

# 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

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## Pressure, Flow, Resistance

- **Perfusion Pressure: Pressure gradient across vascular bed**
  - $\Delta$  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

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### Poiseuille equation

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

$\Delta P$  = pressure drop

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

$n$  = viscosity

$l$  = length of tube

$Q$  = flow

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### Hemodynamics

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

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

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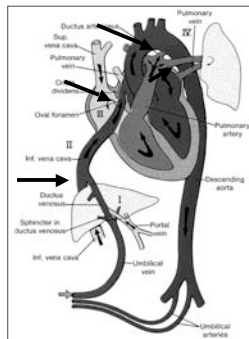
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### Two parallel fetal circulations

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




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### **Ductus Venosus and Streaming**

- **Ductus venosus diverts O<sub>2</sub> blood through liver to IVC and RA**
  - Amount varies from 20-90%
- **Streaming of blood in IVC**
  - O<sub>2</sub> blood from the DV→FO→LA→LV
  - De-O<sub>2</sub> blood from R hep, IVC →TV→ RV
- **SVC blood flows across TV→RV**
  - <5% SVC flow crosses FO

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### **O<sub>2</sub> blood to high priority organs**

- **RV pumps De-O<sub>2</sub> blood to PA→DA→ DescAo → lower body and placenta**
- **LV pumps O<sub>2</sub> blood to AscAo→ coronary + cerebral circ**
- **Aortic isthmus connects the two separate vascular beds**

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### **Fetal Shunts Equalize Pressure**

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

**Unlike postnatal life unless a large communication persists...**

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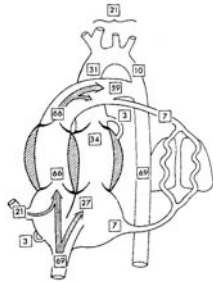
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### RV is “work horse” of fetal heart



- **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**

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### Transition from Fetal to Neonatal Circulation

- **Lose placenta**
  - ↑SVR
- **Lungs expand mechanically**
- **↑O<sub>2</sub> vasodilates pulm vasc bed**
  - ↓PVR
- **↑ PBF + ↑LA venous return**
  - ↑LAp
- **DV constricts**
  - ↓RAp

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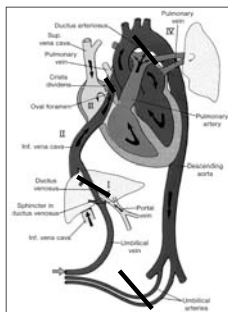
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### Three Fetal Shunts Close



- **LAp > RAp**
  - FO closure
- **↑O<sub>2</sub> and ↓PGE<sub>1</sub>**
  - DA and DV constrict
- **RV CO ↓**
  - RV wall thickness ↓
- **LV CO ↑**
  - LV hypertrophies

**RV CO = LV CO**  
**Postnatal circulation in series**

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### **Regulation of Pulmonary Vascular Tone**

- **Vasoconstriction**
  - 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)

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### **Fetal Pulmonary Vascular Bed**

- Placenta is the organ of gas exchange
- Goal to bypass the fetal lungs
  
- **Pulmonary Pressure >> Ao Pressure**
  - Low O<sub>2</sub> tension causes Vasoconstriction
  - Medial wall hypertrophy
- **Pulmonary blood flow << Ao flow**
- **Pulmonary resistance >> Ao resistance**
  - Encourages shunting via DA to aorta

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### **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**

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

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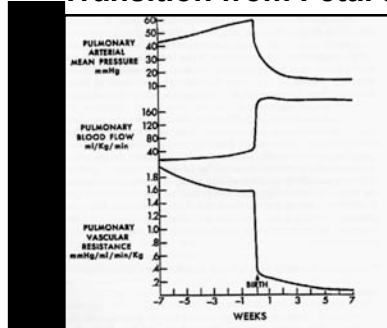
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### Pulmonary Vascular Bed: Transition from Fetal to Adult



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

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### 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

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### Left to Right Shunts

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

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### 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**

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### 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  $\therefore$  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

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### **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**

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### **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**

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### **Metabolic Effects of L to R Shunt**

- **Acute and chronic malnutrition**
- **Mechanism not clear**
  - ↑ metabolic expenditures (↑ O<sub>2</sub> consumption) due to ↑ respiratory effort and myocardial work
  - ↓ nutritional intake
- **Poor growth/ Failure to thrive**

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### **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

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### **Re-Cap**

- Flow, Resistance, Pressure
- Fetal and Transitional Circulation
- Left to Right Shunts and CHF
  
- VSD
- PDA
- AVC
- ASD
- Eisenmenger

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### **“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

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### 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

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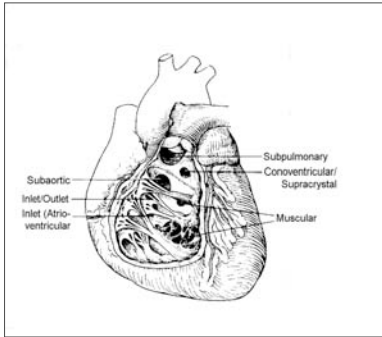
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### Ventricular Septal Defect



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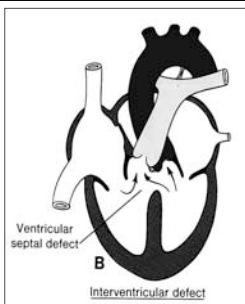
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### VSD: Determinants of L to R shunt



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

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### 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

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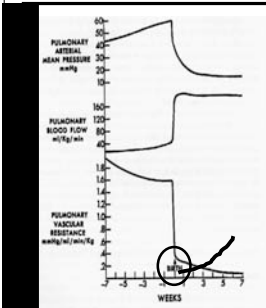
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### Transitional Circulation: Effects on L to R shunt in large VSD



- Fetus: bidirectional shunt
- At Birth: No shunt
- Transition 1-7 wks
  - $PA/RVp \downarrow$  to  $< LVp$
  - $PA$  resistance  $\downarrow$  to  $< Systemic$
  - L to R shunt  $\uparrow$

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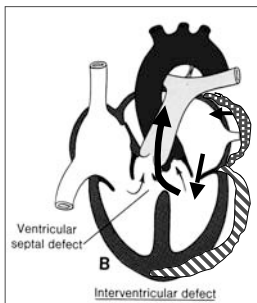
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### Large VSD: Hemodynamic Effects



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

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### 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

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### 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

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### 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

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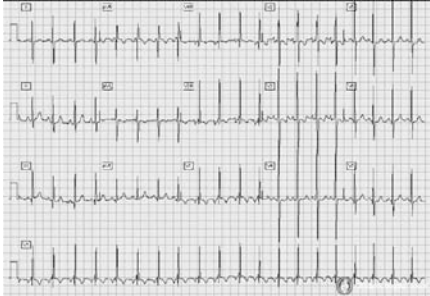
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### VSD: Electrocardiogram



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### VSD: CXR



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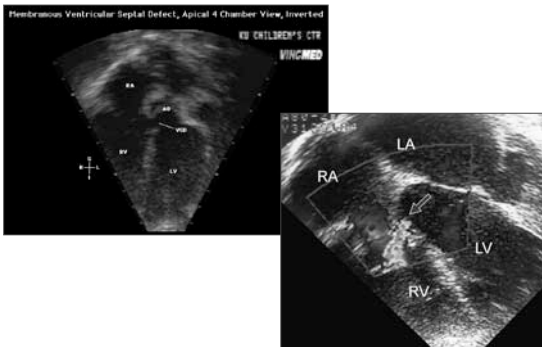
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### VSD: Echocardiogram



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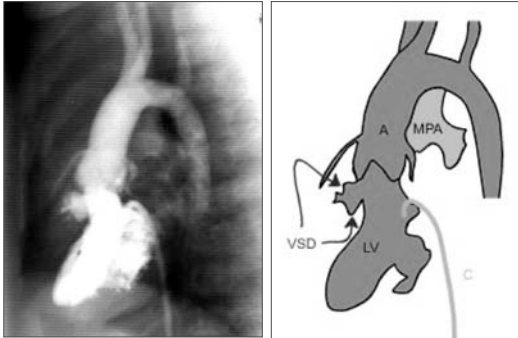
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### VSD: Angiogram



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### 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?

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### 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

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### **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

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### **Patent Ductus Arteriosus (PDA)**

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

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### **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

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### **PDA: Signs/Symptoms**

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

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### **PDA: Physical Exam**

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

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### **PDA: Laboratory Studies**

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

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## PDA: Management

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

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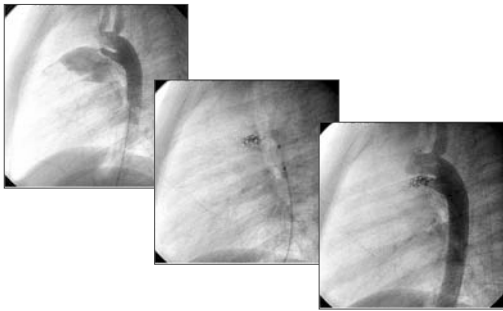
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## PDA Coil Closure



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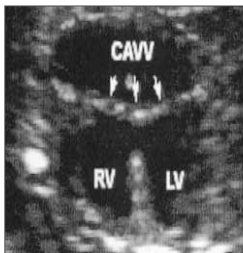
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## Atrioventricular Canal Defect/ Endocardial Cushion Defect



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

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### **AVC: Management**

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- 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

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### **Summary: VSD, PDA and AVC**

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

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### **Atrial Septum Formation**

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- 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

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## 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

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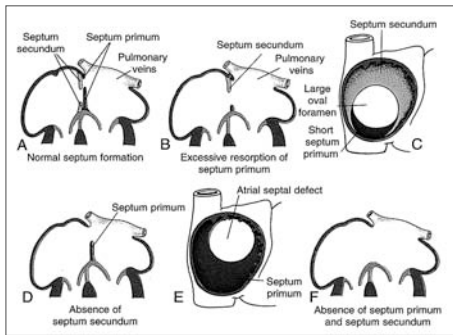
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## Atrial Septal Defect (ASD)




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## 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

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### 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

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### 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

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### 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**

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### **ASD: Signs/Symptoms**

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

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### **ASD: Physical Exam**

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

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### **ASD: Laboratory Studies**

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- **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**

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## ASD: Management

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

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## Eisenmenger's Syndrome

- Dr. Victor Eisenmenger, 1897
- Severe pulmonary vascular obstruction 2° 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

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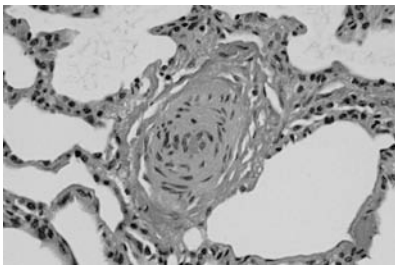
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## Medial Hypertrophy



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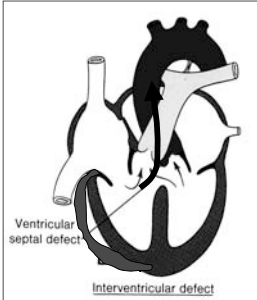
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## Eisenmenger's Syndrome R to L flow via VSD



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

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## 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 2° to infarction/rupture pulm vessels

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## 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**

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### Eisenmenger's: Lab findings

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

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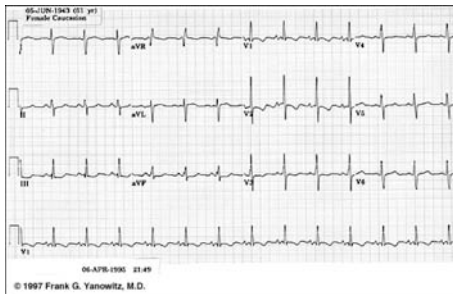
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### EKG: Eisenmenger's Syndrome



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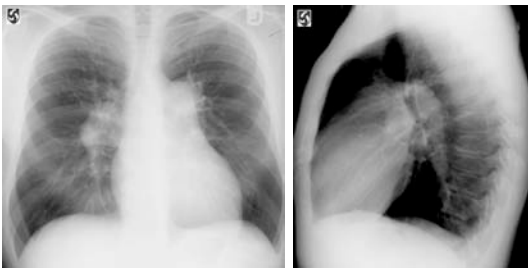
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### Eisenmenger's Syndrome: CXR



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## **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, PGI<sub>2</sub>, Sildenafil
  - 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

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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**

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