Cardiovascular Pathophysiology: Left To Right Shunts

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Learning Objectives

- Learn the relationships between pressure, blood flow, and resistance
- Review the transition from fetal to mature circulation
- Correlate clinical signs and symptoms with cardiac physiology as it relates to left to right shunt lesions:
  - VSD, PDA, ASD
- Discuss Eisenmenger's Syndrome

Pressure, Flow, Resistance

- Perfusion **Pressure:** Pressure gradient across vascular bed
  - Δ Mean Arterial - Venous pressure
- **Flow:** Volume of blood that travels across vascular bed
- **Resistance:** Opposition to flow
  - Vessel diameter
  - Vessel structure and organization
  - Physical characteristics of blood

Poiseuille equation

$$Q = \frac{\Delta P \pi r^4}{8nl} \qquad R = \frac{8nl}{\pi r^4}$$

ΔP = pressure drop

r = radius

n = viscosity

l = length of tube

Q = flow

$$R = \frac{\Delta P}{Q}$$

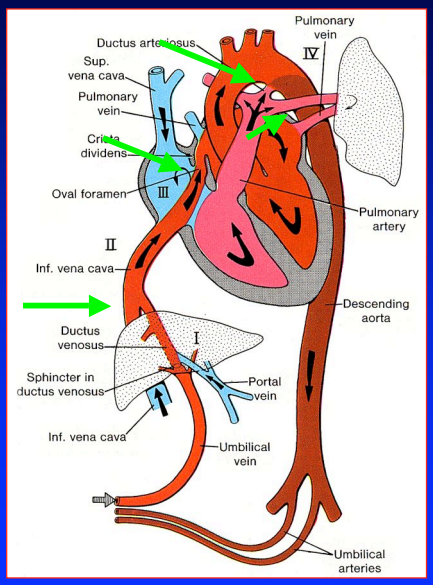
Hemodynamics

$$\text{Flow (Q)} = \frac{\Delta \text{ Pressure}}{\text{Resistance}}$$

$$\text{Resistance} = \frac{\Delta \text{ Pressure}}{\text{Flow}}$$

Two parallel fetal circulations

- Placenta supplies oxygenated blood via ductus venosus
- Foramen ovale directs ductus venous blood to left atrium (40%)
- Pulmonary blood flow minimal (<10%)
- Ductus arteriosus allows flow from PA to descending aorta (40%)



Ductus Venosus and Streaming

- Ductus venosus diverts O_2 blood through liver to IVC and RA
  - Amount varies from 20-90%
- Streaming of blood in IVC
  - O_2 blood from the DV→FO→LA→LV
  - De-O_2 blood from R hep, IVC →TV→ RV
- SVC blood flows across TV→RV
  - <5% SVC flow crosses FO

O_2 blood to high priority organs

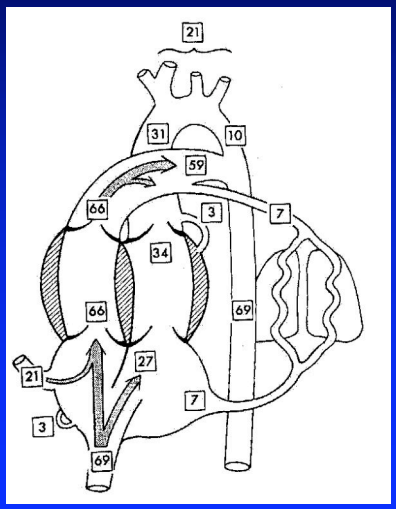
- RV pumps De-O_2 blood to PA→DA→ DescAo → lower body and placenta
- LV pumps O_2 blood to AscAo→ coronary + cerebral circ
- Aortic isthmus connects the two separate vascular beds

Fetal Shunts Equalize Pressure

- RAp = LAp due to FO
- RVp = LVp due to DA

Unlike postnatal life unless a large communication persists…

RV is "work horse" of fetal heart

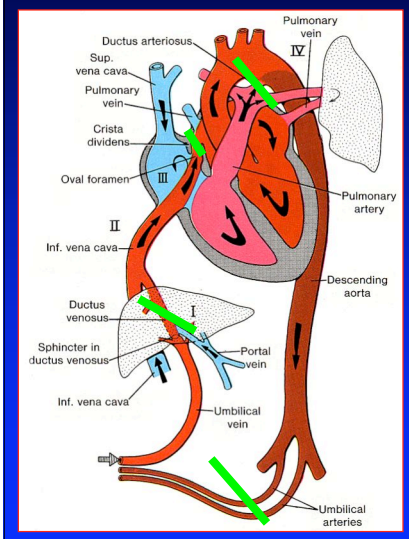


- RV pumps 66% CO
  - 59% goes to DA
    - (88% RV CO)
  - 7% goes to lungs
    - (12% RV CO)
- LV pumps 34% CO
  - 31% goes to AscAo
- Only 10% total CO crosses Ao isthmus

Transition from Fetal to Neonatal Circulation

- Lose placenta
  - ↑SVR
- Lungs expand mechanically
- ↑O_2 vasodilates pulm vasc bed
  - ↓PVR
- ↑ PBF + ↑LA venous return
  - ↑LAp
- DV constricts
  - ↓RAp

Three Fetal Shunts Close



- LAp > RAp
  - FO closure
- ↑O_2 and ↓ PGE_1
  - DA and DV constrict
- RV CO ↓
  - RV wall thickness ↓
- LV CO ↑
  - LV hypertrophies

RV CO = LV CO

Postnatal circulation in series

Regulation of Pulmonary Vascular Tone

- Vascoconstriction
  - Hypoxia/acidosis
  - High blood flow and pressure
  - Failure of vessel maturation (no regression of medial hypertrophy)
- Vasodilation
  - Improved oxygenation
  - Prostaglandin inhibition
  - Thinning of vessel media (regression of medial hypertrophy)

Fetal Pulmonary Vascular Bed

- Placenta is the organ of gas exchange
- Goal to bypass the fetal lungs

- Pulmonary Pressure >> Ao Pressure
  - Low O_2 tension causes Vasoconstriction
  - Medial wall hypertrophy
- Pulmonary blood flow << Ao flow
- Pulmonary resistance >> Ao resistance
  - Encourages shunting via DA to aorta

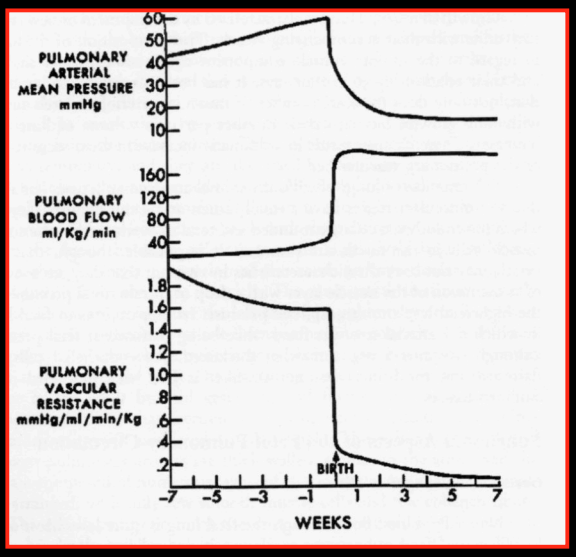
Neonatal Pulmonary Vascular Bed

- Pulmonary Pressure ≈ Ao Pressure
  - Arterial vasodilation
  - Medial wall hypertrophy persists
- Pulmonary Blood flow = Aortic Flow
  - Ductus arteriosus closes
  - Neonatal RV CO = LV CO
- Pulmonary resistance ≈ Ao Resistance

Adult Pulmonary Vascular Bed

- Pulmonary Pressure << Ao Pressure
  - 15 mmHg vs. 60 mmHg
  - Arterial Vasodilation
  - Medial wall hypertrophy regresses - remodeling
- Pulmonary Blood Flow = Aortic Flow
- Pulmonary Resistance << Ao Resistance
  - Resistance = $\frac{\Delta \text{ Pressure}}{\text{Flow}}$

Pulmonary Vascular Bed: Transition from Fetal to Adult



$$R = \frac{\Delta P}{Q}$$

Re-Cap: Fetal to Postnatal

- Fetus
  - Shunts exist
  - Lungs collapsed
  - RV CO > LV CO (Parallel circ)
  - Pulmonary pressure and resistance high
- Newborn
  - Shunts close
  - Lungs open
  - RV CO = LV CO (Series circ)
  - Pulmonary pressure and resistance drop

Left to Right Shunts

- Anatomic Communication between Pulmonary and Systemic circulations
- Excess blood flow occurs from the Systemic (Left) to the Pulmonary (Right) circulation

Qp:Qs

- Extra flow is represented by the ratio of pulmonary blood flow (Qp) to systemic blood flow (Qs)
- Qp:Qs = 1:1 if no shunts
- Qp:Qs >1 if left to right shunt
- Qp:Qs <1 if right to left shunt
- Qp:Qs of 2:1 means pulmonary blood flow is twice that of systemic blood flow

Why do we care?

- Already oxygenated pulmonary venous blood is *recirculated* through the lungs
- Excess PBF causes heart failure (CHF)
- Size of the shunt and ∴ the amount of PBF (Qp) determine how much CHF
- Shunt size determined by:
  - Location of communication
  - Size of communication
  - Age of the patient
  - Relative resistances to blood flow on either side of the communication

Pulmonary Effects of L to R Shunt

- ↑ PBF = ↑ extravascular lung fluid
  - transudation of fluid across capillaries faster than lymphatics can clear
- Altered lung mechanics
  - Tidal volume and lung compliance ↓
  - Expiratory airway resistance ↑
- Pulmonary edema results if Qp and Pulm Venous pressure very high
- Tachypnea

Neurohumoral Effects of L to R Shunt

- Sympathetic nervous system and renin-angiotensin system activation
  - plasma [NE] and [Epi] ↑
  - cardiac hormone B-type natriuretic peptide (BNP) ↑
- Tachycardia
- Diaphoresis

Metabolic Effects of L to R Shunt

- Acute and chronic malnutrition
- Mechanism not clear
  - ↑ metabolic expenditures (↑ O2 consumption) due to ↑ respiratory effort and myocardial work
  - ↓ nutritional intake
- Poor growth/ Failure to thrive

Pulmonary Hypertension: End Stage

- ↑ PBF causes sustained ↑ PAp
- Pulm vascular bed fails to remodel
  - Alveolar hypoxia may exacerbate
- Gradual effacement of the pulm arterioles
  - Overgrowth of vascular smooth muscle
  - Intimal proliferation
- Abnormal local vascular signaling
- Impaired endothelial function
- Pulm bed loses normal vasoreactivity
  - fixed pulmonary HTN and irreversible pulmonary vascular disease

Re-Cap

- Flow, Resistance, Pressure
- Fetal and Transitional Circulation
- Left to Right Shunts and CHF

- VSD
- PDA
- AVC
- ASD
- Eisenmenger

"Top 4" Left to Right Shunt Lesions

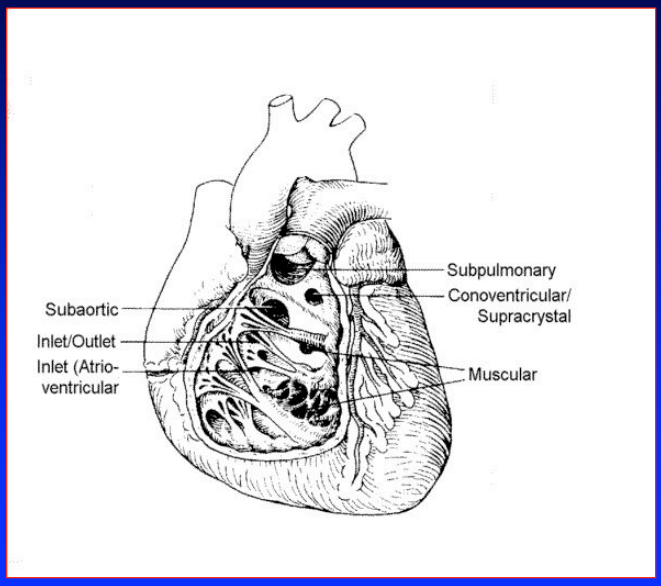
- Ventricular Septal Defect (VSD)
  - Left ventricle to Right ventricle
- Patent Ductus Arteriosus (PDA)
  - Aorta to Pulmonary artery
- Atrioventricular Canal Defect (AVC)
  - Left ventricle to Right ventricle
  - Left atrium to Right atrium
- Atrial Septal Defect (ASD)
  - Left atrium to Right atrium

VSD most common CHD (20%)

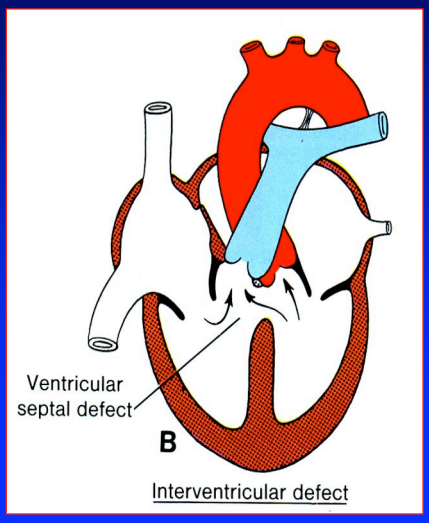
- 2/1000 live births
- Can occur anywhere in the IVS
- Location of VSD has no effect on shunt

- Perimembraneous most common (75%)
- Muscular (15%) most likely to close
- Outlet (5%) most likely to involve valves
  - ↑ incidence in Asian pop (30%)
- Inlet (5%) assoc with AVC

Ventricular Septal Defect



VSD: Determinants of L to R shunt

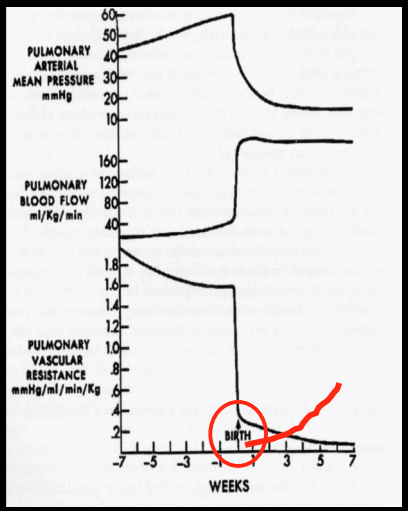


- Size of VSD
- Difference in resistance between Pulmonary and Systemic circulations
- Difference in pressure between RV and LV

VSD: Determinants of L to R shunt

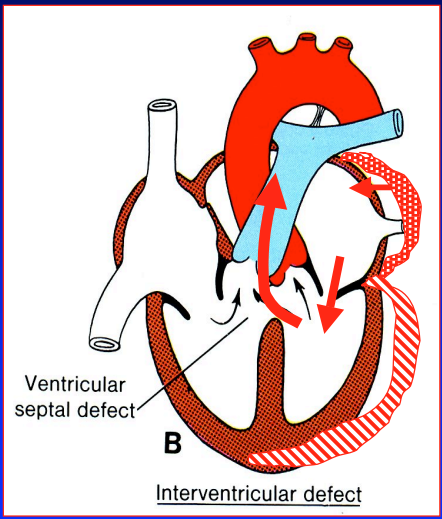
- **Small (restrictive) VSD:** L to R shunt flow limited by size of hole
- **Large (unrestrictive) VSD:** L to R shunt flow is determined by Pressure and Resistance
  - If RVp < LVp, L to R shunt occurs
  - If RVp = LVp, L to R shunt occurs if pulmonary < aortic resistance
- **Shunt flow occurs in systole**

Transitional Circulation: Effects on L to R shunt in large VSD



- Fetus: bidirectional shunt
- At Birth: No shunt
- Transition 1-7 wks
  - PA/RVp ↓ to < LVp
  - PA resistance ↓ to < Systemic
  - L to R shunt ↑

Large VSD: Hemodynamic Effects



- Flow LV→ RV→ PA
- ↑ Pulm Venous Return
- LA/LV volume overload
- ↑ LV SV initially by Starling mechanism
- ↑ LV dilation leads to systolic dysfxn & CHF
- ↑ Pulm circ leads to pulm vascular disease

VSD: Signs/Symptoms

- Asymptomatic at birth: PA = Ao Pressure and Resistance
- Signs of congestive heart failure as pulmonary pressure and resistance ↓
  - Poor feeding
  - Failure to thrive (FTT) with preserved height and low weight
  - Tachypnea
  - Diaphoresis
  - Hepatomegaly
  - Increased respiratory illness

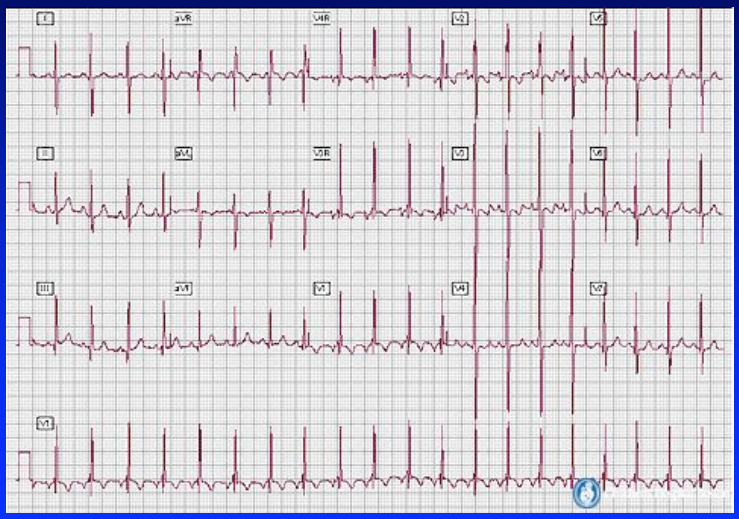
VSD: Physical Exam

- **Harsh Holosystolic murmur**
  - loudest LLSB radiating to apex and back
  - Smaller VSD = louder murmur
- **Precordial Thrill** 2° turbulence across VSD
- **Mid-Diastolic rumble** 2° ↑ trans-Mitral flow
- **LV heave** 2° LV dilation
- Signs of **CHF**
  - Gallop (S3), Hepatomegaly, Rales
- Signs of **Pulm Vasc Disease**
  - ↓murmur, RV heave, loud S2, cyanosis

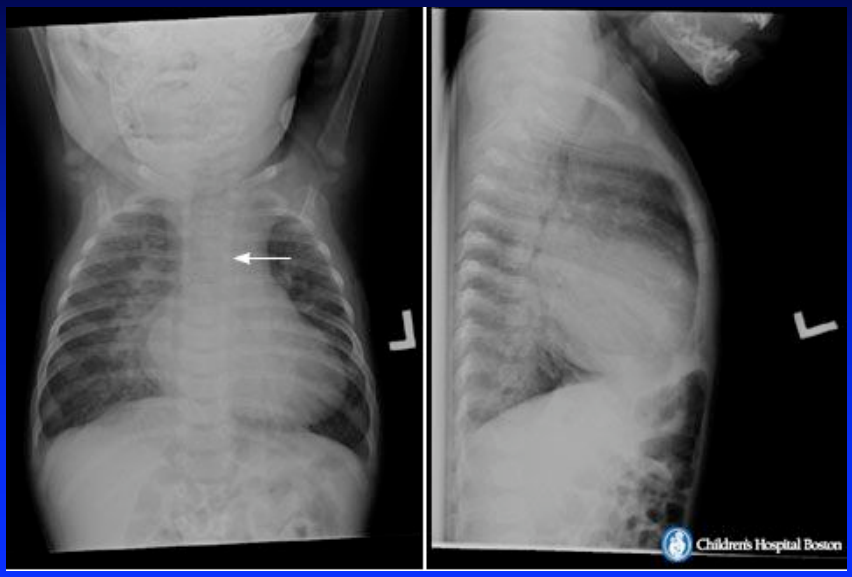
VSD: Laboratory Findings

- **CXR:** Cardiomegally, ↑PVM
  - Pulm Vasc Dz: large PAs
- **EKG:** LAE, LVH
  - Pulm Vasc Dz: RVH
- **ECHO:** Location/Size VSD
  - Amount/direction of shunt
  - LA/LV size
  - Estimation RV pressure
- **CATH:** only if suspect ↑PVR
  - O2 step up in RV

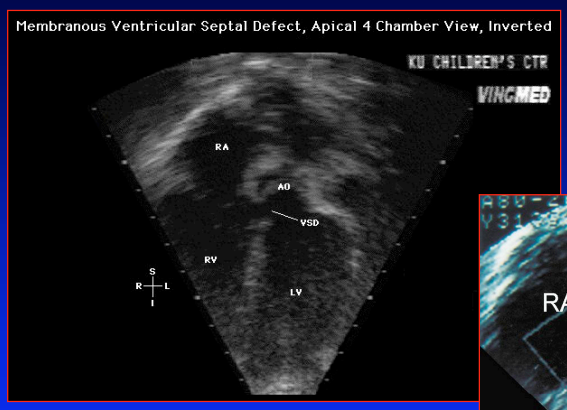
VSD: Electrocardiogram

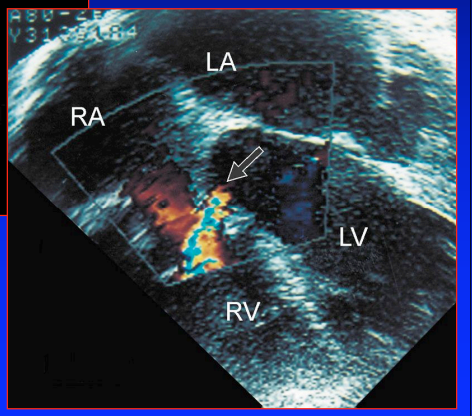


VSD: CXR

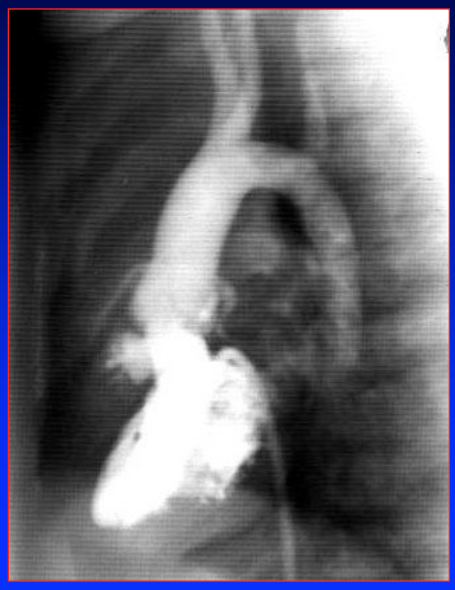


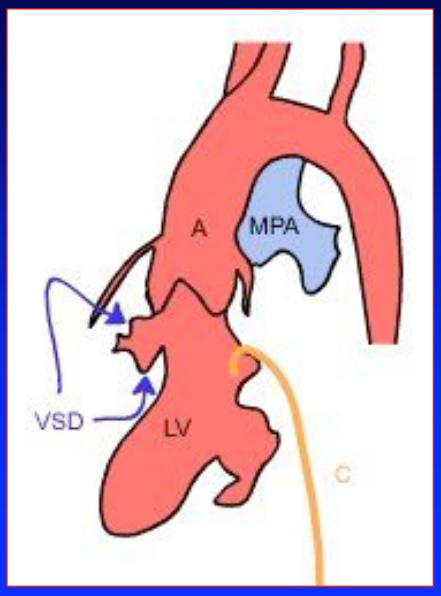
VSD: Echocardiogram





VSD: Angiogram





VSD: Management

- Does the patient have symptoms?
  - size of the defect, RV/LV pressure, Pulm/Ao resistance
- Will the VSD close or ↓in size?
- Is there potential for complications?
  - Valve damage, Pulm HTN
- Will the surgery be difficult? Will the surgery be successful?

VSD: Management

- Medical
  - Digoxin
  - Lasix
  - Increased caloric intake
  - 50% VSD size ↓ and CHF resolves
- Surgical
  - Persistent CHF
  - ↑ pulmonary vascular resistance
  - Valve damage
  - Within first two years of life
- Catheter

VSD: Endocarditis Prophylaxis

- Not for isolated VSD
- Yes for 1st 6 mo following repair of VSD with prosthetic material or device
- Yes for life if there is a residual defect at or adjacent to the site of a prosthetic device
- For dental and respiratory tract procedures ONLY
  - no longer for GI or GU procedures

Patent Ductus Arteriosus (PDA)

- Communication between Aorta and Pulmonary Artery
- 1/2500-5000 live births
- Risk factors: prematurity, rubella, high altitude

PDA: Determinants of L to R shunt

- Magnitude L to R shunt depends on
  - Length and diameter of ductus
  - Relative resistances of Ao and PA
- ↑ L to R shunt as Pulm resistance ↓
  - Volume overload of PA, LA, LV
- Shunt flow occurs in systole and diastole

PDA: Signs/Symptoms

- **Small PDA:** asymptomatic
- **Large PDA:** CHF
  - Diaphoresis
  - Tachypnea
  - Poor feeding
  - FTT
  - Hepatomegaly
  - Respiratory infections
- **Moderate PDA:** Fatigue, Dyspnea, palpitations in adol/adults
  - Afib 2º to LAE

PDA: Physical Exam

- Continuous machine-like murmur at left subclavian region
  - Ao>PA pressure in systole and diastole
- Congestive heart failure

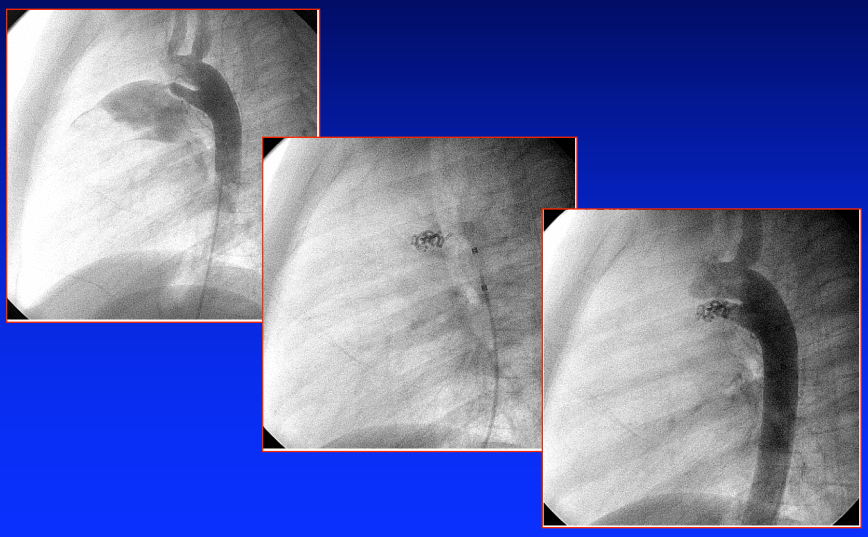
PDA: Laboratory Studies

- CXR: cardiomegally, ↑ PVM
- EKG: LAE, LVH
- ECHO: measures size PDA, shunt and gradient, estimate PAp
- CATH: O2 step up in PA

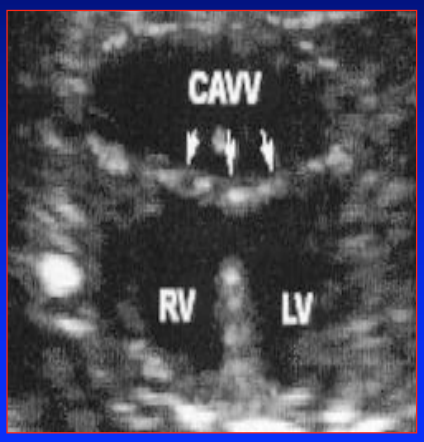
PDA: Management

- Indications for Closure
  - CHF/failure to thrive
  - Pulmonary hypertension
- Closure Methods
  - Indomethacin if preemie
  - Surgical ligation
  - Transcatheter closure
    - Coil
    - Device

PDA Coil Closure



Atrioventricular Canal Defect/ Endocardial Cushion Defect



- Atrial Septal Defect (Primum)
- Inlet VSD
- Common Atrioventricular Valve

AVC: Management

- Closure always indicated
- Timing of surgery (elective by 6 mos.)
  - Congestive Heart Failure
    - Large left to right shunt
    - Mitral insufficiency
  - Pulmonary hypertension
- Surgical repair
  - ASD, VSD closure
  - Repair of AV-Valves

Summary: VSD, PDA and AVC

- Asymptomatic in fetus and neonate
- Progressive ↑ in L to R shunt from 3-8 wks of life as pulmonary pressure and vascular resistance ↓
- Indications for intervention
  - Congestive heart failure: FTT
  - Pulmonary vascular disease
- End stage: Eisenmenger's syndrome

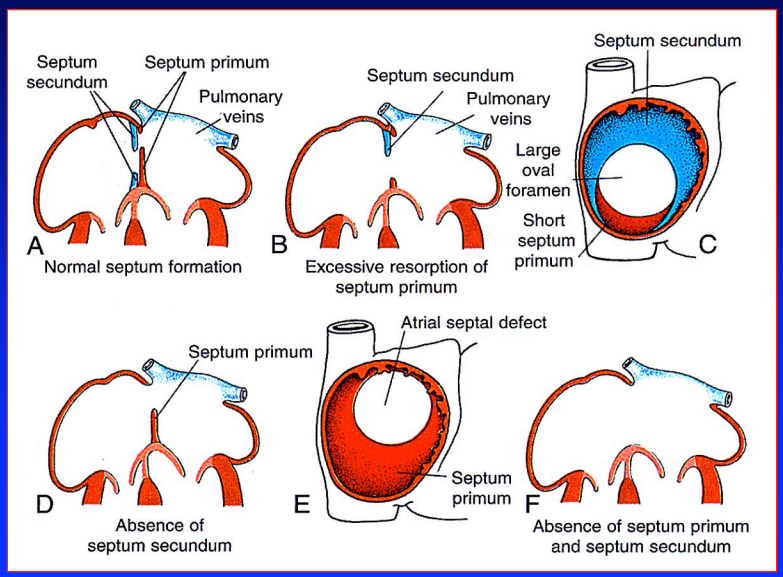
Atrial Septum Formation

- Septum Primum grows downward
- Ostium Primum obliterates
- Fenestration in septum primum forms ostium secundum
- Septum secundum grows downward and fuses with endocardial cushions
  - Leaves oval-shaped opening Foramen ovale
- Superior edge of septum primum regresses
  - Lower edge becomes flap of FO

Atrial Septal Defect

- Persistent communication between RA and LA
- Common: 1/1500 live births
  - 7% of CHD
- Can occur anywhere in septum
- Physiologic consequences depend on:
  - Location
  - Size
  - Association with other anomalies

Atrial Septal Defect (ASD)



ASD Types

- Ostium Secundum ASD (70%)
  - 2:1 F>M
  - Familial recurrence 7-10%
    - Holt-Oram syndrome - upper limb defects
  - Region of FO
  - Defect in septum primum or secundum
- Ostium Primum ASD
  - Inferior portion of septum
  - Failure of fusion between septum primum and endocardial cushions
  - Cleft in MV or CAVC

ASD Types

- Sinus Venosus ASD (10%)
  - Incomplete absorption of sinus venosus into RA
    - IVC or SVC straddles atrial septum
  - Anomalous pulmonary venous drainage
- Coronary Sinus ASD
  - Unroofed coronary sinus
  - Wall between LA and coronary sinus missing
  - Persistent L-SVC

Patent Foramen Ovale

- Prevalence 30% of population
- Failure of fusion of septum primum and secundum (flap of FO)
- Remains closed as long as LAp>RAp
  - LAp<RAp
    - Pulmonary HTN / RV failure
    - Valsalva
  - Paradoxical embolism and STROKE

ASD: Manifestations

- L to R shunt between LA and RA
  - Amount of flow determined by:
    - Size of defect
    - Relative compliance of RV / LV
  - Shunt flow occurs only in diastole
  - L to R shunt ↑ with age
    - RV compliance ↑
    - LV compliance ↓
- RA and RV volume overload

ASD: Signs/Symptoms

- Infant/child usually asymptomatic
  - DOE, fatigue, lower respiratory tract infections
- Adults (prior age 40)
  - Palpitations (Atrial tach 2º RAE)
  - ↓ stamina (Right heart failure)
  - Survival less than age-matched controls (5th-6th decade)

ASD: Physical Exam

- Small for age
- Wide fixed split S2
- RV heave
- Systolic murmur LUSB
  - ↑ flow across PV
- Mid-Diastolic murmur LLSB
  - ↑ flow across TV

ASD: Laboratory Studies

- **CXR:** cardiomegally, ↑ PVM
- **EKG:** RAD, RVH, RAE, IRBBB
  - Primum ASD: LAD
- **ECHO:** RAE, RV dilation, ASD size, location, amount and direction of shunt
- **CATH:** O2 step up in RA

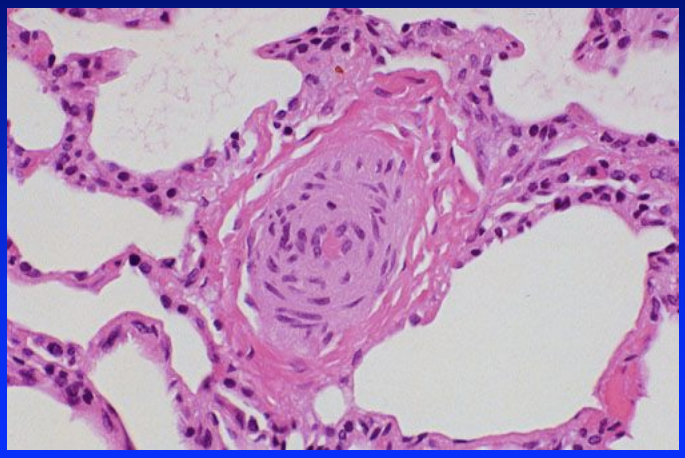
ASD: Management

- Indications for closure
  - RV volume overload
  - Pulmonary hypertension
  - Thrombo-embolism
- Closure method
  - Surgical
  - Catheter Delivered Device
    - Cardioseal
    - Amplatzer septal occluder

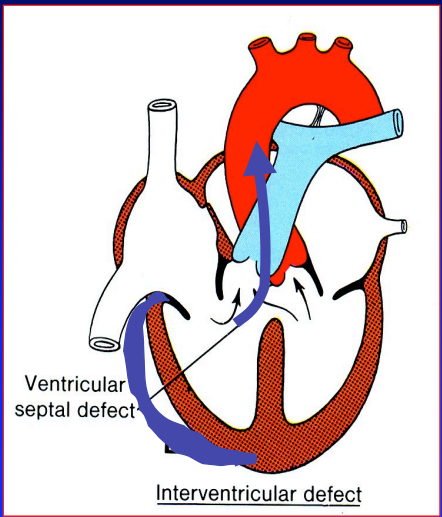
Eisenmenger's Syndrome

- Dr. Victor Eisenmenger, 1897
- Severe pulmonary vascular obstruction 2º to chronic left to right shunts
- Pathophysiology
  - High pulmonary blood flow→ Shear Stress
  - Medial hypertrophy + intimal proliferation leads to ↓cross-sectional area of pulm bed
  - Perivascular necrosis and thrombosis
  - Replacement of normal vascular architecture
- Pulmonary vascular resistance increases
  - Right to left shunt
  - Severe cyanosis

Medial Hypertrophy



Eisenmenger's Syndrome
R to L flow via VSD



- Pressure:
  - Pulmonary = Aortic
- Resistance
  - Pulmonary > Aorta
- RV hypertrophy
- Blood flow: RV to LV
- Cyanosis
- Normal LA/LV size

Eisenmenger's: Signs/Symptoms

- Infancy:
  - CHF improves with ↓ left to right shunt
- Young adulthood:
  - Cyanosis/Hypoxia: DOE, exercise intolerance, fatigue, clubbing
  - Erythrocytosis/hyperviscosity: H/A, stroke
  - Hemoptysis 2º to infarction/rupture pulm vessels

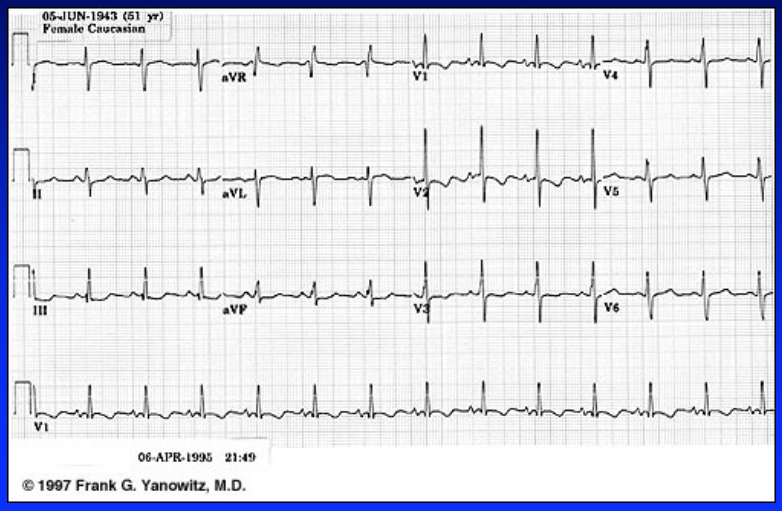
Eisenmenger's: Physical Exam

- Clubbing
- Jugular venous a-wave pulsations
  - ↑RV pressure during atrial contraction
- Loud S2
- RV heave (RV hypertension)
- Diastolic pulm insufficiency murmur
- No systolic murmur

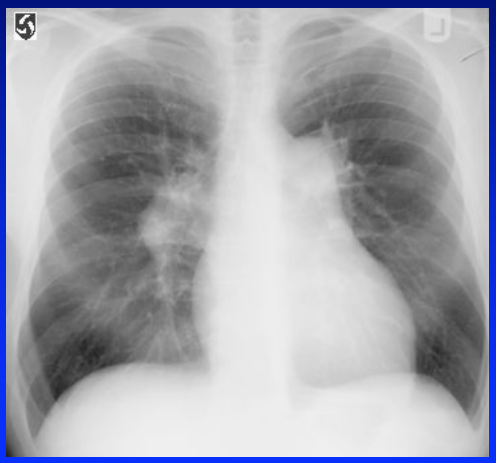
Eisenmenger's: Lab findings

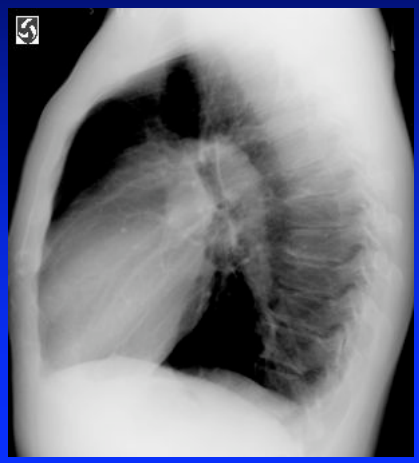
- No LV volume overload / ↑ RV pressure
- CXR: Clear lung fields, prominent PA segment with distal pruning, small heart
- EKG: RAE, RVH ± strain
- ECHO: RV hypertrophy, right to left shunt at VSD, PDA, or ASD

EKG: Eisenmenger's Syndrome



Eisenmenger's Syndrome: CXR





Eisenmenger's: Management

- Avoid exacerbating right to left shunt
  - No exercise, high altitude, periph vasodilators
  - Birth Control: 20-40% SAB, >45% mat mortality
- Medical Therapy:
  - Pulmonary vasodilators: Calcium channel blocker, PGI2, Sidenafil
  - Inotropic support for Right heart failure
  - Anticoagulation
- Transplant
  - Heart-Lung vs Lung transplant, heart repair
- Do NOT close Defect
  - VSD/PDA/ASD must stay open
  - Decompress high pressure RV, prevent RV failure and provide cardiac output

Learning Objectives

- Learn the relationships between pressure, blood flow, and resistance
- Review the transition from fetal to mature circulation
- Correlate clinical signs and symptoms with cardiac physiology as it relates to left to right shunt lesions:
  - VSD, PDA, ASD
- Discuss Eisenmenger's Syndrome