of the systemic circulation. A smaller portion of the normal shunt is related to the coronary circulation draining through the thebesian veins into the left ventricle. Anatomic shunts found in disease states can be classified as intracardiac or intrapulmonary shunts. Intracardiac shunts occur when right atrial pressures are elevated and deoxygenated blood travels from the right atrium to the left atrium through an atrial septal defect or patent foramen ovale. Intrapulmonary anatomic shunts consist primarily of arteriovenous malformations or telangiectasias. With a physiologic right-to-left shunt, a portion of the pulmonary arterial blood passes through the normal vasculature but does not come into contact with alveolar air. This is an extreme example of ventilation-perfusion mismatch ($\dot{V}/\dot{Q} = 0$). Physiologic shunt can be caused by diffuse flooding of the alveoli with fluid, as seen in congestive heart failure or acute respiratory distress syndrome. Alveolar flooding with inflammatory exudates, as seen in lobar pneumonia, also causes a shunt. The fraction of blood shunted (Qs/Qt) can be calculated when the F_{IO_2} is 100% by the following equation:

$$Qs/Qt = (Cc_{O_2} - Ca_{O_2})/(Cc_{O_2} - Cv_{O_2})$$

where Qs is the shunted blood flow, Qt is the total blood flow, Cc_{O_2} is the end-pulmonary capillary oxygen content; Ca_{O_2} is the arterial oxygen content; and Cv_{O_2} is the mixed venous oxygen content.

If the shunt is severe enough, mechanical ventilation and PEEP are required to improve arterial oxygenation. At values less than 50% of the cardiac output, a shunt has very little effect on Pa_{CO_2} (Fig. 15-17). With shunting, the A-a gradient is elevated while the Pa_{CO_2} is within normal range or may be low. In contrast to hypoxemia due to hypoventilation or low $\dot{V}/\dot{Q}$, oxygen administration does not correct hypoxemia due to shunt because the shunted blood has no exposure to oxygen in the alveoli. However, the Pa_{O_2} may increase somewhat because the higher F_{IO_2} improves oxygenation of blood traveling to low $\dot{V}/\dot{Q}$ areas that commonly coexist with shunt.

The fourth cause of hypoxemia is diffusion impairment. With normal cardiopulmonary function, the blood spends, on average, 0.75 second in the pulmonary capillaries. Typically, it takes only 0.25 second for the alveolar oxygen to diffuse across the thin alveolar capillary membrane and equilibrate with pulmonary arterial blood (see Fig. 15-13). However, if there is impairment to diffusion across this membrane, such as thickening of the alveolar capillary membrane by fluid, fibrous tissue, cellular debris, or inflammatory cells, it will take longer for the oxygen in the alveoli to equilibrate with pulmonary arterial blood. If the impediment to diffusion is such that it takes longer than 0.75 second for oxygen to diffuse, hypoxemia ensues, and the A-a gradient widens. Alternatively, if the time a red blood cell spends traversing the pulmonary capillary decreases to 0.25 second or less, hypoxemia may develop. Hypoxemia may be evident only during exercise in individuals with diffusion impairment because of the shortened red cell transit time. In these cases, the A-a gradient may be normal at rest but increases with exercise. With diffusion impairment, the Pa_{CO_2} usually is within the normal range. As with hypoxemia due to hypoventilation or ventilation-perfusion mismatch, administration of a higher F_{IO_2} improves hypoxemia due to impaired diffusion by raising the alveolar P_{O_2}.

An additional cause of hypoxemia is low inspired oxygen. This may occur at high altitude: The F_{IO_2} is normal, but the P_{O_2} is low because the barometric pressure (P_{atm}) is low. Rarely, circumstances occur in which the F_{IO_2} is low (e.g., rebreathing air). Hypoxemia due to low inspired oxygen is associated with a normal A-a gradient and is usually accompanied by a low Pa_{CO_2}. Supplemental oxygen corrects this form of hypoxemia. Finally, a low mixed venous P_{O_2} predisposes individuals to hypoxia (Fig. 15-18).

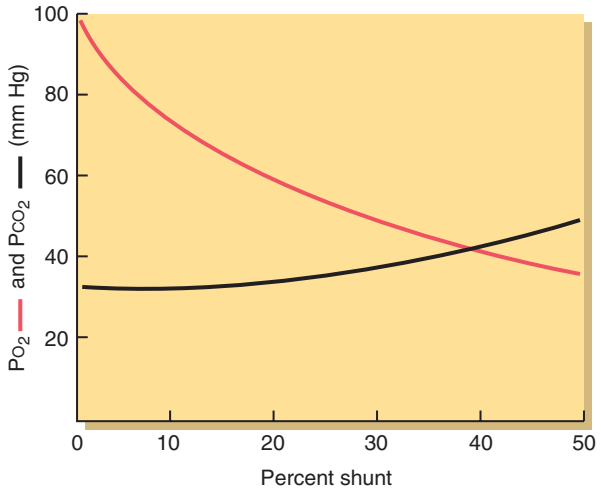

FIGURE 15-17 The effects of increasing shunt on the arterial partial pressures of oxygen (P_{O_2}) and carbon dioxide (P_{CO_2}). The minute ventilation has been held constant in this example. Under usual circumstances, the hypoxemia would lead to increased minute ventilation and a fall in the P_{CO_2} as the shunt increased. (From Dantzker DR: Gas exchange abnormalities. In Montenegro H, editor: Chronic obstructive pulmonary disease, New York, 1984, Churchill Livingstone, pp 141–160.)

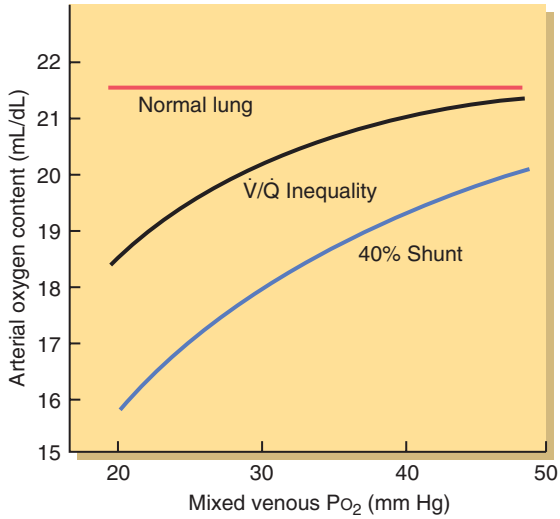

FIGURE 15-18 The effects of increasing mixed venous partial pressure of oxygen (P_{O_2}) on the arterial oxygen content under three assumed conditions: a normal lung, severe ventilation-perfusion inequality ($\dot{V}/\dot{Q}$), and the presence of a 40% shunt. For each situation, the patient is breathing 50% oxygen and the mixed venous P_{O_2} is altered, keeping all other variables constant. (From Dantzker DR: Gas exchange in the adult respiratory distress syndrome, Clin Chest Med 3:57–67, 1982.)