MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Departments of Electrical Engineering, Mechanical Engineering, and the Harvard-MIT Division of Health Sciences and Technology

6.022J/2.792J/BEH.371J/HST542J: Quantitative Physiology: Organ Transport Systems

PROBLEM SET 9

SOLUTIONS

April 23, 2004

Problem 1

Emphysema is one of the leading causes of death in the United States. Our ability to treat emphysema is severely limited because the principal physiologic deficiency results from the destruction of the architecture of the lung. The development of lung transplantation was the first direct approach to the treatment of advanced emphysema. However, most patients with severe disease are precluded from undergoing this surgery by advanced age and coexisting conditions.

Lung-reduction surgery is the newest therapeutic option for patients with emphysema and one that is potentially available to many more patients. The idea of removing 25 percent or more of the lung from a patient with marginal lung function appears, to say the least, counterintuitive. Nevertheless, in certain patients with emphysema, lung-reduction surgery can result in substantial lessening of dyspnea and improved overall function and quality of life for up to a year after surgery.

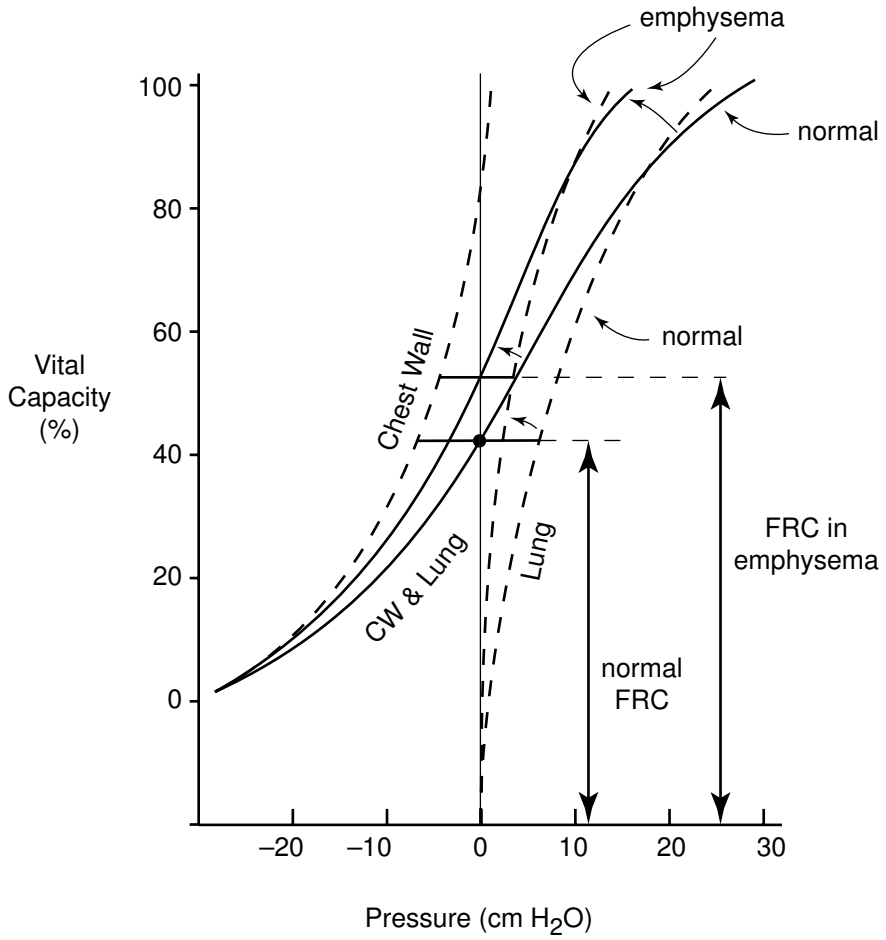
A. First, draw the normal chest wall and lung compliance curves. Then, draw the changes that result from emphysema, which increases compliance of the lungs. Assume that the chest wall doesn't change. What happens to FRC with emphysema?

B. Second, draw the effects of removing 25 percent of lung tissue. What happens to the amount of pressure and work required to inspire a similar tidal volume?

In emphysema, the increase in compliance leads to a steeper lung compliance curve, and FRC will increase. This leads the respiratory system to function on the high part of the pressure-volume curve, which requires more work to inspire a given tidal volume, even though lung compliance has increased. Removing 25

The emphysematous destruction of lung tissue causes a loss of elastic recoil. This loss of recoil has several important consequences. First, airways tethered to lung parenchyma lose their support; thus, their diameter at any specific lung volume is reduced. This mechanism contributes to the increase in specific airway resistance and reduced maximal expiratory flow. Second, the volume at which lungs and chest cavity operate increases because the outward recoil of the chest wall is opposed to a lesser extent by the inward recoil of the lungs and because reduced expiratory flows cause dynamic hyperinflation. Operating at high volumes not only places the inspiratory muscles at a mechanical disadvantage but also increases their elastic load from inadvertent positive end-expiratory pressure. Compounding the mechanical consequences of emphysema is the impaired gas exchange function of the lung.

The success of lung reduction surgery implies that these patients were limited by mechanical constraints on the respiratory system. Of note, the loss of gas exchange surface from lung resection does not aggravate the problem, a further emphasis of the intimate relationship between mechanical impairment and gas exchange function.

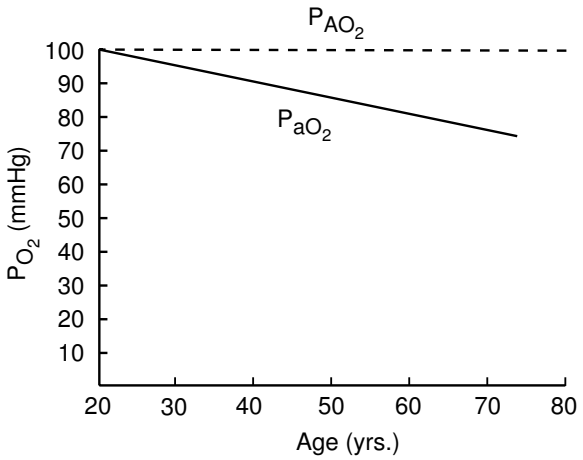

emphysema
normal
normal
Chest Wall
CW & Lung
Lung
FRC in
emphysema
normal
FRC
Vital
Capacity
(%)
100
80
60
40
20
0
–20
–10
0
10
20
30
Pressure (cm H_2O)

Problem 2

Alveolar-Arterial Oxygen Pressure Difference

The normal P_{aO_2} is age-dependent, declining slightly over the years. This decline reflects shifts in ventilation/perfusion (V/Q) ratios in the aging lung. In contrast, alveolar partial pressure of oxygen (P_{AO_2}) depends only on the pressure of inspired oxygen (P_{IO_2}), respiratory quotient (R), and alveolar partial pressure of carbon dioxide (P_{ACO_2}). Since none of these values is age-dependent, P_{AO_2} does not change as we age. The horizontal line in Figure 1 below shows normal P_{AO_2} breathing ambient air ($F_{IO_2} = 0.21$) at sea level; the difference between the diagonal band and the horizontal P_{AO_2} line is the alveolar-arterial oxygen pressure difference $P_{(A-a)O_2}$. Note that normal $P_{(A-a)O_2}$ breathing ambient air can reach approximately 30 mmHg in elderly people.

Figure 1:



Changes in P_{aO_2} and $P_{(A-a)O_2}$ with age. The line for P_{aO_2} is based on the regression equation, $P_{aO_2} = 109 - 0.43$ (age in years), P_{aO_2}, measured at PB 760 mmHg. (From Sorbini, C.A., Grassi, V., Solinas, E., et al.: Respiration 25:3, 1968.)

A. Based on the above graphs: A 35-year-old patient has a P_{aO_2} of 90 mmHg. Are his lungs working properly to transfer oxygen? Is more information needed?

   More information is needed, namely P_{aCO_2} or P_{ACO_2}, to calculate P_{AO_2}. (And, you'd have to know that he was inspiring room air.)

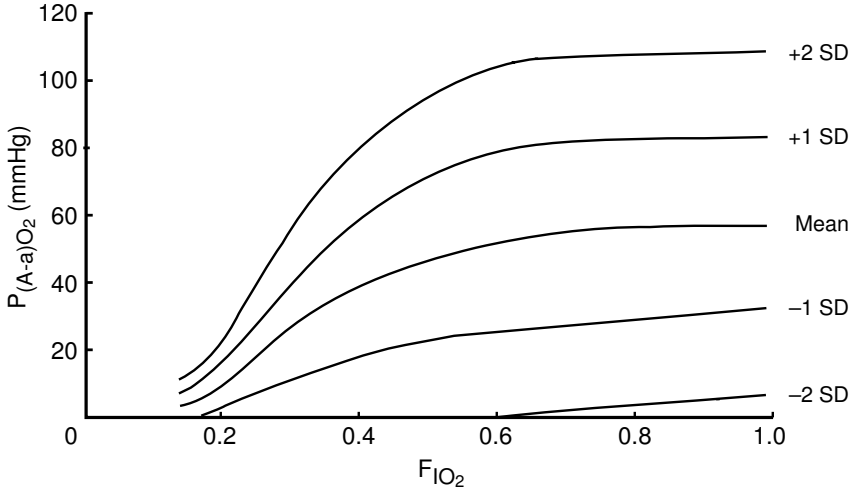
B. A 45-year-old patient has an arterial P_{O_2} at sea level of 85 mmHg. For each of the following F_{IO_2} and P_{aCO_2} values, state if his lungs are transferring oxygen properly. Assume R = 0.8.

   (i) F_{IO_2} = 0.21, P_{aCO_2} = 25 mmHg

$$\begin{aligned} P_{AO_2} &= P_{IO_2} - \frac{P_{ACO_2}}{R} = (760 - 47) \cdot 0.21 - \frac{25}{0.8} = 118 \; mmHg \\ P_{(A-a)O_2} &= 118 - 85 = 33.5 \; mmHg \end{aligned}$$

Abnormal

Figure 2:



Normal range of $P_{(A-a)O_2}$ from F_{IO_2} of 0.21 to 1.00, based on data obtained from 16 healthy subjects aged 40 to 50 years. Lines represent mean values and + or – 2 SD (standard deviations). The $P_{(A-a)O_2}$ increases up to 0.6 and then plateaus with increasing F_{IO_2}. Note that $P_{(A-a)O_2}$ may exceed 100 mmHg on an F_{IO_2} of 1.00 in "normal" people.

Similarly,

(ii) $F_{IO_2} = 0.21$, $P_{aCO_2} = 40$ mmHg

$$\begin{aligned} P_{AO_2} &= P_{IO_2} - \frac{P_{ACO_2}}{R} = (760 - 47) \cdot 0.21 - \frac{40}{0.8} = 99.7 \; mmHg \\ P_{(A-a)O_2} &= 99.7 - 85 = 14.7 \; mmHg \end{aligned}$$

Borderline to abnormal (+2SD)

(iii) $F_{IO_2} = 0.21$, $P_{aCO_2} = 50$ mmHg

$$\begin{aligned} P_{AO_2} &= P_{IO_2} - \frac{P_{ACO_2}}{R} = (760 - 47) \cdot 0.21 - \frac{50}{0.8} = 87.2 \; mmHg \\ P_{(A-a)O_2} &= 87.2 - 85 = 2.2 \; mmHg \end{aligned}$$

Normal

(iv) $F_{IO_2} = 0.40$, $P_{aCO_2} = 30$ mmHg

$$\begin{aligned} P_{AO_2} &= P_{IO_2} - \frac{P_{ACO_2}}{R} = (760 - 47) \cdot 0.21 - \frac{30}{0.8} = 247.7 \; mmHg \\ P_{(A-a)O_2} &= 247.7 - 85 = 162.7 \; mmHg \end{aligned}$$

Abnormally high (> 2SD from mean)

C. Which of the following are potential causes of increased $P_{(A-a)O_2}$ in a patient who is healthy except for the indicated physiologic condition?

(i) Thickening of alveolar-capillary membrane
(ii) Elevated P_{aCO_2}
(iii) Ventilation-perfusion imbalance
(iv) Anemia
(v) Right-to-left intrapulmonary shunting
(vi) Right-to-left intracardiac shunting
(vii) High altitude
(viii) Carbon monoxide inhalation

Potential causes of increased $P_{(A-a)O_2}$:

Thickening of alveolar-capillary membrane.
Ventilation-Perfusion imbalance.
Right-to-left intrapulmonary shunting.
Right-to-left intracardiac shunting.

Note: Anemia and carbon monoxide poisoning will decrease oxygen content of the blood, but the P_{O_2} will not be changed.

Problem 3

A drunk driver strikes a sidewalk victim. The victim has pain in his chest and is taken to an intensive care unit. Measurements are made through catheters:

Hemoglobin: 14 gm/100 ml

Superior vena cava and inferior vena cava blood saturation: 52

Right atrium blood saturation: 52

Right ventricle blood saturation: 77

Pulmonary artery blood saturation: 77

Systemic arterial blood saturation: 98

Pulmonary capillary blood saturation: 99

Oxygen consumption: 200 ml/min

Calculate the shunt in this case. Explain where it is located and the direction. Remember that hemoglobin carries 1.36 ml oxygen/gm Hb. You may neglect the dissolved oxygen in the blood.

Shunt is between the ventricles (L $\rightarrow$ R) since there is a step up in O_2 content going from RA $\rightarrow$ RV.

Please note, Q_P designates the flow through the lungs that undergoes gas exchange, and Q_S designates flow through the body that exchanges oxygen with the tissues. It is possible to have some right-to-left shunt that passes through the pulmonary circulation (for example, when an airway is obstructed) that would not be included in Q_P.

$$Q_P = \frac{\text{O}_2 \text{ consumption}}{C_{\text{PV}_{\text{O}_2}} - C_{\text{PA}_{\text{O}_2}}} = \frac{200 \frac{\text{ml}}{\text{min}}}{(0.98 - 0.77)(14 \frac{\text{g Hb}}{100 \text{ ml blood}})(10)(1.36 \frac{\text{ml O}_2}{\text{g Hb}})}$$

$$\Rightarrow Q_P = 4.5 \text{ L/min}$$

$$Q_S = \frac{\text{O}_2 \text{ consumption}}{C_{\text{a}_{\text{O}_2}} - C_{\text{RA}_{\text{O}_2}}} = \frac{200 \frac{\text{ml}}{\text{min}}}{(0.98 - 0.52)(14)(10)(1.36)}$$

$$\Rightarrow Q_{\text{shunt}} = Q_P - Q_S = 4.5 - 2.3$$

$$= \boxed{2.2 \text{ L/min}}$$

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