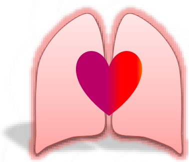


RESPIRATORY MEETING, WISCONSIN

HEART ⇆ LUNG INTERACTIONS 4/26/2011

Stephen Kurachek, MD FAAP TTS CRCCS

INTRODUCTION

Dr. Stephen Hales in the 17th century measured the BP of a horse by inserting a glass tube into the carotid artery. He demonstrated that the heart pumped and BP changed with respirations. Yes, the horse died.

Cardiopulmonary Interactions

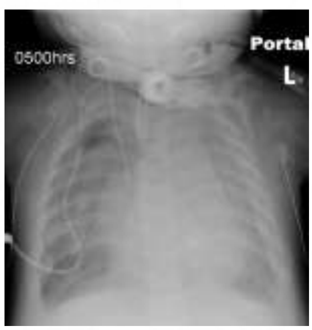
- Geography and Function
- Autonomic Tone
- Venous Return
- Pulmonary Vascular Resistance
- Ventricular Function
- Clinical Implications

GEOGRAPHY

7 year old boy with ARDS requiring 20 cm of PEEP with secondary myocardial dysfunction.

GEOGRAPHY

10 month old with critical mitral valve stenosis with secondary pulmonary edema pleural effusions.



GEOGRAPHY

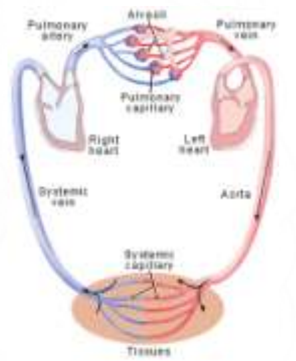
22 month old with status asthmaticus emergently in-tubated for acute respiratory failure complicated with bilateral tension pneumothoraces.

FUNCTION

Oxygen delivery

Cardiac performance
- Heart rate
- Preload
- Afterload
- Contractility

Pulmonary performance
- Respiratory rate
- System compliance
- Airway resistance
- Gas exchange



www.lib.mcg.edu/.../section4/4ch4/s4ch4_16.htm

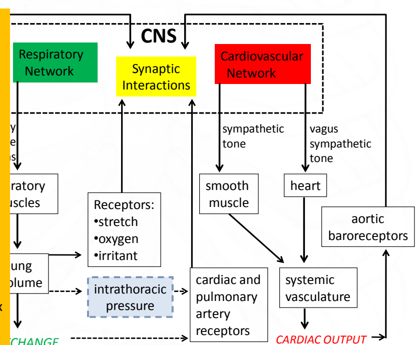
FUNCTION

AUTONOMIC RESPONSES

- Respiratory sinus arrhythmia

  Hyperinflation induced sinus decelleration

  Hyperinflation induced vasodilation
- Atrial stretch receptors :
  - atrial natriuretic peptide
  - antidiuretic hormone
- Pulmonary hypertension reflex
- Tachypnea – heart failure

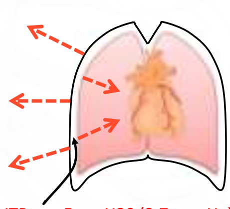


Modified from G.D. Pinna et al. *Am. J. Physiol. Heart Circ. Physiol.* 278: H932–H941, 2000

FUNCTION

- chest wall
- thoracic cavity
- intra-thoracic pressure (ITP)
  - lung elastic recoil pressure
  - rib cage pulls outward
  - balance = subatmospheric pressure
  - functional residual capacity (FRC):

    Equilibrium volume when the elastic recoil of the lung is balanced by the tendency of the chest wall to spring out.

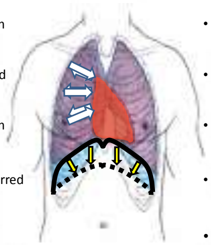


ITP = - 5 cm H20 (3.7 mm Hg)

VENOUS RETURN

Spontaneous breathing

- Descent of the diaphragm ↓ ITP (more negative)
- Reduced ITP is transferred to the right atrium
- Descent of the diaphragm ↑ Pabd
- Increased Pabd is transferred to Pmsv
- **Venous return increases**



Positive pressure breathing

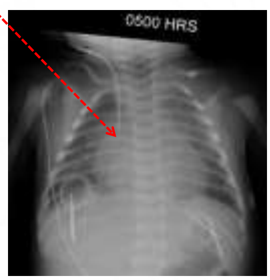
- Positive pressure is applied to the airway and ↑ ITP
- Increased ITP is transferred to the right atrium
- Descent of the diaphragm ↑ Pabd
- Increased Pabd is transferred to Pmsv
- **Venous return decreases**

$$\text{systemic venous return} = \frac{Pmsv - Pra}{Rv}$$

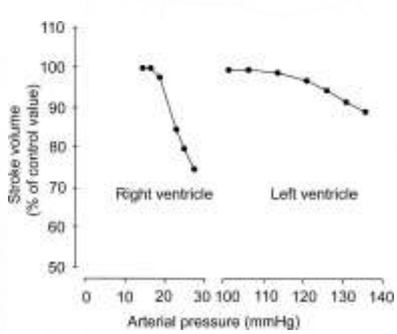
VENOUS RETURN

Determinants of *Right Atrial Pressure* *(CVP)*

- ✓ right atrial volume
- ✓ right atrial compliance
- ✓ right ventricular compliance
- ✓ tricuspid valve integrity
- ✓ intra-thoracic pressure



VENOUS RETURN: RIGHT VENTRICULAR COMPLIANCE



MacNee, W. AJRCCM, 1994; 150:833-852.

PULMONARY VASCULAR RESISTANCE

$$\text{cardiac output } (Q) = \frac{P\overline{AP} - PLa}{PVR}$$

$$PVR = \frac{P\overline{AP} - PLa}{Q}$$

- **RV** compliant low pressure pump
- **PVR** approximates RV afterload
- **PVR** has many determinants:
  - ✓ developmental moment
  - ✓ lung volume
  - ✓ gas exchange
  - ✓ acid – base balance
  - ✓ medications (including NO)

IN UTERO

- Fetal fluid compresses capillaries.
- PVR is almost immeasurably high.
- 90% of the cardiac output is directed away from the lungs.

DEVELOPMENTAL FAILURE

- Pulmonary hypoplasia
- Alveolar capillary dysplasia

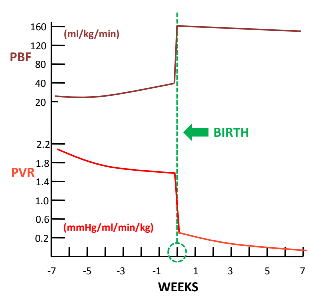
BIRTH

- Expulsion of fetal fluid.
- First breath, rhythmic respirations, ↑ oxygen tension : ↓ PVR.
- Ductus closes; foramen closes; systemic vascular resistance ↑.

TRANSITION FAILURE

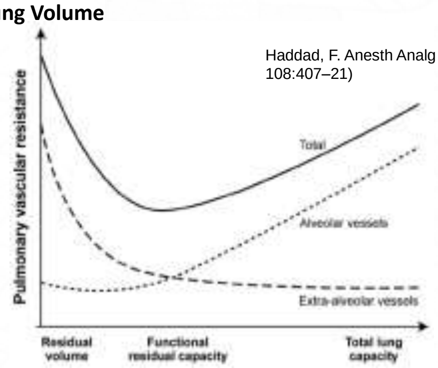
- Persistent pulmonary hypertension of the newborn.

PULMONARY VASCULAR RESISTANCE: Developmental Moment

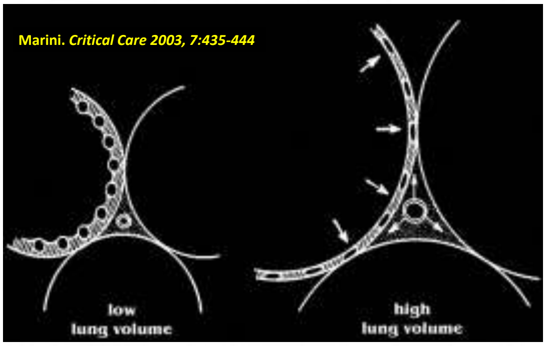


PULMONARY VASCULAR RESISTANCE: Lung Volume

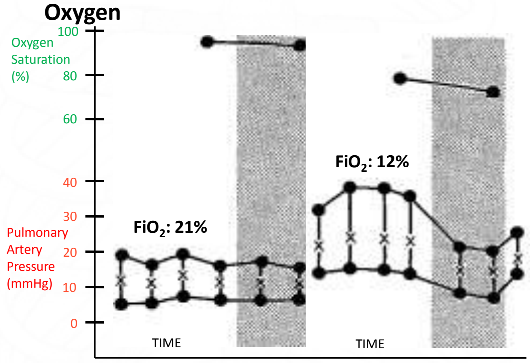
Haddad, F. Anesth Analg 2009; 108:407–21)



PULMONARY VASCULAR RESISTANCE: Lung Volume

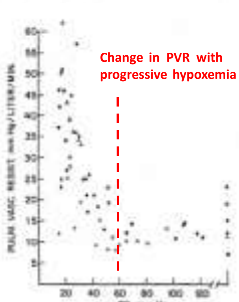


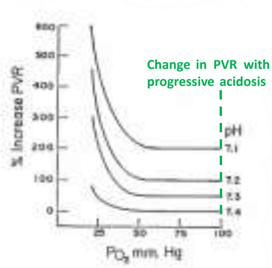
PULMONARY VASCULAR RESISTANCE: Oxygen



Cournand: Nobel Lecture 1956

PULMONARY VASCULAR RESISTANCE: Oxygen and pH

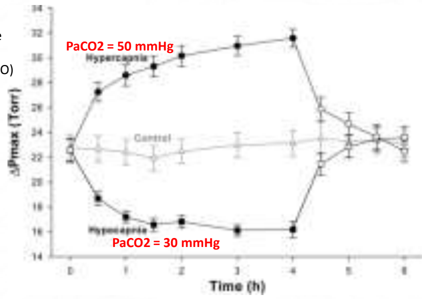




Rudolph AM. JCI: 45; 399, 1966

PULMONARY VASCULAR RESISTANCE: Carbon Dioxide

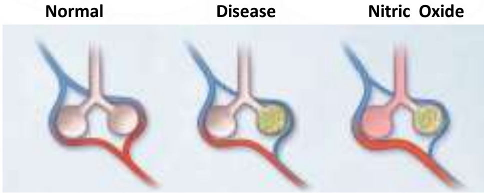
tricuspid valve max pressure gradient (ECHO)



Balanos GM. *J Appl Physiol 94: 1543–1551, 2003*

PULMONARY VASCULAR RESISTANCE: Nitric Oxide

Normal **Disease** **Nitric Oxide**

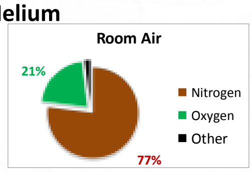


Griffiths MJD. N Engl J Med 2005;353:2683-95

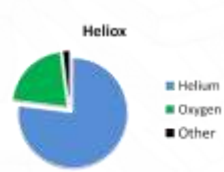
iNo : selective pulmonary vasodilator
rapidly reduces pulmonary artery hypertension
improves impaired oxygenation

Work of Breathing: Helium

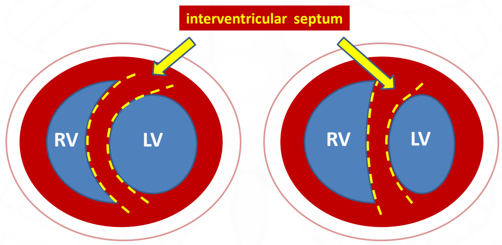
Helium is an inert gas:
- less dense than nitrogen
- ↓ turbulent gas flow
- ↓ airway resistance
- CO2 solubility
- medication solubility



Heliox ⇨ ↓ **work of breathing**
↑ **ITP**
⇨ ↓ **VR** + ↑ **lung vol** ⇨ ↓ **PVR**
⇨ ↓ **LV afterload** ⇨ ↓ **O2 consumption**
↑ **cardiac performance**



LV FUNCTION: Ventricular Interdependence



↑PVR (afterload) and/or ↑ venous return (labored breathing) ⇨ ↑RVEDV ⇨ shift of interventricular septum ⇨ ↓ LV compliance ⇨ ↓ LVEDV ⇨ ↓ CARDIAC OUTPUT

LV FUNCTION: Left Ventricular Afterload

- LV afterload is defined as the maximal LV systolic wall tension:
  - LVEDV
  - ITP
  - arterial impedence
- LV ejection pressure parallels LV afterload:

LVejp = LVsys - ITP

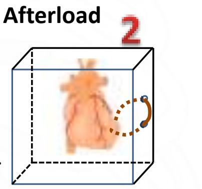
spontaneous breathing	**110 = 70 - (-40)**
positive pressure vent	**45 = 70 - (25)**

+ pressure ventilation ↓ LV afterload

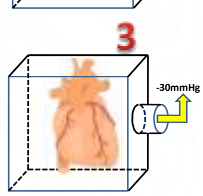
LV FUNCTION: Left Ventricular Afterload

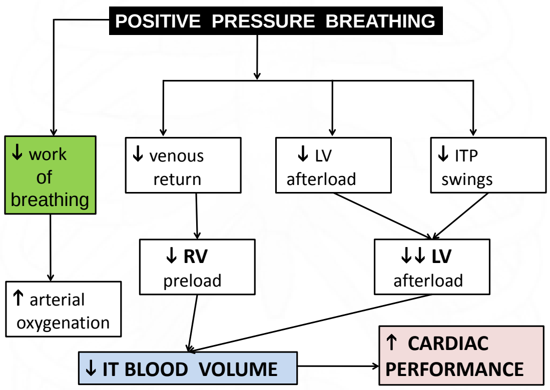
The heart resides in a "box": the thorax. When ITP is negative (and/or excessive) LV contraction is impaired.

LV free wall is fixed to the side of the box with an "elastic suture". Contraction of the LV is impaired.



After removing the suture, suction is applied to the box. LV contraction is impaired.





CLINICAL IMPLICATIONS: LRM

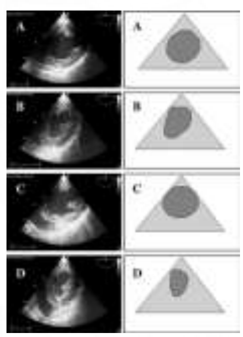
Lung Recruitment Manueuvers and LV Compliance (TEE)

BASELINE STUDY

40CM HOLD FOR 10 SEC

BASELINE STUDY

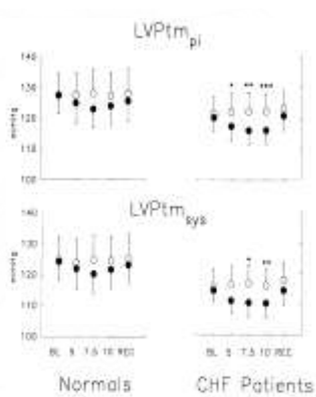
40cm HOLD FOR 20 SEC



Nielsen J, et al. ICM. 2005, 31:1189–1194

CLINICAL IMPLICATIONS: CPAP

CPAP, predictably, decreases LVEP by increasing ITP. This occurs despite patients being on medicinal afterload reducing agents. + ITP AFTERLOADS the LV in CHF patients but not normals.



Naughton, M. T. et al. Circulation 1995;91:1725-1731

CLINICAL IMPLICATIONS: CPR

Adhesive glove device (AGD) with active compression – decompression CPR in a pig model:

Carotid Blood Flow
AGD-CPR: 53.2 27.1%
S-CPR: 19.1 12.5%

Active decompression causes ITP to become more negative increasing venous return. Incomplete chest recoil impedes venous return and thus cardiac output.

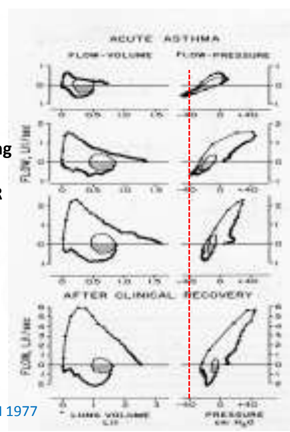
Udassi JP et al. Circulation, 2009;120:S1451

CLINICAL IMPLICATIONS: ASTHMA

Acute asthma

- spontaneous:
  - ↑ work of breathing
  - ↑ VR
  - ↑ hypoxia ⇨ ↑ PVR
  - ↑ PaCO2 ⇨ ↑ PVR
  - ↑ RV dimension
  - ↓ LV dimension
- intubation
  - ↑↑ hyperinflation
  - ↑ PVR
  - ↓ VR
  - ↑ RV dimension
  - ↓ LV dimension

↓ CO



Stalcup & Mellins. NEJM 1977

CLINICAL IMPLICATIONS: ASTHMA

20 year old with acute and severe asthma brought to ED by ambulance receiving bag-mask ventilation. Pt lethargic with poor respiratory effort. Oxygen saturation 80% with 100% FiO2. Poor intake for 48hrs. 2-3 vomiting episodes in the last 24hrs. Pt. arrested on intubation. CPR was unsuccessful.

Terminal asthma: massive hyperinflation; alveolar-capillary compression

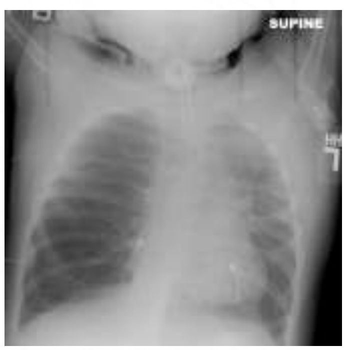
CLINICAL IMPLICATIONS: CDH

Newborn with acute respiratory failure upon delivery. Poor color, desaturation, and poor perfusion resulted in immediate intubation. Initial ABG: pH 6.95, PaCO2 96; PaO2 42. Pt "stabilized" with HFOV, pH correction, NO, and 100% FiO2 but ultimately required ECMO support and CDH repair.
Infant requires chronic ventilation but has a good long term prognosis.

Diaphragmatic hernia: R pneumothorax; bowel in L pleural space.

CLINICAL IMPLICATIONS: AUTONOMIC DYSFUNCTION

4yr old former 24 week pre-mature infant weaning off of chronic mechanical ventilation. At 6mo of age he had "BPD spells". Agitated, he would perform an expiratory breath hold, become cyanotic, brady-cardic, and asystolic. A pace-maker was placed to offset these vagal events.

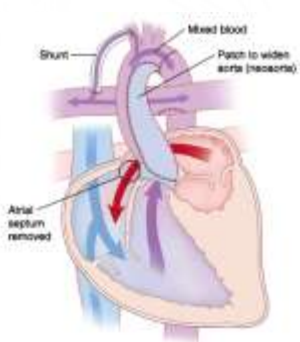


CLINICAL IMPLICATIONS: HLHS

HLHS

- "too pink": ↑ PVR
- "too blue": ↓ PVR

↑ O2 sats ⇨ ↑PBF ⇨ ↓ systemic delivery ⇨ ↑ acidosis ⇨ ↓ CO

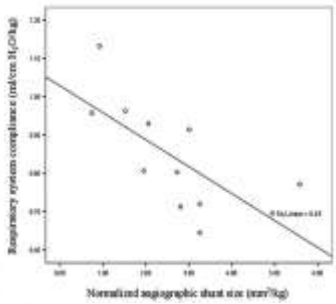


Reddy VM. J Thorac CV Surg 1996;112:437-49

CLINICAL IMPLICATIONS: HLHS

Shunt Size and Respiratory Compliance

Patients with single ventricle physiology. There was an inverse relationship between the normalized size of the shunt (both surgical and naturally occurring) and C_{rs}/kg (r = -0.60, r^2 = 0.36, p = 0.03, n = 14).

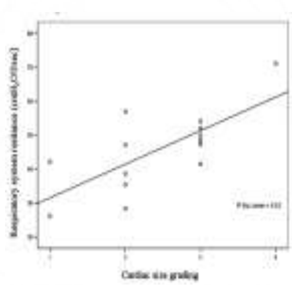


Iren L. Matthews, et al. PCCM. 2009;10;1:60-65.

CLINICAL IMPLICATIONS: HLHS

Cardiac Size and Respiratory Resistance

Patients with single ventricle physiology. There was a direct relationship between the cardiac size on CXR and respiratory system resistance.



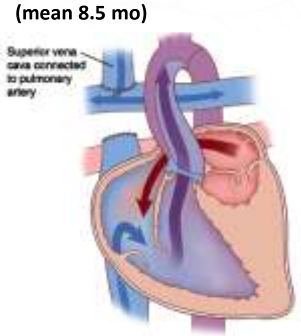
Iren L. Matthews, et al. PCCM. 2009;10;1:60-65.

CLINICAL IMPLICATIONS: HLHS

Bidirectional Glenn: 15 patients ages 4.7 - 15.5 months (mean 8.5 mo)

Glenn shunt

- post-op cyanosis
- ↑ PaCO2 ⇨ ↓ CVR ↑ cerebral, caval, and pulmonary blood flow ⇨ ↑ O2 sats
- if ↑ PVR suspected ⇨ add NO



CLINICAL IMPLICATIONS: HLHS

Extra-cardiac Fontan with Gortex lateral tunnel

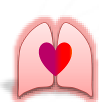
Post-op Fontan
- pulmonary blood flow (VR) is "passive"
- promote PBF:
  - ↓ PVR –
    - O2, ↓ CO2, NO, ↑pH
    - normal lung volume
    - analgesia
  - ↓ ITP –
    - limit PEEP, tidal volume, I-time
    - limit pressure support
    - add spontaneous resps
  - avoid atelectasis / VAP

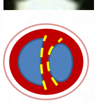
CLINICAL IMPLICATIONS: CHF

Chronic Heart Failure

- abnml lung mechanics
- ↓ lung diffusion
- ↑ dead space ventilation
- ↓ lung compliance
- ↑ airway resistance

SUMMARY





- The heart and lungs are intimate neighbors.
- Autonomic reflexes are linked within a central controller and coupled by ITP.
- ITP changes impact the function of both organs.
- Spontaneous breathing is driven by **-** ITP:
  - ↑ venous return
  - ↑ left ventricular afterload
- Mechanical ventilation is driven by **+** ITP:
  - ↓ venous return
  - ↓ left ventricular afterload
- PVR approximates RV afterload.
- LV ejection pressure parallels LV afterload.
- Airway obstruction *in extremis* results in biventricular failure.
- Heart failure disrupts pulmonary function.
- Heart – lung interactions are common in critical care.