.

Anahtar Sözcükler: Anjiyografi, Görüntüleme, Kızılaltı, Koroner, Termal.

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Tl^{201}	Thallium isotope with mass number 201
Tc^{99m}	Technetium isotope with mass number 99

LIST OF ABBREVIATIONS

CABG	Coronary Artery Bypass Grafting
LAD	Left Anterior Descending Artery of the Heart
CX	Circumflex Artery of the Heart
RCA	Right Coronary Artery of the Heart
MRI	Magnetic Resonance Imaging
ASL	Arterial Spin Labeling
IR	Infrared
SPECT	Single Photon Emmission Computed Tomography
PET	Positron Emmission Tomography
NIR	Near Infrared
FIR	Far Infrared
SWIR	Short Wave Infrared
MWIR	Medium Wave Infrared
LWIR	Long Wave Infrared
fps	Frames Per Second
TVL	Tenth Value Layer
DITI	Digital Infrared Thermal Imaging
EMG	Electromyography
GUI	Graphical User Interface
TCA	Thermal Coronary Angiography

1. INTRODUCTION

Cardiac diseases are the several of the major causes of death in the industrialized world. Cardiovascular disease is the leading cause of death in the western world, especially in the developed countries. Coronary artery disease, mainly due to atherosclerosis of the coronary arteries, not only stands for one of the most popular and budget consuming cardiac disease in the adult, but also is one of the most frequent causes of mortality.

Coronary artery bypass grafting (CABG) is the major surgical treatment modality of coronary artery disease. The major problem that surgeons encounter during and after the operation is anastomosis insufficiency (failure of the blood flow through the suture point of the graft to the native artery) and myocardial hypoperfusion either due to anastomosis insufficiency or due to graft spasm. This problem leads to highly hazardous complications of the surgical procedure, such as perioperative myocardial infarction which has a remarkably high mortality rate. To prevent the occurrence of myocardial hypoperfusion, the surgeon has to check the flow through the graft and the perfusion through myocardium (the muscular tissue of the heart) supplied by the graft, with an objective method. In this study, it will be proposed that the perfusion supplied by the graft can be evaluated quantitatively by using a thermal image processing procedure.

Perfusion is a physiological term that refers to the process of nutritive delivery of arterial blood to a capillary bed in the biological tissue. MRI is the gold standard imaging technique to measure the perfusion of any organ. Two main categories of functional magnetic resonance imaging (MRI) techniques can be used to measure tissue perfusion in vivo. The first is based on the use of injected contrast agent that changes the magnetic susceptibility of blood and thereby the MR signal which is repeatedly measured during bolus passage. The other category is based on arterial spin labeling (ASL) where arterial blood is magnetically tagged before it enters into the tissue of interest and the amount of labeling is measured and compared to a control recording obtained without spin labeling.

There are several methods of coronary perfusion such as scintigraphic methods Tl^{201}, Tc^{99m} myocardial scintillation scan and SPECT, PET and recently, MRI perfusion imaging methods. None of these methods are possible to apply during the operation because of their application techniques and conditions. The only way, currently, to quantitatively assess the myocardial perfusion is by means of thermal imaging.

2. BACKGROUND

2.1 Some Facts About Thermal Imaging

Infrared radiation is electromagnetic radiation of a wavelength longer than visible light, but shorter than microwave radiation. The name means "below red" (from the Latin *infra*, "below"), red being the color of visible light of longest wavelength. Infrared radiation spans three orders of magnitude and has wavelengths between 700 nm and 1 mm.

The Earth's surface absorbs visible radiation from the sun and re-emits much of the energy as infrared back to the atmosphere. Certain gases in the atmosphere, chiefly water vapor, absorb this infrared, and re-radiate it in all directions including back to Earth. This, the greenhouse effect, keeps the atmosphere and surface much warmer than if the infrared absorbers were absent from the atmosphere.

2.1.1 Different Regions in the Infrared

IR is often subdivided into:

- Near infrared NIR, IR-A DIN, 0.7-1.4 μm in wavelength, defined by the water absorption, and commonly used in fiber optic telecommunication because of the low attenuation losses in the SiO2 glass medium.
- Short wavelength IR SWIR, IR-B DIN, 1.4-3 μm Water absorption increases significantly at 1450 nm
- Mid wavelength IR MWIR, IR-C DIN, also intermediate-IR (IIR), 3-8 μm
- Long wavelength IR LWIR, IR-C DIN, 8-15 μm

- Far infrared FIR, 15-1000 μm

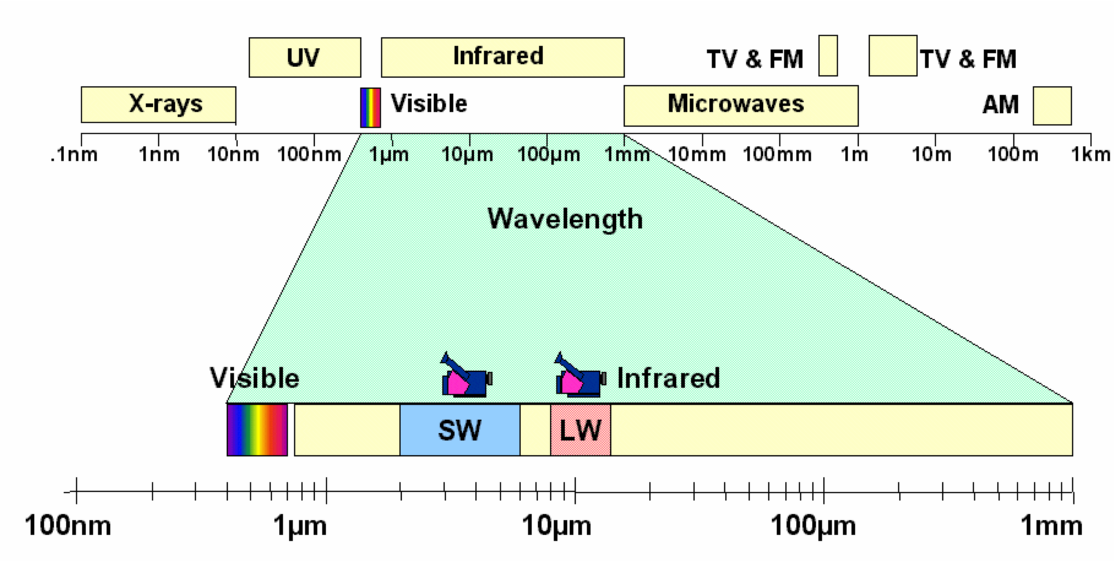

Figure 2.1 The chart of electromagnetic spectrum illustrating the electromagnetic waves by classifying them due to their wavelengths.

However, these terms are not precise, and are used differently in various studies i.e. near (0.7-5 μm) / mid (5-30 μm) / long (30-1000 μm). Especially at the telecom-wavelengths the spectrum is further subdivided into individual bands, due to limitations of detectors, amplifiers and sources. Infrared radiation is often linked to heat, since objects at room temperature or above will emit radiation mostly concentrated in the mid-infrared band (see black body). The common nomenclature is justified by the different human response to this radiation (near infrared = the red you just cannot see, far IR = thermal radiation), other definitions follow different physical mechanisms (emission peaks, vs. bands, water absorption) and the newest follow technical reasons (The common Si-detectors are sensitive to nearly 1050 nm, while InGaAs sensitivity starts around 950 nm and ends between 1700 and 2200 nm, depending on the specific configuration). Unfortunately the international standards for this specifications are not freely available [1].

2.1.2 Telecommunication bands in the infrared

Optical telecommunication in the near infrared is technically often separated to different frequency bands because of availability of light sources, transmitting /absorbing materials and detectors.

- O-Band 1260-1360 nm
- E-band 1360-1460 nm
- S-band 1460-1530 nm
- C-band 1530-1565 nm
- L-band 1565-1625 nm
- U-band 1625-1675 nm

2.1.3 History

The ancient Egyptians moved their hands across the surface of the body to scan and monitor changes in temperature. The fingers acted as sensors and the brain interpreted the relevant changes. They could effectively evaluate the rise in temperature over a period of time. It could be isolated to a specific area, or determined that there was a general increase over the entire body.

The Greek Physician, Hippocrates, wrote in 400 B.C. "In whatever part of the body excess of heat or cold is felt, the disease is there to be discovered." The ancient Greeks immersed the body in wet mud. The area that dried more quickly indicated a warmer region, and was considered the diseased tissue.

Heat is a property of the body. Temperature refers to a certain standard of reference. The use of hands to measure heat emanating from the body remained well into the sixteenth and seventeenth centuries. It wasn't until Galileo, who made a thermoscope from a glass tube, that some form of temperature sensing device was developed, but it did not have a scale. It was the work of Fahrenheit, who fixed a lower point by using salt with ice water and ranged to boiling water at 212 degrees. Celsius, in 1742, created a decimal scale, using "zero" as the boiling point of water and 100 as the freezing point. His scale was reversed by the Swedish botanist Linnaeus. Increasing heat was indicated by higher temperatures. Prof. Carl Wunderlich of Leipzig in 1868 advanced the use of thermometry in medicine with the first set of temperature charts on individual patients with a wide range of diseases. He proposed the design of the present day clinical thermometer, which is now slowly being replaced by disposable sterile thermocouples and radiometers for middle ear temperature.

The use of liquid crystals became another method of displaying skin temperature. Cholesteric esters can have the property of changing color with temperature, and this was established by Lehmann in 1877. The practical application involved the use of elaborate panels that encapsulated the crystals and were applied to the surface of the skin, but due to a large area of contact, they affected the temperature of the skin.

All the above methods for measuring human body temperature are contact methods. The major advances of the last 30 years have been with infrared thermal imaging.The surface of the human body is a highly efficient radiator and it is possible to detect the infrared emission from the skin, and create a thermal map of temperature distribution by remote sensing.

In 1800 the English astronomer William Herschel held a mercury thermometer in the spectrum produced by a glass prism to measure the heat content of different colored lights. He found that the thermometer registered an increase in temperature even when held beyond the red end of the spectrum, where there was no visible light. This was the first experiment to show that heat could be transmitted by an invisible form of light.

2.1.4 Common Applications

Infrared is used in night-vision equipment, when there is insufficient visible light to see an object. The radiation is detected and turned into an image on a screen, hotter objects showing up brighter, enabling the police and military to chase targets.

Smoke is more transparent to infrared than to visible light, so fire fighters use infrared imaging equipment when working in smoke-filled areas. Fire fighters also use this equipment in wood-frame buildings after a fire has been extinguished to look for hot spots behind the walls, where a fire can break out again.

In the fields of building maintenance and property management, IR can be a cost saving tool when used to image various building components and equipment. IR thermography is a type of photography that measures temperature differences in the IR range. This is useful when looking for equipment "hot-spots" or scanning the exterior or roof of a building looking for heat loss.

A more common use of IR is in television remote controls. In this case it is used in preference to radio waves because it does not interfere with other devices in adjoining rooms - this is especially important in areas of high population density (IR does not penetrate walls). IR data transmission is also employed in short-range communication among computer peripherals and personal digital assistants. These devices usually conform to standards published by IrDA, the Infrared Data Association. Remote controls and IrDA devices use infrared light-emitting diodes (LEDs) to emit infrared radiation which is focused by a plastic lens into a narrow beam. The beam is modulated, i.e. switched on and off, to encode the data. The receiver uses a silicon photodiode to convert the infrared radiation to an electric current. It responds only to the rapidly pulsing signal created by the transmitter, and filters out slowly changing infrared radiation from ambient light.

In Infrared photography, infrared filters are used to capture only the infrared spectrum. Digital cameras also often employ infrared blockers.

Medical applications of infrared are uncommon for the time being, but it will be more common in the future.

Medical DITI (Digital Infrared Thermal Imaging) is a noninvasive diagnostic technique that allows the examiner to visualize and quantify changes in skin surface temperature. An infrared scanning device is used to convert infrared radiation emitted from the skin surface into electrical impulses that are visualized in color on a monitor. This visual image graphically maps the body temperature and is referred to as a thermogram. The spectrum of colours indicates an increase or decrease in the amount of infrared radiation being emitted from the body surface. Since there is a high degree of thermal symmetry in the normal body, subtle abnormal temperature asymmetry's can be easily identified.

Medical DITI's major clinical value is in its high sensitivity to pathology in the vascular, muscular, neural and skeletal systems and as such can contribute to the pathogenesis and diagnosis made by the clinician.

Medical DITI has been used extensively in human medicine in the U.S.A., Europe and Asia for the past 20 years. Until now, cumbersome equipment has hampered its diagnostic and economic viability. Current state of the art PC based IR technology designed specifically for clinical application has changed all this.

Common clinical uses for DITI include;

- To define the extent of a lesion of which a diagnosis has previously been made;
- To localize an abnormal area not previously identified, so further diagnostic tests can be performed;
- To detect early lesions before they are clinically evident;

- To monitor the healing process before the patient is returned to work or training.

Skin blood flow is under the control of the sympathetic nervous system. In normal people there is a symmetrical dermal pattern which is consistent and reproducible for any individual. This is recorded in precise detail with a temperature sensitivity of 0.1°C by DITI.

The neuro-thermography application of DITI measures the somatic component of the sympathetic nervous system by assessing dermal blood flow. The sympathetic nervous system is stimulated at the same anatomical location as its sensory counterpart and produces a 'somato sympathetic response'. The somato sympathetic response appears on DITI as a localised area of altered temperature with specific features for each anatomical lesion.

The mean temperature differential in peripheral nerve injury is 1.5°C. In sympathetic dysfunction's, temperature differentials ranging from 1° C to 10° C depending on severity are not uncommon. Rheumatological processes generally appear as 'hot areas' with increased temperature patterns. The pathology is generally an inflammatory process, i.e. synovitis of joints and tendon sheaths, epicondylitis, capsular and muscle injuries, etc.

Both hot and cold responses may coexist if the pain associated with an inflammatory focus excites an increase in sympathetic activity. Also, vascular conditions are readily demonstrated by DITI including Raynauds, Vasculitis, Limb Ischemia, DVT, etc.

- Medical DITI is filling the gap in clinical diagnosis
- X-ray, C.T. Ultrasound and M.R.I. etc., are tests of anatomy.
- E.M.G. is a test of motor physiology.

DITI is unique in its capability to show physiological change and metabolic processes. It has also proven to be a very useful complementary procedure to other diagnostic modalities.

Unlike most diagnostic modalities DITI is non invasive. It is a very sensitive and reliable means of graphically mapping and displaying skin surface temperature. With DITI you can diagnosis, evaluate, monitor and document a large number of injuries and conditions, including soft tissue injuries and sensory/autonomic nerve fibre dysfunction.

Medical DITI can offer considerable financial savings by avoiding the need for more expensive investigations.

Medical DITI can graphically display the very subjective feeling of pain by objectively displaying the changes in skin surface temperature that accompany pain states.

Medical DITI can show a combined effect of the autonomic nervous system and the vascular system, down to capillary dysfunctions. The effects of these changes show as asymmetry's in temperature distribution on the surface of the body.

Medical DITI is a monitor of thermal abnormalities present in a number of diseases and physical injuries. It is used as an aid for diagnosis and prognosis, as well as therapy follow up and rehabilitation monitoring, within clinical fields that include Rheumatology, neurology, physiotherapy, sports medicine, oncology, pediatrics, orthopedics and many others.

Results obtained with medical DITI systems are totally objective and show excellent correlation with other diagnostic tests.

In this study, which is a very uncommon and recent era, medical thermography directly on the heart is performed. By performing the thermography of the heart, blood flow of the coronary arteries and perfusion through the myocardium can be assessed.

2.2 Other Methods Proposed to Assess Coronary Flow During the Operation

- Intraoperative Angioscopy
- High Frequency Epicardial Echocardiography
- Transit-time Ultrasonic Flow Measurements
- Intravascular Ultrasound
- Electromagnetic Flow Measurements

2.3 Methods of Imaging the Perfusion of the Heart

- Magnetic Resonance Imaging
- Positron Emmission Tomography
- Scintigraphy

2.4 Anatomy of the Coronary Arteries

The right and left coronary arteries originate behind their respective aortic valvar leaflets. The orifices usually are located in the upper third of the sinuses of Valsalva, although individual hearts may vary markedly. Because of the oblique plane of the aortic valve, the orifice of the left coronary artery is superior and posterior to that of the right coronary artery. The coronary arterial tree is divided into three segments; two (the left anterior descending artery and the circumflex artery) arise from a common stem. The third segment is the right coronary artery. The dominance of the coronary circulation (right versus left) usually refers to the artery from which the posterior descending artery originates, not the absolute mass of myocardium perfused by the left or right coronary artery. Right dominance occurs in 85% to 90% of normal individuals. Left dominance occurs slightly more frequently in males than females. See figure 2.2.

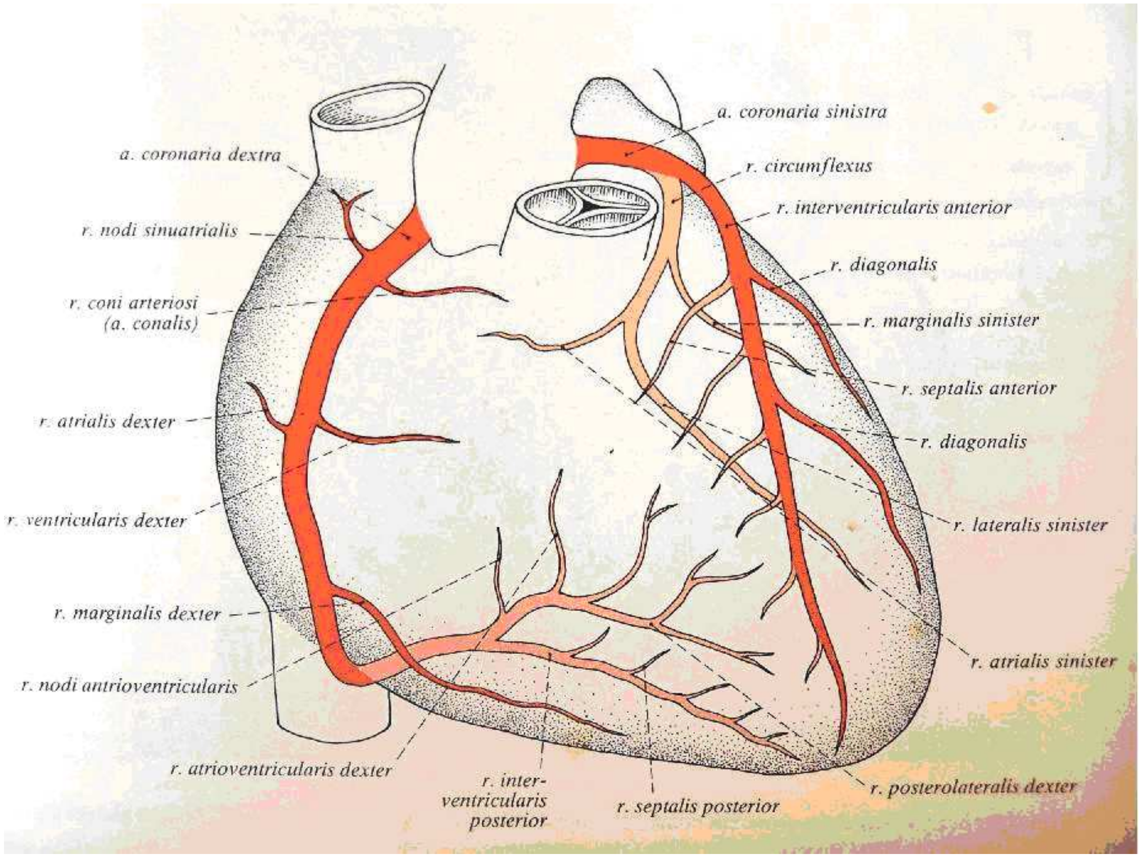

Figure 2.2 Anteroposterior view of the coronary arteries.

2.4.1 The Main Stem of the Left Coronary Artery

The main stem of the left coronary artery courses from the left sinus of Valsalva anteriorly, inferiorly, and to the left between the pulmonary trunk and the left atrial appendage. Typically it is 10 to 20 mm in length but can extend to a length of 40 mm. The left main stem can be absent, with separate orifices in the sinus of Valsalva for its two primary branches (1% of patients). The main stem divides into two major arteries of nearly equal diameter: the left anterior descending artery and the circumflex artery.

2.4.2 Left Anterior Descending Artery

The left anterior descending (or interventricular) coronary artery continues directly from the bifurcation of the left main stem, coursing anteriorly and inferiorly in the anterior interventricular groove to the apex of the heart. Its branches include the diagonals, the septal perforators, and the right ventricular branches. The diagonals, which may be two to six in number, course along the anterolateral wall of the left ventricle and supply this portion of the myocardium. The first diagonal generally is the largest and may arise from the bifurcation of the left main stem (formerly known as the intermediate artery). The septal perforators branch perpendicularly into the ventricular septum. Typically there are three to five septal perforators; the initial one is the largest and commonly originates just beyond the takeoff of the first diagonal. This perpendicular orientation is a useful marker for identification of the left anterior descending artery on coronary angiograms. The septal perforators supply blood to the anterior two thirds of the ventricular septum. Right ventricular branches, which may not always be present, supply blood to the anterior surface of the right ventricle. In approximately 4% of hearts, the left anterior descending artery bifurcates proximally and continues as two parallel vessels of approximately equal size down the anterior interventricular groove. Occasionally, the artery wraps around the apex of the left ventricle to feed the distal portion of the posterior interventricular groove. Rarely, it extends along the entire length of the posterior groove to replace the posterior descending artery.

2.4.3 Circumflex Artery

The left circumflex coronary artery arises from the left main coronary artery roughly at a right angle to the anterior interventricular branch. It courses along the left atrioventricular groove and, in 85% to 95% of patients, terminates near the obtuse margin of the left ventricle. In 10% to 15% of patients, it continues around the atrioventricular groove to the crux of the heart to give rise to the posterior descending artery. The primary branches of the left circumflex coronary artery are the obtuse

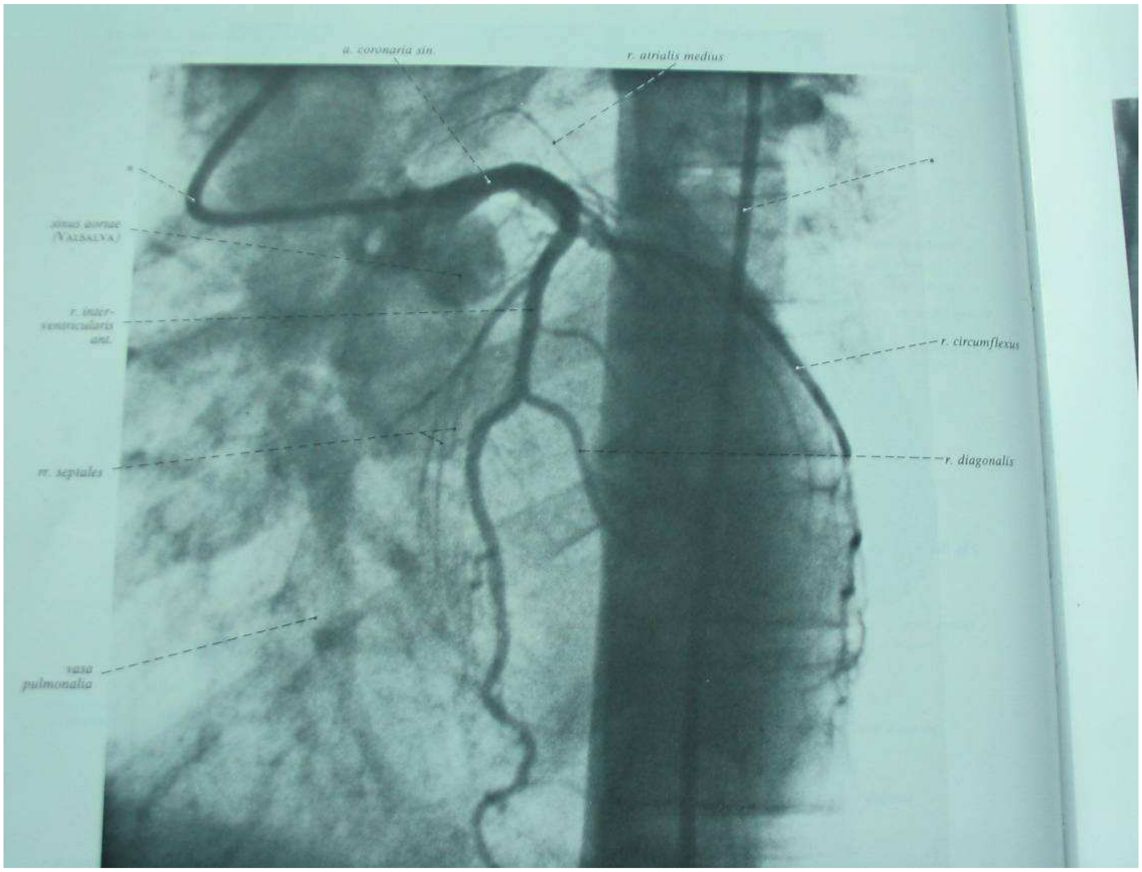

Figure 2.3 A conventional angiography view of the left coronary artery system of the heart.

marginals. They supply blood to the lateral aspect of the left ventricular myocardium, including the posteromedial papillary muscle. Additional branches supply blood to the left atrium and, in 40% to 50% of hearts, the sinus node. When the circumflex coronary artery supplies the posterior descending artery, it also supplies the atrioventricular node.

2.4.4 Right Coronary Artery

The right coronary artery courses from the aorta anteriorly and laterally before descending in the right atrioventricular groove and curving posteriorly at the acute margin of the right ventricle. In 85% to 90% of hearts, the right coronary artery crosses the crux, where it makes a characteristic U-turn before bifurcating into the posterior

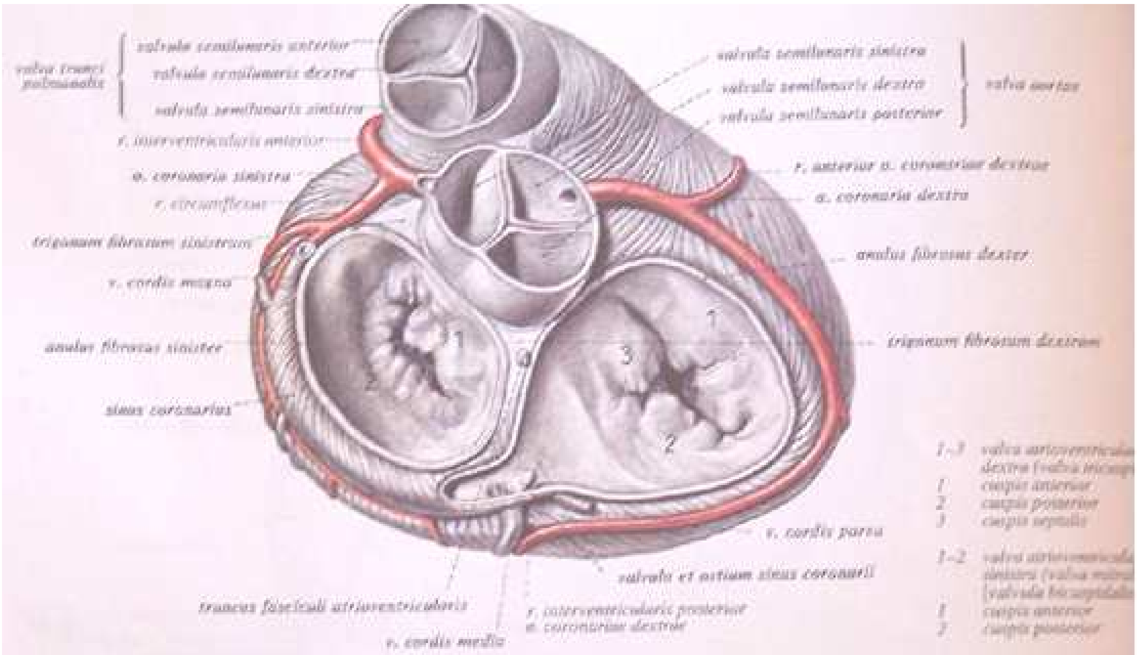

Figure 2.4 Craniocaudal view of the heart demonstrating coronary arteries.

descending artery and the right posterolateral artery. In 50% to 60% of hearts, the artery to the sinus node arises from the proximal portion of the right coronary artery. The blood supply to the atrioventricular node (in patients with right dominant circulation) arises from the midportion of the U-shaped segment. The posterior descending artery runs along the posterior interventricular groove, extending for a variable distance toward the apex of the heart. It gives off perpendicular branches, the posterior septal perforators, that course anteriorly in the ventricular septum. Typically, these perforators supply the posterior one third of the ventricular septal myocardium. The right posterolateral artery gives rise to a variable number of branches that supply the posterior surface of the left ventricle. The circulation of the posteroinferior portion of the left ventricular myocardium is quitevariable. It may consist of branches of the right coronary artery, the circumflex artery, or both.

The acute marginal arteries branch from the right coronary artery along the acute margin of the heart, before its bifurcation at the crux. These marginals supply the anterior free wall of the right ventricle. In 10% to 20% of hearts, one of these acute marginal arteries courses across the diaphragmatic surface of the right ventricle

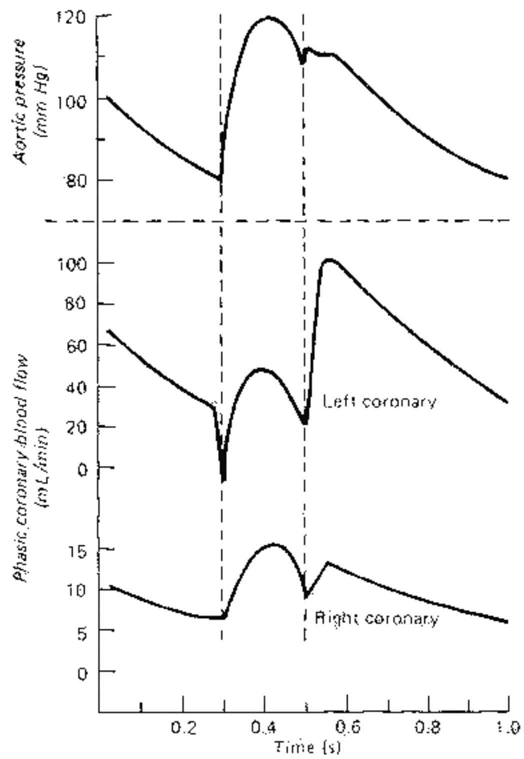

Figure 2.5 Blood flow of the coronary arteries with respect to time.

to reach the distal ventricular septum. The right coronary artery supplies important collaterals to the left anterior descending artery through its septal perforators. In addition, its infundibular (or conus) branch, which arises from the proximal portion of the right coronary artery, courses anteriorly over the base of the ventricular infundibulum and may serve as a collateral to the anterior descending artery. Kugel's artery is an anastomotic vessel between the proximal right coronary and the circumflex coronary artery that can also provide a branch that runs through the base of the atrial septum to the crux of the heart, where it supplies collateral circulation to the atrioventricular node.

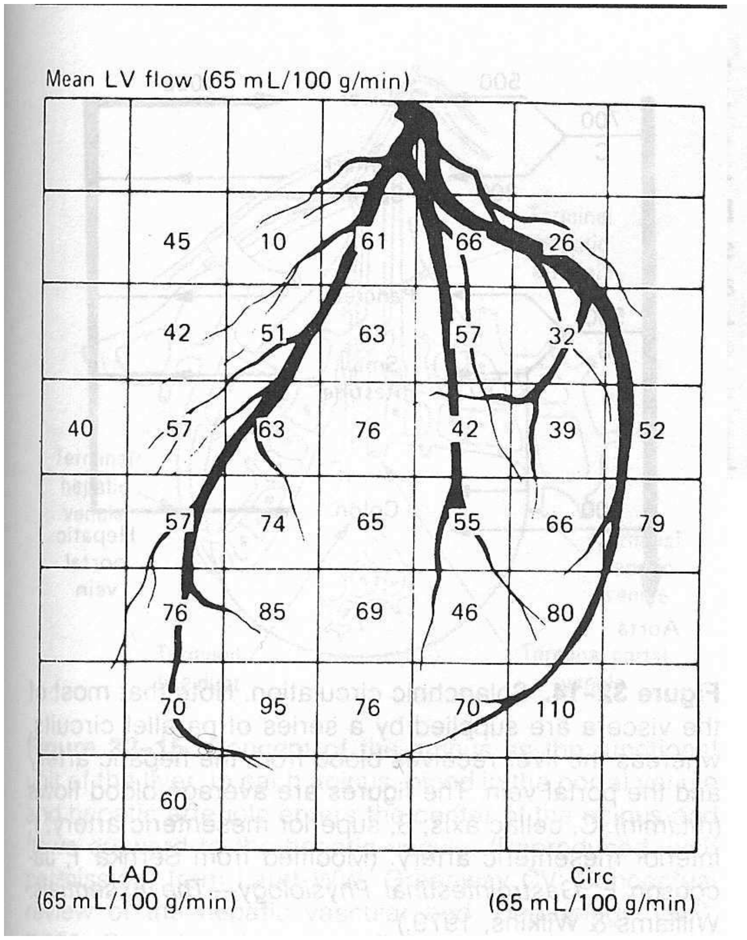

Figure 2.6 Perfusion diagram of the segments of the heart.

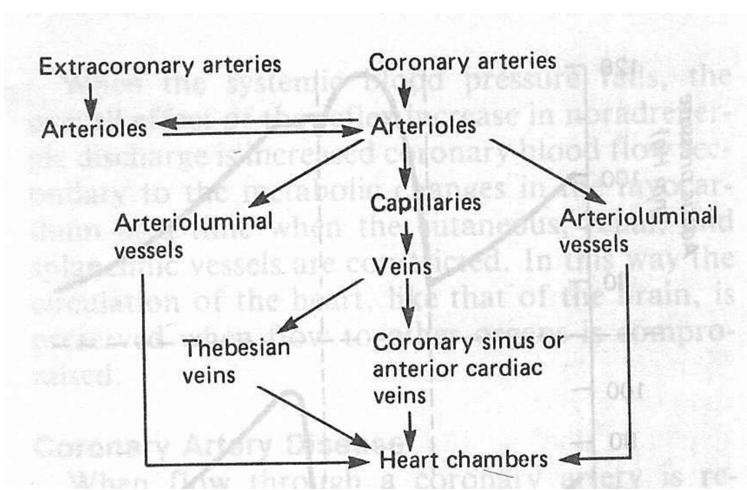

Figure 2.7 Diagram illustrating the coronary circulation.

3. MOTIVATION

As mentioned in the previous chapters, graft failure is one of the major consequences of CABG operation. Perioperative myocardial infarction, which is a frequent and catastrophic complication of CABG surgery, occurs due to graft failure.

Despite the evolution of surgical techniques, coronary artery bypass graft surgery is complicated by early and late graft failure. While late graft failure is usually due to progession of the underlying disease, early graft failure can be caused by technical mistakes at the level of anastomoses. Thermal Coronary Angiography (TCA) has been developed to detect intraoperative graft failures. The method is based on the small temperature gradient that is produced by the inflow of blood into the graft and can be detected using an infrared scanner. TCA is a non-invasive method that requires no ionizing radiation or contrast documents. It allows to demoinstrate graft patency of venous and arterial grafts and allows evaluation of perfusion after revascularization. It is also helpful detect distal stenoses in native coronary arteries. With the development of total endoscopic coronary arery bypass graft procedures using robotic assistance endoscopic TCA may proof to be a valuable tool for quality control in an endoscopic setting. Its value in the field of pediatric cardiac surgery for congenital disease involving reimplantation of coronaries needs yet to be explored.

An early failure rate as high as of 5 % for arterial and 15 % for saphenous vein grafts following coronary artery bypass graft (CABG) surgery has been reported in angiographic studies. Early graft occlusion that may lead to myocardial ischemia wilh catastrophic consequences is often due to technical problems at the level of the distal coronary anastomosis. Using intraoperative angioscopy, high frequency epicardial echocardiography and transit-time ultrasonic flow measurements it has been shown that graft failure can be detected intraoperatively. However, none of these methods combines information on morphology and perfusion. Thermal Coronary Angiography (TCA) was developed as a non-invasive method that provides an anatomical picture of the native coronary vascular bed and allows evaluation of myocardial perfusiori following a revascularization procedure.

Perioperative myocardial infarction has an incidence is around 3-7 % and mortality around 10-15 %. Since thermal imaging is proposed as the most suitable method to examine the coronary circulation during the operation among others, this catastrophic and frequent complication should be prevented via thermography.

The method is designed to give results in minutes during the operation. So, due to the importance of consuming time during the cross clamp period (the period that the systemic outflow of the heart, aorta, is clamped), a method which gives results in a very short time compared to others is strongly favourable.

In summary, TCA is a valuable tool for intraoperative quality control in coronary artery bypass graft procedures and helps to minimize the risk of postoperative complications following myocardial revascularization.

4. THE EQUIPMENT

Since thermal imaging increases its importance and diversity in medical applications, several varieties of thermal imaging equipment on many areas of medicine and surgery became avalilable on the market. A few of these are specifically designed for imaging of the heart. The OPGAL IVA 2000, which is the one used in this study, is one of these.

A computer is coupled with this camera via a capture card. The GUI, which is the essence of this study, is run to process the image on the computer to obtain the data.

The video image obtained from the camera is captured by the Avermedia PCMCIA Capture Card. The captured video image is separated into bitmap picture files in order for the GUI to process and calculate the necessary data. The GUI is developed on MATLAB environment, which is specifically prepared for the calculations and display of the results.

4.1 The IVA 2000 Thermal Scanner

The thermal camera, which is produced by a company in Israel, is designed for thermal imaging of the heart. It is a compact design optimized for operating room usage.

4.1.1 Technical Specifications

- Wavelength Range: 8-12 microns (LWIR)
- FOV: 4.50 Horizontal, 3.40 Vertical (Aspect Ratio:4/3)

- Maximum net thermal sensitivity: 0.10^oC
- Operative distance range (Rc): 0.3 - 1.2 meters
- Highest resolution is about 0.3 mm if Rc=0.8 m
- Required MRTD (Mean Resolvable Temperature Difference) : 200 TVL (Tenth Value Layer) for DT=50^oC and 100 TVL for DT=30^oC [2]

4.2 The Capture Card

The capture card is a PCMCIA card for laptop computers which acquires analog video input and converts to digital video formats.

- Technical Specifications:
  - Max frame resolution 720x576 pixels
  - Max temporal resolution 30 fps
  - Max color depth 16 bits
  - Composite, S-Video and RF inputs
  - Capture in AVI, MPEG, VCD, SVCD and DVD formats
- Additional software Virtual Dub 1.3c to seperate the captured AVI or MPEG image to frames as BMP's

4.3 The GUI

In order to interpret the data, the GUI with an easy to use layout developed on MATLAB environment.

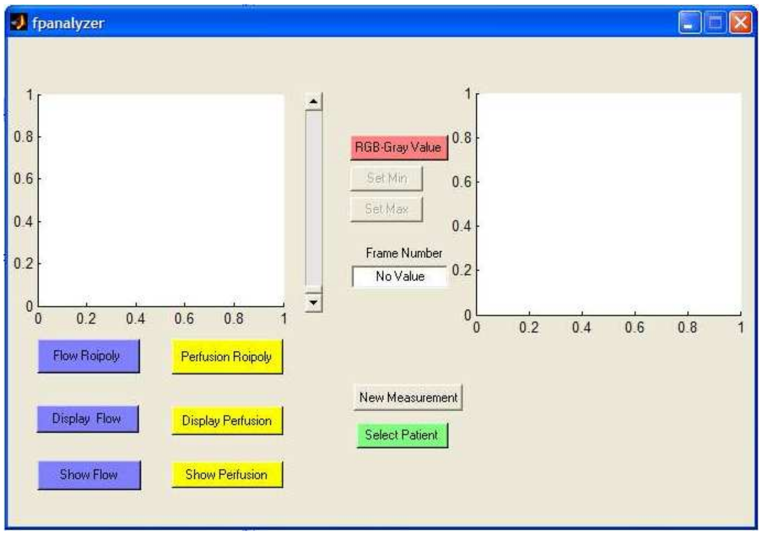

Figure 4.1 The appearance of GUI just after execution.

The first step of usage of the GUI is to select the patient. Selection is made from previously converted images to bitmap via Virtualdub software. These bitmap pictures are put in a folder for each sequence captured from a patient. After selection of the patient, the first bitmap appears on the left side of the GUI.

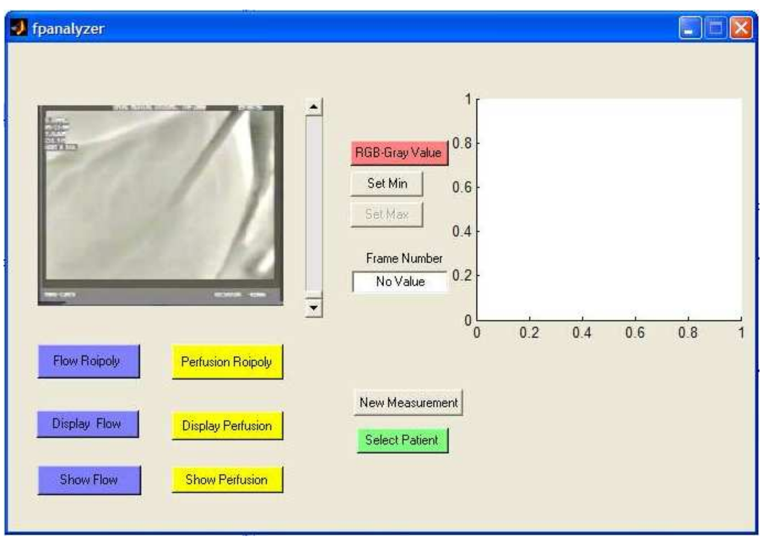

Figure 4.2 The appearance of GUI just after patient selection.

The second step is to select the image interval which is most suitable to perform the measurement on. To do this, the user moves the image with up and down scroll keys and see the sequence. User must select the interval just after the infusion and with least movement.

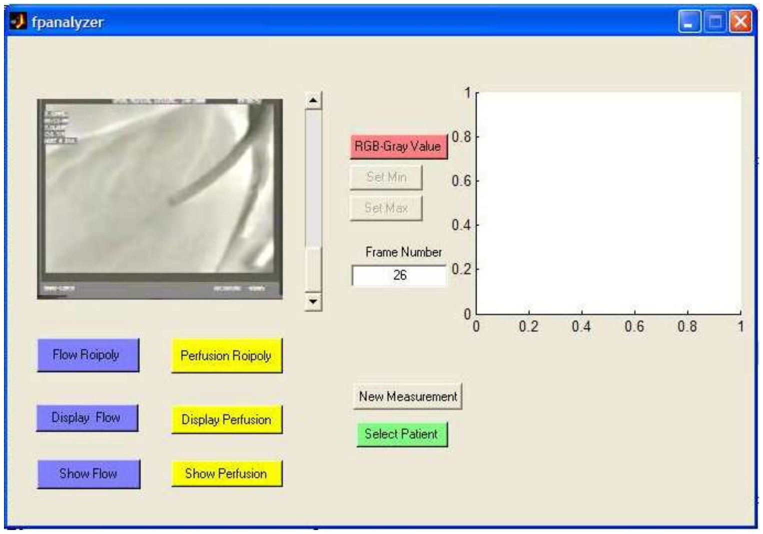

Figure 4.3 Selection of the interval eliminates the other bitmaps and displays only the selected interval.

For the third step, the user decides to measure or display the flow or perfusion. He defines either a rectangular ROI (for flow measurement) or a polygon ROI with any shape (for perfusion assessment).

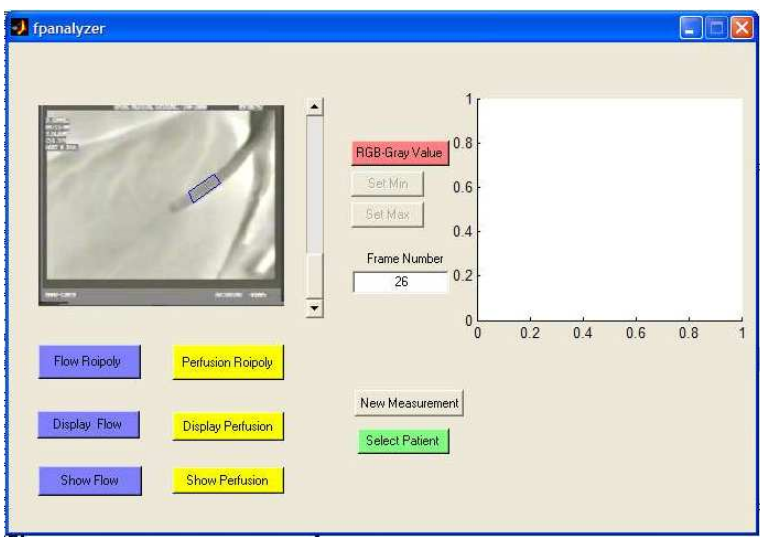

Figure 4.4 The selected ROI for flow measurement.

By pushing the buttons "display flow" and "show flow" respetively, the user notices the flow graphics and the value of flow in terms of liters per second. The flow value may either have a negative or a positive sign but it doesn't matter since we take the absolute value. This sign contradiction occurs because there are two types of measurement, which will be described in the chapter "Theory and Methods". One is performed with an isothermic infusion, which is hotter than the myocardium, the other is performed with a cold infusion, which is colder than the myocardium. The rectangular ROI for flow measurement is divided into three equal parts. The pattern of flow is displayed by a graph with three raw and fitted curves. These curves display the gray levels of the pre-mentioned parts of the ROI with respect to time. The flow is measured by discrete cross-correlation calculation between these curves.

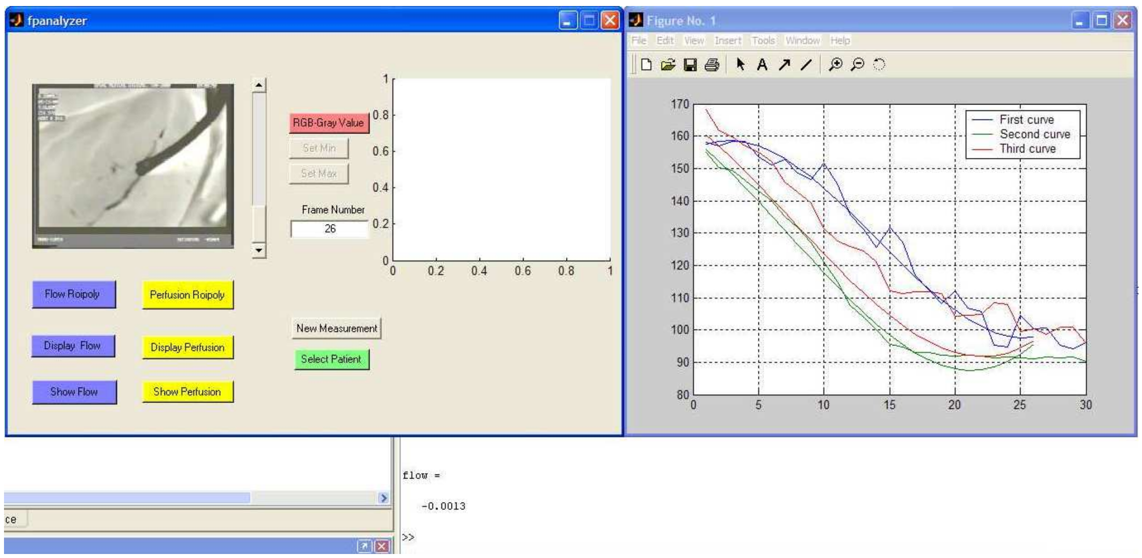

Figure 4.5 The curves and the value of flow displayed.

The same steps are followed for perfusion assessment. However, this system is limited to perfusion display just like the flow display, without parametric measurement. The reason for this, which will be mentioned in the following chapters, is the inappropriate characteristics of the image supplied by the camera. This problem may be managed just by disabling the brightness auto-adjustment function of the camera. But the camera's hardware didn't allow this.

After selecting the ROIs, the user pushes the button "Display Perfusion" in order to display the graphs of average grey levels of the selected ROIs with respect to time.

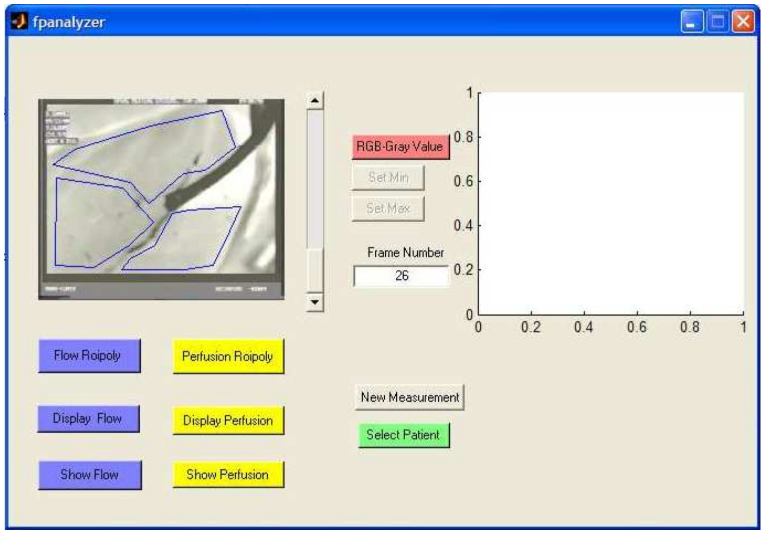

Figure 4.6 Selection of the ROIs for perfusion assessment.

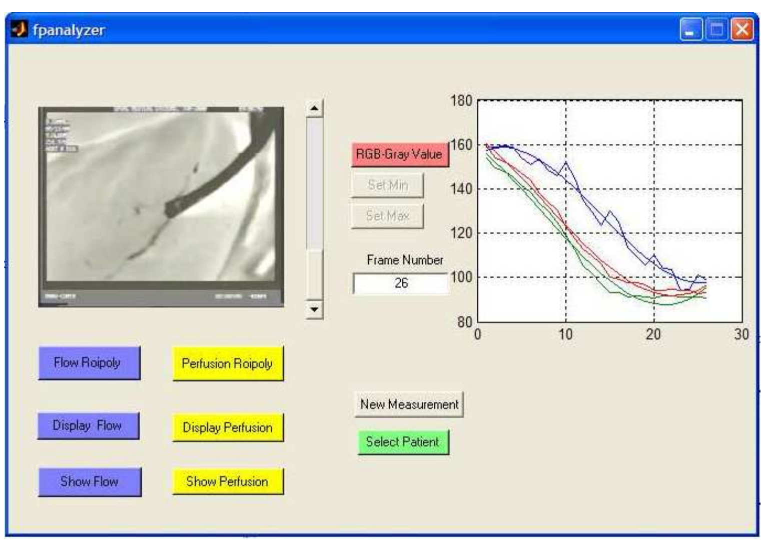

Figure 4.7 Perfusion graphs of the three pre-selected polygonal ROIs.

5. THEORY AND METHODS

Thermal imaging is a system that one can observe the image real time and can give the results of image processing in seconds. As described above, it senses the infrared radiation from the surface of the object and creates the image by way of this surface distribution array of infrared radiation. Since the thermal imaging system provides us the image obtained from the surface of the heart in real time and results in seconds, it is very useful in the operating room conditions. The vast majority of the procedures in cardiac surgery are performed under cardiopulmonary bypass, which means the circulation via heart-lung machine, bypassing the heart and lungs. After cardiopulmonary bypass circuit starts, the cardiac arrest maintained by cardioplegic solutions, local and systemic cooling and cross-clamping of the aorta takes its part. When the procedure (the manipulation on the heart) is to be terminated, patient is re-heated to the physiologic body temperature and cross clamp is removed. After removal of the cross clamp, patient is supported by the heart-lung machine until the blood pressure and the other hemodynamic parameters reach the normal values. After hemodynamic stability is maintained, cardiopulmonary bypass is terminated. All these stages of the cardiac surgery have time limits of safety of the patient. By the way, thermal imaging gains great importance since it is a very quick method. The proposed work is based on the infrared imaging of the region of interest and determination of the change of the temperature in time. There are two ways to perform the method in order to maintain a temperature gradient between the myocardium and the circulating solution in the graft. The first way of the method is, creation of an initial temperature which is same everywhere on the region of interest and starting the imaging procedure synchronously with heating the region of interest. Creation of the initial temperature will be done by a saline injection, which has a heat content to be assumed as infinite, in compared to the myocardium on the region of interest. The enthalpy of the injected saline should be infinite because it should cool the myocardium to the desired temperature, which will be the initial temperature in the procedure. After maintenance of the initial temperature, heating will take its turn. Heating will be done by infusing the serum of constant temperature (28 C) with a constant pressure (60 mmHg), approximately about the same as normal mean blood pressure, from the proximal end of the graft which will later be sutured on the ascending aorta. During the heating process, the temperature of the epicardium (the external surface of the heart, also termed as visceral pericardium) of the region of interest will be monitored and the image data obtained from this monitorization will be processed, finally blood flow will be found out. The second way of the method is directly injection of the cold saline ($4^o C$) directly from the graft. This is done also by constant pressure, which is 60 mmHg. During the heating, again the region of interest is processed and blood flow is found out.

Heating will occur by way of two sources:

1. Conduction
   - The effect coming from endocardium(inner lining of the heart chambers)
2. Convection
   - The effect coming from the perfusion of the constant temperature serum

The procedure is explained step by step as follows:

- Methods to measure the flow:
  - Cold infusion
  - Isothermic infusion
- Method to display the perfusion:
  - Compare the perfusions of the pre-selected regions on the same patient data
- Both the re-heating and the cooling processes of the myocardium mainly occur via convection heat transfer of blood perfusion.

- Conduction from the inner side, endocardium is assumed to be negligible during the first few seconds.

5.1 Method For Isothermic Infusion

- Step 1:
  - Cooling of the myocardium with injection of cold saline (4^oC)
  - Simultaneous blockage of the graft
  - Waiting for a few seconds for saline to cool the myocardium into steady state conditions
- Step 2:
  - Opening the clamp on the graft
  - Imaging of the region of interest with thermal camera during infusion of saline with constant pressure (60 mmHg) and data analysis

5.2 Method for Cold Infusion

- Directly injection of the cold saline through the graft to the isothermic heart (28^oC on-pump)
- Capturing the image during infusion
- Processing the image

5.3 Calculation

- Analzing the re-heating (or cooling) times of the two different parts (first 1/3 and third 1/3) of the ROI

- Using the discrete cross correlation method to define the time lag between the gray level averages of the two segment
- Finding out the flow

To calculate the flow, the discrete cross correlation equation is modified for this purpose as:

$$[\Phi ac]_t = \sum_k A_k C_{k-t} \tag{5.1}$$

Here, A (a) and C (c) are average gray levels of the two (first and third) parts of the rectangular ROI. "t" is the time lag and "k" is the image number of the selected interval. After determining the time lag by this method, flow simply can be calculated as:

$$Flow = \frac{\pi r^2 h}{t} \tag{5.2}$$

The perpendicular side of the rectangular ROI stands for the diameter of the graft and "h" stands for the distance between the midpoints of the first and the third part of the rectangular ROI.

6. RESULTS AND DISCUSSION

In order to use the method performed to measure the graft flow and display the perfusion, images from 21 patients were captured. Images from 7 patients were found to be analyzable. As described in the previous chapters, there are two ways to prepare the image, one is the cold infusion, whereas the other is the isothermic infusion. Isothermic infusion is used on LIMA grafts, whereas the cold infusion is used on saphenous vein grafts.

Figure 6.1 The three frames of the isothermic infusion procedure. On the first frame the infusion is not yet started. On the second frame, the infused fluid flows in the graft but just starts to perfuse the myocardium. On the third frame, the perfusion is completed.

Figure 6.2 The three frames of the cold infusion procedure. The steps are the same as isothermic infusion principally.

The results found for three measurements for each patient are shown on table 6.1.

There is a noticeable variance in the same patient in the data to be obtained. This variance strikes to be less on measuring the graft flows to LAD. Here, the observer may notice the difference of the thickness of the grafts to LAD in relation to grafts

Table 6.1
Flow measurement data from the patients in ml/sec.

	Graft	1st Measurement	2nd Measurement	3rd Measurement
Patient 1	CX	1.89	1.62	0.99
Patient 2	CX	1.17	1.45	0.96
Patient 3	RCA	1.0	1.12	1.26
Patient 4	RCA	0.22	0.32	0.19
Patient 5	CX	0.42	0.55	0.38
Patient 6	LAD	2.2	2.04	1.89
Patient 7	LAD	2.1	1.67	1.96

to the others. There is not a rule that it has to be thicker than the other grafts but in our data, they are thicker. In this case, it is obvious that the number of patients, to interpret the statistical data in order to validate the method, is not enough. On the other hand, the algorithm developed to measure the flow of the graft may need to be revised. The image specifications are also not exactly suitable for this kind of measurement. Quantitative data cannot be obtained with the current system due to the inevitable automatic image adjustment properties of the camera output. Difficulties of good quality image capturing due to movement of the heart and other noise factors also stand for another challenge.

Acquiring the data only from the epicardial surface of the heart, whereas other methods yield transmural data and complexity of the myocardial thermodynamics and heat transfer processes are also disadvantages of the system especially when perfusion measurement is the purpose.

Advantages of the System:

- System gives the result in minutes
- System can be applied to the operating room
- The procedure of the operation can be changed according to the results

- Any breadth and localization of the region of interest can be selected to acquire precise data
- Patient is not exposed to ionizing radiation
- No contrast material or any other medication applied to the patient
- No catheter or any other device insertion to the patient

Future Work

Since thermal imaging gains importance on cardiac surgery, it becomes essential to make this system more practical and strengthen it. To do this, first, a camera which supplies raw thermal image without built-in contrast and brightness enhancement properties. By the way, a function can be added to this system to measure the perfusion in terms of ml/min/gr. Compactness of the system is also necessary to make it more useful and practical. This system may be designed as a compact device, rather than a general purpose computer with a capture card connected to an automatic image-adjusting camera. The surgeon or the assistant needs just to push a button and see the result, due to circumstances in the operating room. The software needs to be strengthened mathematically. The equations of the perfusion calculation should be added to the system for the reasons described above.

Despite all the disadvantages of the system, the method is expected to be valuable method to detect the early graft failures. Since it is reported that about 7 % of all arterial grafts and 3 % of all vein grafts has a probability to encounter early graft failure, this method becomes more important.

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