Part 1

Cardiac Surgery

A brief overview and an introduction to Minimally Invasive Cardiac Surgery

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Outline

• History
• Surgical approaches for heart exposure
• The extracorporeal circulation
• Coronary Artery Bypass Grafting
• Valvular surgery
• Endovascular techniques
History

- **First successful heart operation**: Rehn, 1896
  
  Successful suture of an heart wound

- **Congenital cardiac surgery**
  - Ductus arteriosus: Gross, 1938
  - Coarctation of the aorta: Crafoord, 1944
  - Blalock-Taussig operation: 1944

- **Mitral valvulotomy**: Bailey, 1948
  
  (first case: Souttar, 1925)
History

• **Indirect revascularization of the heart: Beck, 1930**
  
  collateral blood flow to ischemic myocardium

• **First cases direct coronary artery surgery: 1960 – 64**
  
  operations performed on a beating heart

• **First large series of Coronary Artery Bypass Graft patients: Favaloro, Green, 1968**
The heart needs to be stopped to repair intracardiac lesions or to improve coronary surgery

- **Cardiac arrest**: irreversible brain damage occurs if circulatory arrest lasts over **3 minutes** in normothermia

- **Two solutions:**
  1) **Hypothermia**: increases the duration of safe cardio-circulatory arrest by decreasing the oxygen consumption
  2) **Heart lung machine**: replaces the cardiopulmonary function
History

- Hypothermic technique, surface cooling: Lewis, 1952
  
  Closure of an atrial septal defect in a 5-year-old girl
  (five and one-half minutes at 28°C)
History

- **Heart lung machine**: Gibbon, 1953
  
  *Closure of an atrial septal defect
  in an 18-year-old girl*

  By the end of 1956, many programs were launched into open heart surgery around the world.

  Currently, *more than one million operations* are performed each year under extracorporeal circulation, worldwide.

- **Resurgence of beating heart surgery**: Benetti, 1991
- **First robotic operation of the heart**: Carpentier, 1998
Many developments and inventions have been involved in this course:

- Mechanical ventilation
- Defibrillator
- Transfusion
- Heparin
- Antibiotics
- Cardioplegia
- Selective coronary angiography: Sones, 1962
- ...
Surgical approaches for heart exposure
Surgical approaches for heart exposure

- Sternotomy
- Thoracotomoy
- Minimally invasive cardiac surgery
Sternotomy

- Sternotomy approach
  - allows almost all cardiac procedures
  - best overall access to the heart

- The sternum is divided with a saw

Sternotomy

- A retractor is placed
- The pericardium is incised and sutured to the wound towel, elevating the heart for better exposure
Sternotomy

Expansion of the retractor is responsible for chest pain and can cause rib fractures
Sternotomy

- Closure
Right anterolateral thoracotomy

Left posterolateral thoracotomy

Thoracoabdominal incision

The bilateral transverse thoracosternotomy (clam shell incision)

The two major goals of MICS are:

1) To use **smaller incisions**
   - reduce the operative trauma
   - preserve the integrity of the chest
   - more cosmetic

2) To **avoid the extracorporeal circulation**
   *(see latter)*
Minimally invasive cardiac surgery

- MICS remained far behind other specialties:
  - High quality standard of cardiac surgery
  - Many constraints of cardiac surgery (motion of the heart, limited duration of the induced cardiac arrest)

*MICS was progressively introduced owing to progress in cardiopulmonary bypass, intracardiac visualization, and instrumentation*

Many cardiac surgeons remains very critical of MICS because surgery might be unsafe and/or results less satisfactory
Minimally invasive surgery may be performed under direct vision.
But true minimally invasive surgery is performed by passing an endoscope and surgical instruments through tiny incisions.
Limitations in MICS

- Moving the surgical instruments manually during endoscopic surgery is difficult for many reasons:
  - Bidimensional visualization
  - Using a long instrument through a tiny incision: fulcrum-effect
  - Fixed port access in the rigid intercostal space
  - Lost of force feedback due to friction
  - Limited DOF (4 + 1) versus the 20 DOF of the human hand
  - Limited ergonomy, operator fatigue & loss of concentration

Robotics may solve these problems, at least partially
Limitations in MICS

- *Others limitations and requirements are related to the limited access or vision of the heart:*
  - Monitoring of the operation during conventional technique involves direct observation of the heart: new monitoring technique are required as Transesophageal Echocardiography
  - Because of the possible occurrence of a peroperative problem (cardiac arrest, massive hemorrhage), a conversion must available at all time
  - Operative techniques are very rigorous and surgeons must be taught through training programs and must perform a reasonable number of such operations
Specific tools & instruments
<table>
<thead>
<tr>
<th>Group</th>
<th>Vision</th>
<th>Instruments</th>
<th>Time (min)</th>
<th>Quality *</th>
<th>Difficulty **</th>
<th>Anastomotic patency ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Direct vision</td>
<td>Conventional instruments</td>
<td>6.7 +/- 0.5</td>
<td>2.8 +/- 0.5</td>
<td>1.0 +/- 0.0</td>
<td>1.0 +/- 0.0</td>
</tr>
<tr>
<td>II</td>
<td>Endoscopic vision</td>
<td>Endoscopic instruments</td>
<td>22.4 +/- 3.0</td>
<td>1.8 +/- 1.0</td>
<td>4.0 +/- 0.0</td>
<td>1.5 +/- 0.8</td>
</tr>
<tr>
<td>III</td>
<td>Direct vision</td>
<td>Endoscopic instruments</td>
<td>21.1 +/- 2.1</td>
<td>1.0 +/- 0.0</td>
<td>4.0 +/- 0.0</td>
<td>1.5 +/- 0.55</td>
</tr>
<tr>
<td>IV</td>
<td>Endoscopic vision</td>
<td>Conventional instruments</td>
<td>10.5 +/- 1.6</td>
<td>2.5 +/- 0.55</td>
<td>1.0 +/- 0.0</td>
<td>1.0 +/- 0.0</td>
</tr>
<tr>
<td>V</td>
<td>Telemanipulation robotic technology</td>
<td></td>
<td>8.87 +/- 1.44</td>
<td>2.0 +/- 0.0</td>
<td>1.3 +/- 0.5</td>
<td>1.0 +/- 0.0</td>
</tr>
</tbody>
</table>

* Surgeon’s satisfaction with quality of anastomosis at completion: good = 3, fair = 2, poor = 1
** Degree of difficulty of anastomosis: easy = 1, somewhat easy = 2, somewhat difficult = 3, difficult = 4
*** Patency of anastomosis: 100 % = 1, 50 % = 2, < 50 % = 3

Heart-lung machine

The extracorporeal circulation (ECC)
The extracorporeal circulation

- Venous cannulation
- Venous line
- Reservoir
- Suction
- Pump
- Heat exchanger
- Arterial cannulation
- Arterial line
- Filter
- Oxygenator
Operation under ECC (1)

- **Sternotomy**
- Opening of the pericardium & exposure of the heart
- Confection of *pursestring*

- **Heparin:** high dose
- **Cannulation, connections to tubing**

*From: Manual of Cardiac Surgery, Harlan & Starr, Springer-Verlag, New York, 1995*
Operation under ECC (2)

- Initiation of ECC
- Cooling
Operation under ECC (3)

- Cardioplegic arrest
  - Clamping of the aorta
  - $K^+$ injection into the coronary system:
    « chemical arrest » of the heart », flaccid heart
Procedure
Heart arrested (ECG: no activity)
Lungs deflated
Operation under ECC (4)

- Release of the aortic clamp
  - Sinusal rhythm
  - Ventricular fibrillation: defibrillator
  - Block: pace-maker

If open-heart surgery
daireing before unclamping the aorta
(air embolization)
Operation under ECC (5)

• **Assistance**
  - Recovery of the heart
  - Rewarming

• **ECC discontinuation**
  *progressive weaning: transition between ECC and native circulation*

• **Once hemodynamic stability is acquired**
  - Remove of cannula
  - Administration of protamine (restoration of coagulation)

• **Drainage**

• **Closure**
Flow (L/min)

- **Initiation of ECC**

- **Aortic cross clamping**

- **ECC duration**

- **Assistance and weaning**

- **End of ECC**

**Flow (L/min)**

- 0
- 1
- 2
- 3
- 4
- 5

**Time**

**ECC**

**Heart**
Femoro-femoral ECC

- Open or percutaneous technique

Femoro-femoral ECC

• percutaneous technique
Percutaneous insertion of a femoral cannula - Principle

1. Puncture of the vessel
2. Guide wire insertion into the vessel
3. Incision of the skin

Once the guide wire is in the vessel, the cannula can be inserted relatively safely.

The technique is the same for arterial or venous cannula.

4. Dilators are inserted into the vessel
5. The cannula is inserted into the vessel
6. Cannula in place
Port-Access system

Equipment - Monitoring

ECG and hemodynamic monitoring

Tranesophageal echocardiography monitoring
Preoperative imaging

- Coronarography
- Echocardiography
- CT-scan
- MRI
Coronary surgery

Coronary Artery Bypass Grafting (CABG)
What is a CABG?

- A vascular graft is sutured to the coronary artery beyond the stenosis.
Saphenous vein graft

Traditional incisions

Endoscopic incisions

From: The Society of Thoracic Surgeons Web site
http://www.sts.org
Internal thoracic artery graft

From: The Society of Thoracic Surgeons Web site
http://www.sts.org
Other arterial grafts

Stomach

Right gastroepiploic artery
Other arterial grafts

Radial artery
Coronary anastomosis

Distal anastomosis

Sequential anastomosis

Some example of CABG
Various combinations are possible
Arterial graft must be favored

LITA: left internal thoracic artery
RITA: right internal thoracic artery
GEA: gastroepiploic artery
SVG: saphenous vein graft
RA: Radial artery
CABG - Operative technique

Under ECC with cardioplegia

Beating-heart surgery (without ECC)

Video

Video
Cardiac motion of an epicardial beacon

From: Borst et al, J Am Coll Cardiol 1996;27:1356-64

Figure 2. Example of two-dimensional epicardial beacon motion in the obtuse marginal area during an open-chest procedure. Beacon motion is depicted during one half respiratory cycle when the heart is unrestrained (A) and when it is immobilized locally by the encircling Octopus (B). The inset shows a magnification of the residual cardiac motion (B). The Octopus limited cardiac wall motion to about 1 x 1 mm. Data points are plotted at 20-ms intervals.
Valvular surgery
Generality

In adult, valvular surgery is mostly used for the aortic valve and mitral valve.

Repair must be favored because of a higher valve prosthesis morbidity.

- **Aortic valve**
  - Aortic valve replacement: most cases
  - Valvuloplasty: some cases

- **Mitral valve**
  - Valvuloplasty: most cases
  - Mitral valve replacement if valvuloplasty is impossible
Aortic valve replacement

Mitral valve repair

Mitral valve replacement

Endovascular techniques
Open technique
Endoaortic prosthesis

Video
Part 2

Introduction to Computer Assisted Medical Intervention in Cardiac Surgery
Computer Assisted Medical Intervention
Introduction

Motion of the heart

Figure 2. Example of two-dimensional epicardial beacon motion in the obtuse marginal area during an open-chest procedure. Beacon motion is depicted during one half respiratory cycle when the heart is unrestrained (A) and when it is immobilized locally by the encircling Octopus (B). The inset shows a magnification of the residual cardiac motion (B). The Octopus limited cardiac wall motion to about 1 x 1 mm. Data points are plotted at 20-ms intervals.

From: Borst et al, J Am Coll Cardiol 1996;27:1356-64

Introduction

Motion of the chest during normal respiration
Introduction

Motion of the chest during apnea
Introduction

Problems of echography

Video
Problems of CAMI in cardiac surgery

**Problematic of soft tissue**

**Heart**
- Mobile organ: regular, arrhythmic, extrasystolic
- Deformable organ
- Geometric modification due to hemodynamic status

**Environmental risk:**
- Great vessels, lungs, liver...

**Mobility of the chest:**
- Breathing

**Imaging:**
- Bad resolution of echocardiography

**Buckling of the needle**

**Solutions**

- Synchronization
- Stabilization
- Robotic motion cancellation
- Pacemaker

- Improved acquisition
- Sensor redundancy
- Peroperative imaging & Updated image guidance

- Planning

- B-blockade
- Volume control

- Jet ventilation
- Apnea
CASPER
Computer ASsisted PERicardiocentesis
Classical pericardiocentesis (1)

Pericardial effusion
Classical pericardiocentesis (2)
Classical pericardiocentesis (3)

Operator-dependant technique

*difficult and often blind*

*risk of failure or accidental puncture of organs*

*A computer assisted system could enhance this procedure*
CASPER - Principle

Echocardiography
The problem of the heart motion may be solved by finding a stable target along the course of the cardiac cycle, the "stable region"
CASPER - Principle

- **Problem of mobility**
  - Heart: modeling « stable region »
  - Respiration: apnea, alarm of displacement

![Apnea](image1.png) ![Normal Respiration](image2.png)

**Apnea**

**Normal Respiration**
CASPER - Principle

Perception → modeling → Puncture
CASPER - Method

- Perception
  - Selection of the best view & choice of the region of interest
  - Acquisition of a set of images: 20 to 30 images
CASPER - Method

• **Modeling (1)**
  - average plane: a "**referential plane**" is computed
  
  *the behavior of the effusion will be modeled in this plane*

• The zone of interest is **manually segmented** on each image
CASPER - Method

• modeling (2)
  - the **stable region** is computed by intersection: safe target along the cardio-respiratory movement
  - the surgeon defines the **trajectory** for the needle so that it will avoid anatomical structures
CASPER - Method

- **Puncture**
  - The surgeon is assisted by a **passive guidance system** based on super-imposed crosses on the user interface.

It is a real time surgical tool guidance.
ETAPÉ DE GUIDAGE
Diamètre du cercle intérieur est de 2,5 mm

Hauteur [mm]

croix :+ jaune : extrémité de l'aiguille
x bleu : axe de l'aiguille

Revoir le guidage

Table

Patient

Aiguille

distance par rapport à la cible (en mm) :
0 nm

seuil de déplacement patient

10 nm

Le patient n'a pas bougé !!
ÉTAPE DE GUIDAGE
Diamètre du cercle intérieur est de 2.5 mm

Zoom : 1 à 5

Revoir le guidage

Table
Patient
Aiguille
distance par rapport à la cible (en mm)

seuil de déplacement patient
0 mm 10 mm

Le patient n'a pas bougé !!
ETAPE DE GUIDAGE

Diamètre du cercle intérieur est de 2.5 mm

Le patient n'a pas bougé !!
ÉTAPE DE GUIDAGE

Diamètre du cecile interne est de 2.5 mm

Table

Distance par rapport à la cible (en mm)
0 mm - 10 mm

Patient

Seuil de déplacement patient

Aiguille

Le patient n'a pas bougé !!
ÉTAPE DE GUIDAGE
Diamètre du cercle intérieur est de 2.5 mm

Le patient n'a pas bougé !!
Étape de guidage
Diamètre du cercle intérieur est de 2,5 mm

Table
Patient
Aiguille

Distance par rapport à la cible (en mm):

Seuil de déplacement patient
0 mm 10 mm

Le patient n'a pas bougé !!
CASPER - Results

- In vivo validation was performed on a porcine model with an accuracy of at least 2.5mm


- A phase of improvement have been implemented


- A successful procedure was performed on a patient

  Marmignon et al. CASPER, a Computer ASsisted PERicardial puncture system. First clinical results. *Comput Aid Surg (in press)*
The assessment of accuracy is problematic: virtual target

The precision is limited by many factors:
- a strict immobility is required between acquisition and puncture
- deformability of soft tissue (echography & puncture)
- precision of the localizer
- quality of calibration (echographic probe & needle)
- precision of computing
- quality of modeling
  - lost of information: size of the images set (cardiac & respiratory cycle)
  - segmentation accuracy
- difficulties in performing the puncture
  - deformability of soft tissue, buckling of the needle
  - tiredness of the operator, lost of concentration

Heaviness of the procedure

Learning curve
CASPER - Perspectives
CASPER - Perspectives

PADyC
Passive Arm with Dynamic Constraint
CASPER - PADyC

The surgeon is free to propose any direction of motion to the arm. The system filters these moves to keep only those which are compatible with the pre-planned task.

http://www-timc.imag.fr/gmcao/
CASPER - PADyC

- Passive arm with dynamic constraint
  - Purely passive device
  - Each encoded joint is equipped with a patented mechanism:
    2 freewheels mounted in opposition and
    2 electrical motors: clutch or unclutch the freewheels independently
    In each joint there are 4 possible functions:
      - F1: joint can be moved in forward and backward directions
      - F2: joint can be moved in forward direction only
      - F3: joint can be moved in backward direction only
      - F4: joint cannot be moved
Preoperative planning in MI CS

Modeling

Planning

Preoperative

Peroperative

Matching calibration

Augmented reality
Conclusions