Review Test

1. Which of the following lung volumes or capacities can be measured by spirometry?

(A) Functional residual capacity (FRC)
(B) Physiologic dead space
(C) Residual volume (RV)
(D) Total lung capacity (TLC)
(E) Vital capacity (VC)

2. An infant born prematurely in gestational week 25 has neonatal respiratory distress syndrome. Which of the following would be expected in this infant?

(A) Arterial P_{O_2} of 100 mm Hg
(B) Collapse of the small alveoli
(C) Increased lung compliance
(D) Normal breathing rate
(E) Lecithin:sphingomyelin ratio of greater than 2:1 in amniotic fluid

3. In which vascular bed does hypoxia cause vasoconstriction?

(A) Coronary
(B) Pulmonary
(C) Cerebral
(D) Muscle
(E) Skin

QUESTIONS 4 AND 5

A 12-year-old boy has a severe asthmatic attack with wheezing. He experiences rapid breathing and becomes cyanotic. His arterial P_{O_2} is 60 mm Hg and his P_{CO_2} is 30 mm Hg.

4. Which of the following statements about this patient is most likely to be true?

(A) Forced expiratory volume$_1$/forced vital capacity (FEV_1/FVC) is increased
(B) Ventilation/perfusion (V/Q) ratio is increased in the affected areas of his lungs
(C) His arterial P_{CO_2} is higher than normal because of inadequate gas exchange
(D) His arterial P_{CO_2} is lower than normal because hypoxemia is causing him to hyperventilate
(E) His residual volume (RV) is decreased

5. To treat this patient, the physician should administer

(A) an α_1-adrenergic antagonist
(B) a β_1-adrenergic antagonist
(C) a β_2-adrenergic agonist
(D) a muscarinic agonist
(E) a nicotinic agonist

6. Which of the following is true during inspiration?

(A) Intrapleural pressure is positive
(B) The volume in the lungs is less than the functional residual capacity (FRC)
(C) Alveolar pressure equals atmospheric pressure
(D) Alveolar pressure is higher than atmospheric pressure
(E) Intrapleural pressure is more negative than it is during expiration

7. Which volume remains in the lungs after a tidal volume (V_T) is expired?

(A) Tidal volume (V_T)
(B) Vital capacity (VC)
(C) Expiratory reserve volume (ERV)
(D) Residual volume (RV)
(E) Functional residual capacity (FRC)
(F) Inspiratory capacity
(G) Total lung capacity

8. A 35-year-old man has a vital capacity (VC) of 5 L, a tidal volume (V_T) of 0.5 L, an inspiratory capacity of 3.5 L, and a functional residual capacity (FRC) of 2.5 L. What is his expiratory reserve volume (ERV)?

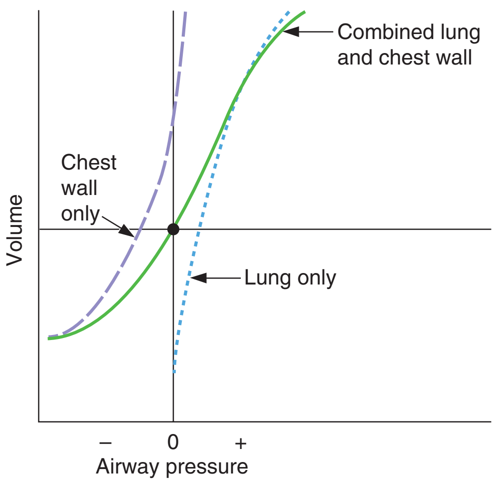
(A) 4.5 L
(B) 3.9 L
(C) 3.6 L
(D) 3.0 L
(E) 2.5 L
(F) 2.0 L
(G) 1.5 L

9. When a person is standing, blood flow in the lungs is

(A) equal at the apex and the base
(B) highest at the apex owing to the effects of gravity on arterial pressure

(C) highest at the base because that is where the difference between arterial and venous pressure is greatest
(D) lowest at the base because that is where alveolar pressure is greater than arterial pressure

10. Which of the following is illustrated in the graph showing volume versus pressure in the lung–chest wall system?



(A) The slope of each of the curves is resistance
(B) The compliance of the lungs alone is less than the compliance of the lungs plus chest wall
(C) The compliance of the chest wall alone is less than the compliance of the lungs plus chest wall
(D) When airway pressure is zero (atmospheric), the volume of the combined system is the functional residual capacity (FRC)
(E) When airway pressure is zero (atmospheric), intrapleural pressure is zero

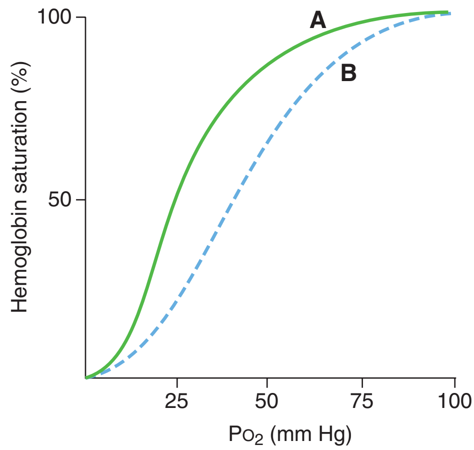
11. Which of the following is the site of highest airway resistance? غير مطلوب

(A) Trachea
(B) Largest bronchi
(C) Medium-sized bronchi
(D) Smallest bronchi
(E) Alveoli

12. A 49-year-old man has a pulmonary embolism that completely blocks blood flow to his left lung. As a result, which of the following will occur?

(A) Ventilation/perfusion (V/Q) ratio in the left lung will be zero
(B) Systemic arterial P_{O_2} will be elevated
(C) V/Q ratio in the left lung will be lower than in the right lung
(D) Alveolar P_{O_2} in the left lung will be approximately equal to the P_{O_2} in inspired air
(E) Alveolar P_{O_2} in the right lung will be approximately equal to the P_{O_2} in venous blood

QUESTIONS 13 AND 14



13. In the hemoglobin–O_2 dissociation curves shown above, the shift from curve A to curve B could be caused by

(A) increased pH
(B) decreased 2,3-diphosphoglycerate (DPG) concentration
(C) strenuous exercise
(D) fetal hemoglobin (HbF)
(E) carbon monoxide (CO) poisoning

14. The shift from curve A to curve B is associated with

(A) increased P_{50}
(B) increased affinity of hemoglobin for O_2
(C) impaired ability to unload O_2 in the tissues
(D) increased O_2-carrying capacity of hemoglobin
(E) decreased O_2-carrying capacity of hemoglobin

15. Which volume remains in the lungs after a maximal expiration?

(A) Tidal volume (V_T)
(B) Vital capacity (VC)
(C) Expiratory reserve volume (ERV)
(D) Residual volume (RV)
(E) Functional residual capacity (FRC)
(F) Inspiratory capacity
(G) Total lung capacity

16. Compared with the systemic circulation, the pulmonary circulation has a

(A) higher blood flow
(B) lower resistance
(C) higher arterial pressure
(D) higher capillary pressure
(E) higher cardiac output

17. A healthy 65-year-old man with a tidal volume (V_T) of 0.45 L has a breathing frequency of 16 breaths/min. His arterial P_{CO_2} is 41 mm Hg, and the P_{CO_2} of his expired air is 35 mm Hg. What is his alveolar ventilation?

(A) 0.066 L/min غير مطلوب
(B) 0.38 L/min
(C) 5.0 L/min
(D) 6.14 L/min
(E) 8.25 L/min

18. Compared with the apex of the lung, the base of the lung has

(A) a higher pulmonary capillary P_{O_2}
(B) a higher pulmonary capillary P_{CO_2}
(C) a higher ventilation/perfusion (V/Q) ratio
(D) the same V/Q ratio

19. Hypoxemia produces hyperventilation by a direct effect on the

(A) phrenic nerve
(B) J receptors
(C) lung stretch receptors
(D) medullary chemoreceptors
(E) carotid and aortic body chemoreceptors

20. Which of the following changes occurs during strenuous exercise?

(A) Ventilation rate and O_2 consumption increase to the same extent
(B) Systemic arterial P_{O_2} decreases to about 70 mm Hg
(C) Systemic arterial P_{CO_2} increases to about 60 mm Hg
(D) Systemic venous P_{CO_2} decreases to about 20 mm Hg
(E) Pulmonary blood flow decreases at the expense of systemic blood flow

21. If an area of the lung is not ventilated because of bronchial obstruction, the pulmonary capillary blood serving that area will have a P_{O_2} that is

(A) equal to atmospheric P_{O_2}
(B) equal to mixed venous P_{O_2}
(C) equal to normal systemic arterial P_{O_2}
(D) higher than inspired P_{O_2}
(E) lower than mixed venous P_{O_2}

22. In the transport of CO_2 from the tissues to the lungs, which of the following occurs in venous blood?

(A) Conversion of CO_2 and H_2O to H^+ and HCO_3^- in the red blood cells (RBCs)
(B) Buffering of H^+ by oxyhemoglobin
(C) Shifting of HCO_3^- into the RBCs from plasma in exchange for Cl^-
(D) Binding of HCO_3^- to hemoglobin
(E) Alkalinization of the RBCs

23. Which of the following causes of hypoxia is characterized by a decreased arterial P_{O_2} and an increased A–a gradient? غير مطلوب

(A) Hypoventilation
(B) Right-to-left cardiac shunt
(C) Anemia
(D) Carbon monoxide poisoning
(E) Ascent to high altitude

24. A 42-year-old woman with severe pulmonary fibrosis is evaluated by her physician and has the following arterial blood gases: pH = 7.48, Pa_{O_2} = 55 mm Hg, and Pa_{CO_2} = 32 mm Hg. Which statement best explains the observed value of Pa_{CO_2}?

(A) The increased pH stimulates breathing via peripheral chemoreceptors
(B) The increased pH stimulates breathing via central chemoreceptors
(C) The decreased Pa_{O_2} inhibits breathing via peripheral chemoreceptors
(D) The decreased Pa_{O_2} stimulates breathing via peripheral chemoreceptors
(E) The decreased Pa_{O_2} stimulates breathing via central chemoreceptors

25. A 38-year-old woman moves with her family from New York City (sea level) to Leadville Colorado (10,200 feet above sea level). Which of the following will occur as a result of residing at high altitude?

(A) Hypoventilation
(B) Arterial P_{O_2} greater than 100 mm Hg
(C) Decreased 2,3-diphosphoglycerate (DPG) concentration
(D) Shift to the right of the hemoglobin–O_2 dissociation curve
(E) Pulmonary vasodilation
(F) Hypertrophy of the left ventricle
(G) Respiratory acidosis

26. The pH of venous blood is only slightly more acidic than the pH of arterial blood because

(A) CO_2 is a weak base
(B) there is no carbonic anhydrase in venous blood
(C) the H^+ generated from CO_2 and H_2O is buffered by HCO_3^- in venous blood
(D) the H^+ generated from CO_2 and H_2O is buffered by deoxyhemoglobin in venous blood
(E) oxyhemoglobin is a better buffer for H^+ than is deoxyhemoglobin

27. In a maximal expiration, the total volume expired is

(A) tidal volume (V_T)
(B) vital capacity (VC)
(C) expiratory reserve volume (ERV)
(D) residual volume (RV)
(E) functional residual capacity (FRC)
(F) inspiratory capacity
(G) total lung capacity

28. A person with a ventilation/perfusion (V/Q) defect has hypoxemia and is treated with supplemental O_2. The supplemental O_2 will be *most* helpful if the person's predominant V/Q defect is

(A) dead space
(B) shunt
(C) high V/Q
(D) low V/Q
(E) V/Q = 0
(F) V/Q = ∞

29. Which person would be expected to have the largest A–a gradient?

غير مطلوب

(A) Person with pulmonary fibrosis
(B) Person who is hypoventilating due to morphine overdose
(C) Person at 12,000 feet above sea level
(D) Person with normal lungs breathing 50% O_2
(E) Person with normal lungs breathing 100% O_2

30. Which of the following sets of data would have the highest rate of O_2 transfer between alveolar gas and pulmonary capillary blood?

غير مطلوب

	$P_{I_{O_2}}$ (mm Hg)	$P_{V_{O_2}}$ (mm Hg)	Surface Area (relative)	Thickness (relative)
(A)	150	40	1	1
(B)	150	40	2	2
(C)	300	40	1	2
(D)	150	80	1	1
(E)	190	80	2	2

Answers and Explanations

1. **The answer is E** [I A 4, 5, B 2, 3, 5]. Residual volume (RV) cannot be measured by spirometry. Therefore, any lung volume or capacity that includes the RV cannot be measured by spirometry. Measurements that include RV are functional residual capacity (FRC) and total lung capacity (TLC). Vital capacity (VC) does not include RV and is, therefore, measurable by spirometry. Physiologic dead space is not measurable by spirometry and requires sampling of arterial P_{CO_2} and expired CO_2.

2. **The answer is B** [II D 2]. Neonatal respiratory distress syndrome is caused by lack of adequate surfactant in the immature lung. Surfactant appears between the 24th and the 35th gestational week. In the absence of surfactant, the surface tension of the small alveoli is too high. When the pressure on the small alveoli is too high ($P = 2T/r$), the small alveoli collapse into larger alveoli. There is decreased gas exchange with the larger, collapsed alveoli, and ventilation/perfusion (V/Q) mismatch, hypoxemia, and cyanosis occur. The lack of surfactant also decreases lung compliance, making it harder to inflate the lungs, increasing the work of breathing, and producing dyspnea (shortness of breath). Generally, lecithin:sphingomyelin ratios greater than 2:1 signify mature levels of surfactant.

3. **The answer is B** [VI C]. Pulmonary blood flow is controlled locally by the P_{O_2} of alveolar air. Hypoxia causes pulmonary vasoconstriction and thereby shunts blood away from unventilated areas of the lung, where it would be wasted. In the coronary circulation, hypoxemia causes vasodilation. The cerebral, muscle, and skin circulations are not controlled directly by P_{O_2}.

4. **The answer is D** [VIII B 2 a]. The patient's arterial P_{CO_2} is lower than the normal value of 40 mm Hg because hypoxemia has stimulated peripheral chemoreceptors to increase his breathing rate; hyperventilation causes the patient to blow off extra CO_2 and results in respiratory alkalosis. In an obstructive disease, such as asthma, both forced expiratory volume (FEV_1) and forced vital capacity (FVC) are decreased, with the larger decrease occurring in FEV_1. Therefore, the FEV_1/FVC ratio is decreased. Poor ventilation of the affected areas decreases the ventilation/perfusion (V/Q) ratio and causes hypoxemia. The patient's residual volume (RV) is increased because he is breathing at a higher lung volume to offset the increased resistance of his airways.

5. **The answer is C** [II E 3 a (2)]. A cause of airway obstruction in asthma is bronchiolar constriction. β_2-adrenergic stimulation (β_2-adrenergic agonists) produces relaxation of the bronchioles.

6. **The answer is E** [II F 2]. During inspiration, intrapleural pressure becomes *more negative* than it is at rest or during expiration (when it returns to its less negative resting value). During inspiration, air flows into the lungs when alveolar pressure becomes lower (due to contraction of the diaphragm) than atmospheric pressure; if alveolar pressure were not lower than atmospheric pressure, air would not flow inward. The volume in the lungs during inspiration is the functional residual capacity (FRC) *plus* one tidal volume (V_T).

7. **The answer is E** [I B 2]. During normal breathing, the volume inspired and then expired is a tidal volume (V_T). The volume remaining in the lungs after expiration of a V_T is the functional residual capacity (FRC).

8. **The answer is G** [I A 3; Figure 4.1]. Expiratory reserve volume (ERV) equals vital capacity (VC) minus inspiratory capacity [Inspiratory capacity includes tidal volume (V_T) and inspiratory reserve volume (IRV)].

9. **The answer is C** [VI B]. The distribution of blood flow in the lungs is affected by gravitational effects on arterial hydrostatic pressure. Thus, blood flow is highest at the base, where arterial hydrostatic pressure is greatest and the difference between arterial and venous pressure is also greatest. This pressure difference drives the blood flow.

10. **The answer is D** [II C 2; Figure 4.3]. By convention, when airway pressure is equal to atmospheric pressure, it is designated as zero pressure. Under these equilibrium conditions, there is no airflow because there is no pressure gradient between the atmosphere and the alveoli, and the volume in the lungs is the functional residual capacity (FRC). The slope of each curve is compliance, not resistance; the steeper the slope is, the greater the volume change is for a given pressure change, or the greater compliance is. The compliance of the lungs alone or the chest wall alone is greater than that of the combined lung–chest wall system (the slopes of the individual curves are steeper than the slope of the combined curve, which means higher compliance). When airway pressure is zero (equilibrium conditions), intrapleural pressure is negative because of the opposing tendencies of the chest wall to spring out and the lungs to collapse.

11. **The answer is C** [II E 4]. The medium-sized bronchi actually constitute the site of highest resistance along the bronchial tree. Although the small radii of the alveoli might predict that they would have the highest resistance, they do not because of their parallel arrangement. In fact, early changes in resistance in the small airways may be "silent" and go undetected because of their small overall contribution to resistance.

12. **The answer is D** [VII B 2]. Alveolar Po_2 in the left lung will equal the Po_2 in inspired air. Because there is no blood flow to the left lung, there can be no gas exchange between the alveolar air and the pulmonary capillary blood. Consequently, O_2 is not added to the capillary blood. The ventilation/perfusion (V/Q) ratio in the left lung will be infinite (not zero or lower than that in the normal right lung) because Q (the denominator) is zero. Systemic arterial Po_2 will, of course, be decreased because the left lung has no gas exchange. Alveolar Po_2 in the right lung is unaffected.

13. **The answer is C** [IV C 1; Figure 4.8]. Strenuous exercise increases the temperature and decreases the pH of skeletal muscle; both effects would cause the hemoglobin–O_2 dissociation curve to shift to the right, making it easier to unload O_2 in the tissues to meet the high demand of the exercising muscle. 2,3-Diphosphoglycerate (DPG) binds to the β chains of adult hemoglobin and reduces its affinity for O_2, shifting the curve to the right. In fetal hemoglobin, the β. chains are replaced by γ chains, which do not bind 2,3-DPG, so the curve is shifted to the left. Because carbon monoxide (CO) increases the affinity of the remaining binding sites for O_2, the curve is shifted to the left.

14. **The answer is A** [IV C 1; Figure 4.8]. A shift to the right of the hemoglobin–O_2 dissociation curve represents decreased affinity of hemoglobin for O_2. At any given Po_2, the percent saturation is decreased, the P_{50} is increased (read the Po_2 from the graph at 50% hemoglobin saturation), and unloading of O_2 in the tissues is facilitated. The O_2-carrying capacity of hemoglobin is the mL of O_2 that can be bound to a gram of hemoglobin at 100% saturation and is unaffected by the shift from curve A to curve B.

15. **The answer is D** [I A 3]. During a forced maximal expiration, the volume expired is a tidal volume (V_T) plus the expiratory reserve volume (ERV). The volume remaining in the lungs is the residual volume (RV).

16. **The answer is B** [VI A]. Blood flow (or cardiac output) in the systemic and pulmonary circulations is nearly equal; pulmonary flow is slightly less than systemic flow because about 2% of the systemic cardiac output bypasses the lungs. The pulmonary circulation is characterized by both lower pressure and lower resistance than the systemic circulation, so flows through the two circulations are approximately equal (flow = pressure/resistance).

17. **The answer is D** [I A 5 b, 6 b]. Alveolar ventilation is the difference between tidal volume (V_T) and dead space multiplied by breathing frequency. V_T and breathing frequency are given, but dead space must be calculated. Dead space is V_T multiplied by the difference between arterial

P_{CO_2} and expired P_{CO_2} divided by arterial P_{CO_2}. Thus: dead space = 0.45 × (41 – 35/41) = 0.066 L. Alveolar ventilation is then calculated as: (0.45 L – 0.066 L) × 16 breaths/min = 6.14 L/min.

18. The answer is B [VII C; Figure 4.10; Table 4.5]. Ventilation and perfusion of the lung are not distributed uniformly. Both are lowest at the apex and highest at the base. However, the differences for ventilation are not as great as for perfusion, making the ventilation/perfusion (V/Q) ratios higher at the apex and lower at the base. As a result, gas exchange is more efficient at the apex and less efficient at the base. Therefore, blood leaving the apex will have a higher P_{O_2} and a lower P_{CO_2}.

19. The answer is E [VIII B 2]. Hypoxemia stimulates breathing by a direct effect on the peripheral chemoreceptors in the carotid and aortic bodies. Central (medullary) chemoreceptors are stimulated by CO_2 (or H^+). The J receptors and lung stretch receptors are not chemoreceptors. The phrenic nerve innervates the diaphragm, and its activity is determined by the output of the brain stem breathing center.

20. The answer is A [IX A]. During exercise, the ventilation rate increases to match the increased O_2 consumption and CO_2 production. This matching is accomplished without a change in mean arterial P_{O_2} or P_{CO_2}. Venous P_{CO_2} increases because extra CO_2 is being produced by the exercising muscle. Because this CO_2 will be blown off by the hyperventilating lungs, it does not increase the arterial P_{CO_2}. Pulmonary blood flow (cardiac output) increases manifold during strenuous exercise.

21. The answer is B [VII B 1]. If an area of lung is not ventilated, there can be no gas exchange in that region. The pulmonary capillary blood serving that region will not equilibrate with alveolar P_{O_2} but will have a P_{O_2} equal to that of mixed venous blood.

22. The answer is A [V B; Figure 4.9]. CO_2 generated in the tissues is hydrated to form H^+ and HCO_3^- in red blood cells (RBCs). H^+ is buffered inside the RBCs by deoxyhemoglobin, which *acidifies* the RBCs. HCO_3^- leaves the RBCs in exchange for Cl^- and is carried to the lungs in the plasma. A small amount of CO_2 (not HCO_3^-) binds directly to hemoglobin (carbaminohemoglobin).

23. The answer is B [IV A 4; IV D; Table 4.4; Table 4.5]. Hypoxia is defined as decreased O_2 delivery to the tissues. It occurs as a result of decreased blood flow or decreased O_2 content of the blood. Decreased O_2 content of the blood is caused by decreased hemoglobin concentration (anemia), decreased O_2-binding capacity of hemoglobin (carbon monoxide poisoning), or decreased arterial P_{O_2} (hypoxemia). Hypoventilation, right-to-left cardiac shunt, and ascent to high altitude all cause hypoxia by decreasing arterial P_{O_2}. Of these, only right-to-left cardiac shunt is associated with an increased A–a gradient, reflecting a lack of O_2 equilibration between alveolar gas and systemic arterial blood. In right-to-left shunt, a portion of the right heart output, or pulmonary blood flow, is not oxygenated in the lungs and thereby "dilutes" the P_{O_2} of the normally oxygenated blood. With hypoventilation and ascent to high altitude, both alveolar and arterial P_{O_2} are decreased, but the A–a gradient is normal.

24. The answer is D [VIII B; Table 4.7]. The patient's arterial blood gases show increased pH, decreased Pa_{O_2}, and decreased Pa_{CO_2}. The decreased Pa_{O_2} causes hyperventilation (stimulates breathing) via the peripheral chemoreceptors, but not via the central chemoreceptors. The decreased Pa_{CO_2} results from hyperventilation (increased breathing) and causes increased pH, which *inhibits* breathing via the peripheral and central chemoreceptors.

25. The answer is D [IX B; Table 4.9]. At high altitudes, the P_{O_2} of alveolar air is decreased because barometric pressure is decreased. As a result, arterial P_{O_2} is decreased (<100 mm Hg), and hypoxemia occurs and causes hyperventilation by an effect on peripheral chemoreceptors. Hyperventilation leads to respiratory alkalosis. 2,3-Diphosphoglycerate (DPG) levels increase adaptively; 2,3-DPG binds to hemoglobin and causes the hemoglobin–O_2 dissociation curve to shift to the right to improve unloading of O_2 in the tissues. The pulmonary vasculature vasoconstricts in response to alveolar hypoxia, resulting in increased pulmonary arterial pressure and hypertrophy of the right ventricle (not the left ventricle).

26. The answer is D [V B]. In venous blood, CO_2 combines with H_2O and produces the weak acid H_2CO_3, catalyzed by carbonic anhydrase. The resulting H^+ is buffered by deoxyhemoglobin, which is such an effective buffer for H^+ (meaning that the pK is within 1.0 unit of the pH of blood) that the pH of venous blood is only slightly more acid than the pH of arterial blood. Oxyhemoglobin is a less effective buffer than is deoxyhemoglobin.

27. The answer is B [I B 3]. The volume expired in a forced maximal expiration is forced vital capacity, or vital capacity (VC).

28. The answer is D [VII]. Supplemental O_2 (breathing inspired air with a high PO_2) is most helpful in treating hypoxemia associated with a ventilation/perfusion (V/Q) defect if the predominant defect is low V/Q. Regions of low V/Q have the highest blood flow. Thus, breathing high PO_2 air will raise the PO_2 of a large volume of blood and have the greatest influence on the total blood flow leaving the lungs (which becomes systemic arterial blood). Dead space (i.e., $V/Q = \infty$) has no blood flow, so supplemental O_2 has no effect on these regions. Shunt (i.e., $V/Q = 0$) has no ventilation, so supplemental O_2 has no effect. Regions of high V/Q have little blood flow, thus raising the PO_2 of a small volume of blood will have little overall effect on systemic arterial blood.

29. The answer is A [IV D]. Increased A–a gradient signifies lack of O_2 equilibration between alveolar gas (A) and systemic arterial blood (a). In pulmonary fibrosis, there is thickening of the alveolar/pulmonary capillary barrier and increased diffusion distance for O_2, which results in lack of equilibration of O_2, hypoxemia, and increased A–a gradient. Hypoventilation and ascent to 12,000 feet also cause hypoxemia, because systemic arterial blood is equilibrated with a lower alveolar PO_2 (normal A–a gradient). Persons breathing 50% or 100% O_2 will have elevated alveolar PO_2, and their arterial PO_2 will equilibrate with this higher value (normal A–a gradient).

30. The answer is C [III D]**.** The diffusion of O_2 from alveolar gas to pulmonary capillary blood is proportional to the partial pressure difference for O_2 between inspired air and mixed venous blood entering the pulmonary capillaries, proportional to the surface area for diffusion, and inversely proportional to diffusion distance, or thickness of the barrier.