Coronary Circulation

Coronary Artery Disease
Reading

• Klabunde, Cardiovascular Physiology Concepts
  – Chapter 7 (Organ Blood Flow) pages 151-155 (Section on Coronary Circulation)
  – Chapter 4 (Cardiac Function) pages 85-88
Coronary Artery Anatomy
Coronary Vascular Resistance

• Epicardial conductance vessels
  – Only a small % of resistance normally
  – Stenotic lesions

• Intramyocardial vessels (arterioles)
  – Contribute most to total coronary vascular resistance
Capillary Density in the Heart

<table>
<thead>
<tr>
<th>Skeletal muscle</th>
<th>Cardiac muscle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre diameter</td>
<td>50 μm</td>
</tr>
<tr>
<td>Capillaries per</td>
<td>400 mm²</td>
</tr>
<tr>
<td></td>
<td>3000 mm²</td>
</tr>
<tr>
<td></td>
<td>18 μm</td>
</tr>
</tbody>
</table>
Determinants of Myocardial Oxygen Supply and Demand
Vascular Resistance

- Metabolic Control
- Extravascular Compressive Forces
- Diastolic Phase

Coronary Blood Flow

- Neural Control
- Endothelial Control
- Autoregulation

SUPPLY

O$_2$-Carrying Capacity

DEMAND

- Heart Rate
- Contractility
- Systolic Wall Tension
Myocardial Oxygen Supply
# Resting O2 Consumption of Various Organs

<table>
<thead>
<tr>
<th>Organ</th>
<th>O2 Consumption (ml/100 g/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>2.0</td>
</tr>
<tr>
<td>Kidneys</td>
<td>6.0</td>
</tr>
<tr>
<td>Brain</td>
<td>3.3</td>
</tr>
<tr>
<td>Skin</td>
<td>0.3</td>
</tr>
<tr>
<td>Skeletal muscle</td>
<td>0.2</td>
</tr>
<tr>
<td>Cardiac muscle</td>
<td>9.7</td>
</tr>
<tr>
<td>Whole body</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Coronary Perfusion Pressure

- Pressure gradient that drives blood through the coronary circulation.

Coronary Perfusion Pressure =
Diastolic BP – LVEDP (or PCWP)
Myocardial Oxygen Supply
Oxygen Content of Blood

- **O2 Content** =
  
  \( (1.36 \, \text{cc O2/g Hgb/100 ml blood} \times \text{Hgb} \times \% \text{Saturation}) + (\text{pO2} \times 0.003) \)

- **O2 delivered to myocardium** =
  
  O2 content \times \text{coronary blood flow}
Myocardial Oxygen Supply

• Oxygen Extraction
  – The heart extracts oxygen to a greater extent than any other organ
  
  – Coronary sinus pO2 value is normally in range of 20-22 mmHg (% sat = 32-38%)
  
  – Can only minimally increase O2 extraction
  
  – Increases in O2 demand must be met by increased coronary blood flow
Myocardial Oxygen Supply

Regulation of Coronary Blood Flow
Coronary Blood Flow

- Metabolic control
- Autoregulation
- Endothelial control of coronary vascular tone
- Extravascular compressive forces
- Neural control
Regulation of Coronary Blood Flow
Metabolic Control

- Coronary circulation is exquisitely sensitive to myocardial tissue oxygen tension.

- Increased oxygen demand results in a lower tissue oxygen tension. This causes vasodilation and increased blood flow.
  - Adenosine
  - Nitric oxide
  - Prostaglandins
  - $K^{+}_{ATP}$ channels
Metabolic Control of Blood Flow

- Lack of oxygen?
- Formation of vasodilators?
- Combination of both?

- Precapillary Sphincter
- Capillary

- Relaxation of smooth muscle

- Increased Blood Flow
Autoregulation

- Ability of a vascular network to maintain constant blood flow over a range of arterial pressures.
- Autoregulation is an independent determinant of CBF.
- The set point at which CBF is maintained depends on MVO2.
Autoregulation

Maximal Available Coronary Blood Flow

Autoregulation in Anemia or LVH

Normal Autoregulation

Flow

Coronary Perfusion Pressure
Endothelial Control of Coronary Vascular Tone
When Damage to Endothelium Occurs

• Damage to endothelial cells will lead to:
  – Decreased Nitric Oxide and Prostacyclin production
  – Increased Endothelin production

• This will lead to:
  – Vasoconstriction
  – Vasospasm
  – Thrombosis
Neural Control

• Coronary blood flow is controlled predominantly by local metabolic, autoregulatory, and endothelial factors

• Neural control of the coronary circulation complements the above local effects
Neural Control

• Sympathetic Control
  – Alpha = constrict coronary vessels
  – Beta = dilate coronary vessels
    • Beta_1 in conduit arteries
    • Beta_2 in resistance arterioles

• Parasympathetic Control
  – Acetylcholine
    • Vasodilation in healthy subjects
    • Vasoconstriction in patients with atherosclerosis
Extravascular Compressive Forces

• The heart influences its blood supply by the squeezing effect of the contracting myocardium on the blood vessels coursing through the heart
Extravascular Compressive Forces

• Left Ventricle
  – Early Systole > Initial Flow Reversal
  
  – Remainder of Systole > Flow follows aortic pressure curve, but at a much reduced pressure
  
  – Early Diastole > Abrupt pressure rise (80-90% of LV flow occurs in early diastole)
  
  – Remainder of Diastole > Pressure declines slowly as aortic pressure decreases
Extravascular Compressive Forces

Pulsatile nature of left coronary artery blood flow. Flow is lower during phases of isovolumetric contraction (a) and ejection (b) than during diastole (c).
Extravascular Compressive Forces

• Right Ventricle
  – Lower pressure generated by thin right ventricle in systole
  – No reversal of blood flow during early systole
  – Systolic blood flow constitutes a much greater proportion of total blood flow
Transmural Distribution of Myocardial Blood Flow

- Extravascular compressive forces are greater in the subendocardium (inner) and least near the subepicardial layer (outer)

- Under normal resting conditions this does not impair subendocardial blood flow as increased flow during diastole compensates
  - Subendocardial to subepicardial ratio: 1.25/1
  - Due to preferential dilatation of the subendocardial vessels
  - Secondary to increased wall stress and, therefore, increased MVO2 in the subendocardium
Transmural Distribution of Myocardial Blood Flow

• The subendocardium is more susceptible to ischemia than the midmyocardium or subepicardium

• Epicardial coronary stenoses are associated with reductions in the subendocardial to subepicardial flow ratio
Coronary Flow Reserve

• Difference between baseline blood flow and maximal flow
  – Usually measured following pharmacologic coronary vasodilation

• In the absence of coronary artery disease, maximal flow is 4 – 5 times as great as at rest

• Coronary flow reserve decreases with increasing severity of coronary artery disease
Correlation of coronary anatomy and physiology: The concept of coronary flow reserve

Anatomy
- Normal epicardial artery
- Epicardial stenosis
- Microvascular disease

Physiology
- Arteriolar vasodilatation (Papaverine)
- Time

ECHO in Context
Myocardial Oxygen Demand
Myocardial Oxygen Consumption

- Oxygen consumption is defined as the volume of oxygen consumed per minute (usually expressed per 100 grams of tissue weight)
Myocardial Oxygen Demand is Related to Wall Stress

- LaPlace’s Law

\[ \sigma \propto \frac{\Pr}{h} \]
Factors Increasing Myocardial Oxygen Consumption

- Increased Heart Rate
- Increased Inotropy (Contractility)
- Increased Afterload
- Increased Preload
  - Changes in preload affect myocardial oxygen consumption less than do changes in the other factors
Oxygen Cost of Myocardial Work

• Pressure work is much more costly than volume work for the heart
  – Pressure work = increasing arterial pressure at a constant cardiac output

  – Volume work = increasing cardiac output while maintaining a constant pressure
Coronary Artery Disease
Coronary Artery Disease

• Myocardial ischemia occurs when myocardial availability is inadequate to meet metabolic requirements.
Effects of Coronary Stenoses
Coronary Flow Reserve

Figure 2. Effects of reducing LAD radius on maximal distal blood flows. A 60% reduction in LAD radius (40% of max radius) decreases maximal distal flow capacity by more than 25%.
Coronary Stenosis and Resistance

Degree of Stenosis

R

30%
50%
70%
80%
90%
Myocardial Ischemia
Na/H Exchanger

Increase activity

Na-K ATPase

Decreased activity

Na/Ca Exchanger

Decreased activity

Ischemia

Increased intracellular Na

Increased intracellular Ca
Myocardial Ischemia

- Intracellular Acidosis
  - Increased Na/H Exchange
    - Increased H Extruded
  - Decreased Na-K ATPase Activity
    - Increased Intracellular Na
      - Decreased Na/Ca Exchange
        - Intracellular Ca++ Overload
          - Impaired Myocardial Contraction and Cell Death
Effects of Myocardial Ischemia

- Systolic dysfunction
  - Normal myocardium thickens and shortens during systole

  - Ischemia causes alterations that may range from minimal impairment to absence of movement (akinesia) to systolic lengthening and post- systolic shortening (dyskinesia)

  - May have compensation by surrounding areas of normal muscle
Effects of Myocardial Ischemia

Diastole

Normal

Ischemic

Systole
Effects of Myocardial Ischemia

• Diastolic Dysfunction
  – When a sufficient amount of myocardium is rendered ischemic, then LVEDP rises
  – Relaxation is impaired, and myocardial compliance decreases
Effects of a combination of systolic dysfunction (decreased inotropy) and diastolic dysfunction (decreased compliance) on left ventricular pressure-volume loop. Heart rate and systemic vascular resistance are unchanged.
Myocardial Ischemia

• Myocardial Stunning
  – After a brief episode severe ischemia, prolonged myocardial dysfunction with gradual return of contractile activity occurs.

• Myocardial Hibernation
  – Presence of impaired resting LV function, owing to reduced CBF that can be restored toward normal by revascularization.
Myocardial Ischemia

- Myocardial Infarction
  - No Return of Contractile Function
- Chronic Ischemia without Infarction
  - Hibernating Myocardium
  - Relief of Ischemia
- Acute Ischemia
  - Myocardial Stunning
  - Return of Contractile Function
Myocardial Ischemia

- Systolic and diastolic dysfunction
- Angina
- CHF or Pulmonary Edema
- Arrhythmias
- Myocardial Infarction
- Ventricular Rupture or VSD
- Cardiogenic Shock
- Death
Drugs Used for Treatment of Ischemia

• Oxygen
• Beta-Blockers
• Nitrates
• Antiplatelet/Anticoagulant Drugs
• Analgesics
• Calcium-Channel Blockers
Interventions for the Treatment of Myocardial Ischemia

• Coronary artery bypass surgery (CABG)

• Percutaneous Coronary Interventions
  – Coronary Balloon Angioplasty
  – Bare-metal Coronary Stents
  – Drug-eluting Stents
How long should you wait before doing elective surgery after PCI?

• Bare-metal Stent
  – Cardiac complications are lowest after 90 days

• Drug-eluting Stent
  – 1 year is recommended
Perioperative Medical Therapy

- Volatile anesthetic agents may be preferred
  - Anesthetic Preconditioning
- Beta-blockers
- Statins
  - Stabilize plaque
  - Anti-inflammatory
Perioperative Medical Therapy

• Alpha-2-agonists
  – Clonidine
  – Useful in patients not able to take Beta-blockers (e.g., asthmatic)

• Calcium channel blockers

• The use of Nitroglycerin as a prophylactic drug during anesthesia is unclear. No study has clearly demonstrated a change in outcome from its routine use.
Collateral Blood Flow
Collateral Blood Flow

• Coronary collateral vessels develop in response to impairment of coronary blood flow

• Collaterals develop between branches of occluded and non-occluded arteries and can contribute a significant amount of blood flow.

• They originate from pre-existing arterioles that undergo proliferative changes of the endothelium and smooth muscle.
  – Monocyte chemoattractant protein-1 (MCP-1)
  – Vascular endothelial growth factor (VEGF)
Ischemic Preconditioning
Ischemic Preconditioning

- Laboratory and clinical investigations have demonstrated that single or multiple brief periods of ischemia can be protective against a subsequent prolonged ischemic insult. The brief periods of ischemia appear to "precondition" myocardium against reversible or irreversible tissue injury, including stunning, infarction, and the development of malignant ventricular arrhythmias. This process is known as *ischemic preconditioning* (IPC).

- Inhaled anesthetic agents have effects that mimic IPC
  - ANESTHETIC PRECONDITIONING

- $K^+_{\text{ATP}}$ channels play an important role
The End