Cardiorespiratory Interactions:
The Heart - Lung Connection and the Role of HFV

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Optimizing CRI

- Cardiorespiratory Economics
- \( \text{O}_2 \): supply vs. demand
- CRI: The Heart
- CRI: The Lung
- Conventional Ventilation
- Non-Conventional Ventilation
- Clinical Applications
Cardiorespiratory Economics

• **O₂ Delivery:**
  
  \[ \text{DO}_2 = \text{C. O.} \times (\text{CaO}_2) \]
  
  \[ \text{CaO}_2 = 1.36 \times \text{Hgb} \times \text{SaO}_2 + \text{PaO}_2 \times 0.003 \]

• **O₂ Consumption** = amount of oxygen used for aerobic metabolism

• Failure to meet the demands results in anaerobic metabolism
Cardiorespiratory Economics
Optimizing CRI

• ↑ O2 delivery
  ↑ O2 content: ↑ Hgb, ↑ O2 sat, ↑ PaO2
  ↑ cardiac output
  cardiac interventions: another talk
  pulm interventions: this talk

• ↓ O2 consumption: ↓ patient WOB
Cardiorespiratory Interactions

Definition

- Effects of intrathoracic pressure, lung volume, and gas exchange on:
  - Cardiovascular events such as venous return, ventricular performance, and arterial outflow.
Congenital Heart Disease

- 25,000 Babies/yr with Moderate to Severe CHD
  - Surgical correction/palliation within first year
- Exposure to Systems:
  - Cardiopulmonary bypass (CPB): Exposure to foreign surface
  - Hemodilution: Contributes to the development of pulmonary edema
  - Hypothermia: Cellular injury
  - DHCA/Low flow CPB – worsens lung mechanics
  - Reperfusion: Causes reperfusion injury
System’s Effects

• Acute Changes Complicate Management:
  • Pro-inflammatory
  • Pro-thrombotic
  • Oxidant stress pathways

• Systemic inflammation response and diffuse capillary permeability contributes to organ dysfunction (de Mendonca-Filho, 2006)
  – Infants are more susceptible to inflammation following CPB
Infants Have an Exaggerated Post-CPB Inflammatory Response

- Mechanism well understood
  - Peak inflammatory effect 4-6 hours post-CPB
  - Preceded by oxidant stress
- CPB precipitates hemolysis
  - Generates oxidants
  - Increases vascular permeability
- CPB-induced hemolysis is more severe in infants
  - Greater relative exposure to non-endothelialized surfaces
  - Ischemia/reperfusion with DHCA
  - Smaller cannulae size with ↑ mechanical shear stress
  - CPB circuit primed with stored blood
Low Cardiac Output Syndrome
Decrease in CI in Newborns post ASO

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Post CPB Lung Injury in Infants

• Surfactant Inactivation (Greise, 1999)
  • Interstitial and alveolar edema
  • Immature antioxidant defenses

• Risk and severity of lung injury in infants
  • ↑ Duration of CPB (Rady, CCM, 1997)
  • Younger age
  • ↑ IL-6, IL-8, TNF-α (Liu, 2009)

• Early pulmonary dysfunction associated with
  ↑ morbidity, ↑ MODS, ↑ LOS, ↑ mortality
  (Laffey, 2002)
Heart Lung System

SVC / IVC

R. A.

R. V.

Lungs

Extrathoracic

Intrathoracic

Pericardial Space
Right Ventricular Filling

Effects on RV

Vena Cava

Thorax

Positive Pressure Ventilation

RA

RV

PA
Systemic Venous Return (RV Preload)

\[ P_{SV} \]

\[ \text{RAP} = \text{mean systemic venous pressure} \]

PPV increases right atrial pressure

spontaneous breathing

Right Atrial Pressure

Systemic Venous Return

Max
Effects of PPV on Right Ventricle

• ↑ intrathoracic pressure ↓ C.O.
  • ↓ RV preload
  • ↑ PVR

• Best strategy for the failing RV is to limit intrathoracic pressure
Effects of PPV on LV Filling

Thoracic Pump Augmentation

Thoracic Cavity

Lung

LA

LV

AO
Effects of PPV on LV Filling

Thoracic Pump Augmentation

Thoracic Cavity
Positive Pressure Ventilation
Effects of PPV on LV Afterload

Spontaneous

LV$_{TM}$=130

-30

PPV

LV$_{TM}$=70

+30

Thorax

100

AO

LV

130

100

LV

70
Effects of PPV on Left Ventricle

- ↑es in intrathoracic pressure ↑ C.O.:
  - ↑ ing LV preload when low
  - ↓ ing LV afterload
  - ↓ preload when excessive (RV) effects
- Best strategy for the failing LV is to utilize intrathoracic pressure to optimize preload & afterload
Optimizing CRI

- Cardiorespiratory Economics
- CRI: The Heart
- CRI: The Lung
  - The pulmonary vasculature
- Conventional Ventilation
- Non-conventional Ventilation
- Clinical Applications
Effect of Lung Volume on PVR

- Atelectasis
- Overexpansion
- Total PVR
- Small Vessels
- Large Vessels

- PVR
- FRC
- Lung Volume
TR Jet = 103: PRV = 103 + PRA
Effects of pH on PVR

Lyrene RK, 1985

*p < 0.05 vs Hypoxia
Effects of PaCO2 on PVR

- Change in PaCO2
- Change in PVR

PCaO2
↓PCaO2

$r=0.7$, $P<0.05$
$r=0.11$, $P=ns$

pH = 7.4

Malik, 1973, J Appl Phys
Pulmonary Vasculature

- Optimize lung volume:
  - avoid overexpansion / atelectasis

- Avoid hypoxic vasoconstriction, if possible

- Avoid hypercapnia; promote alkalosis

- Neonates at ↑ed risk for pulm HTN

- Inhaled gases modify PVR
Overdistention

Volume (mL)

Exhalation

Overdistention

Inspiration

Airway Pressure (cmH20)
Overdistention and C.O.

Cardiac Output (mL/min)

PEEP 5
PEEP 10

Tidal Volume (mL/kg)

Cheifetz: CCM 1998
Overdistention and PVR

PVR (d-sec/cm$^5$)

Tidal Volume (mL/kg)

PEEP 5

PEEP 10

10
15
20

1000
1500
2000
2500
3000
3500
4000
4500
5000
Overdistention

- Pulmonary effects
  - Barotrauma; pneumothorax

- Cardiac effects
  - Increased RV afterload; increased PVR; decreased cardiac output
Intrinsic PEEP

Beginning of Inspiration

End of Inspiration

Beginning of Exhalation

Termination of Exhalation

End of Inspiration

Premature termination of Exhalation

Retained Gas Results in PEEPi

Premature initiation of Inspiration
Intrinsic PEEP

- Expiratory gas flow continues at the end of the time allotted for exhalation.
- PEEPi may lead to excessive MAP.
  - Pulmonary effects:
    - Barotrauma
  - Cardiac effects:
    - Impedance of venous return
    - Decreased cardiac output
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Relative Risk of Death in the Hospital across Relevant Subsamples after Multivariate Adjustment — Survival Effect of Ventilation Pressures.

Non-conventional Ventilation

- HFOV
- HFJV
- Negative pressure ventilation
- Inhaled nitric oxide
HFOV

**PIP at Machine**

**Delta P at Machine**

**MAP at Machine**

**PEEP at Machine**

**MAP at Alveolus**

**PEEP at Alveolus**

**Delta P at Alveolus**

**PIP at Alveolus**

**HFOV**
HFOV

• HFOV decreases cardiac output??
  • Many studies have shown decreased CO

• Common theme: Cardiac output decreases with “significantly” ↑ed MAP. But, studies did not control for preload.
Preload Augmentation

Right Atrial Pressure

$P_{sv}$

HFOV

CMV

Systemic Venous Return

Max

R. A.

R. V.

Lung
Preload Augmentation

\[ P_{SV} \]

HFOV

Right Atrial Pressure

CMV

Systemic Venous Return

Max

S/IVC

R. A.

R. V.

Lung
In this observational clinical study, we found that a decrease of MAP by elevation of PEEP from 10 to 20 cm H2O predicted fluid responsiveness in patients with septic shock. A modest or no decrease in MAP (less than 8%) ruled out a positive response to a subsequent fluid challenge defined as an increase in CO of 15 % or more.
HFOV and CRI: Summary

- Cardiac output is usually maintained during HFOV.

- In a given pt, C.O may be ↓ed if:
  - MAP is “significantly” ↑ed.
    - Consider volume loading
    - Consider inotropes

- Bottom line: Oxygen delivery
  - If C.O. can be maintained & oxygenation is ↑ed, oxygen delivery will ↑
High-frequency Jet Ventilation

- Intermittent pulse delivery of gas
- Frequency: 180 - 900
- Passive exhalation- continuous
- Special ETT adaptor required
- Weight/size limitation (Bunnell Jet)
- Many misconceptions
Effects of HFJV on CRI

* p < 0.01 vs HFJV

- **Paw**
  - Pre: 9.4
  - HFJV: 4.6
  - Post: 9.4

- **PVR**
  - Pre: 3.8
  - HFJV: 1.6
  - Post: 3.7

- **C.I.**
  - Pre: 2.3
  - HFJV: 2.9
  - Post: 2.4

**Effects of HFJV on CRI**
High-frequency Jet Ventilation

- **CMV provides:** MAP / Oxygentaion
  Need more oxygenation simply \( \uparrow \) PEEP
  Oxygenation all about MAP

- **HFJV provides:** Gentalation
  Need more ventilation? Simply \( \uparrow \) PIP, \( \downarrow \) Rate
Inhaled NO

\[ P_{A}O_2, \ cGMP \ \downarrow \ Ca^{++}, \ \downarrow \ PVR \]

Oxygen

Epithelial Cells

Interstitium

Endothelial Cells

Injured

NO

EDRF

Hgb

Muscle

Capillary

NO \rightarrow cGMP \rightarrow CA^{++} \rightarrow Relaxation

NO \rightarrow Met Hgb
Nitric Oxide In CHD


- 126 Pts, randomized
- No difference in mortality
- Patients with passive flow, worse response, better in “small vessels”
- Use lowest dose, wean daily.
- Use sildenafil
RV Dysfunction Pulmonary HTN Ventilation Manipulations

• Conventional Ventilatory Strategies
  –↓MAP but maintain FRC
  –Alkalinize with normocapnia

• Nonconventional Modes
  –HFJV
  –Negative pressure ventilation

• Inhaled Medical Gases
  –↑FiO2 (↑CaO₂)
  –Nitric oxide
LV Dysfunction

• Conventional Ventilatory Strategies
  – Thoracic pump augmentation of LV preload ("low" ventilatory rate with "high" TV)
  – ↓ LV afterload ↓ MAP but maintain FRC

• Nonconventional Modes
  – HFJV or HFOV if MAP > 15 - 20 cm H₂O
    (optimize O₂ delivery & ↓ barotrauma)

• Inhaled Medical Gases
  – ↑FiO₂ (↑ CaO₂)
Respiratory Dysfunction
Ventilation Manipulations

• Conventional Ventilatory Strategies
  –Maintain ideal lung volume
  –Titrate PEEP / optimize MAP
  –Alkalosis

• Nonconventional Modes
  –HFOV if PAW > 15 - 20 cm H₂O
    –(optimize O₂ delivery & ↓ barotrauma)

• Inhaled Medical Gases
  –↑FiO₂ (↑CaO₂)
  –Nitric oxide
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