Remember to Breathe

Question

In basic open-water classes, divers are told "never to hold their breath" for fear of lung injuries due to the expansion of compressed gas during ascent. Further, students are told that the most dangerous part of the ascent is closest to the surface. Why is this? What is the actual mechanism by which lungs are injured by expanding gas? Do they actually rip and tear? Since the lungs are surrounded by a fluid-filled sac, where does the expansion occur? Is there empty space between the lungs, the sac, and the rest of the body? Finally, why exactly would the last bit of the ascent be more dangerous, say, than covering the same vertical distance much deeper? Doesn't the ambient pressure change as much between 60 and 30 feet as it does between 30 feet and the surface?

Answer

Lung expansion injuries can be the most dramatic and life-threatening emergencies in scuba diving. They are generally a result of lung overinflation due to pathological air trapping (lung disease), or breathholding during ascent. A good understanding of lung anatomy is essential to comprehending the associated risks. The main bronchi divide into smaller airways called bronchioles and continue to branch and reduce in size until they form the respiratory bronchioles, which terminate in the alveolar sacs. The alveoli are the key functional unit of the respiratory system where gas exchange takes place. These fragile air sacs are surrounded by a delicate membrane only one- to two-cell layers thick and are encompassed by a network of tiny blood capillaries. Exposed to atmospheric pressures at sea level, our lungs are in a state of equilibrium as we inhale and exhale. Slight pressure changes occur as we change elevation, yet equalization of the pressures inside and outside the lung is a passive and inconspicuous event with each breath. During descent into water, all gas-containing spaces in the body tend to shrink as the pressure surrounding the body increases; for example the lung volume of a breathhold diver becomes smaller with the descent in the water column. Because scuba regulators deliver breathing gas at the ambient pressure of the diver, higher concentrations of the breathing gas enter the lungs, preventing the reduction in volume that would occur. In the reverse situation, if we would ascent holding our breath, the lungs will progressively increase in volume until the elastic limit of the alveoli is exceeded and lung injury occurs. This forces gas into one of three locations:

1. the space within the chest cavity (pleural space), a condition known as pneumothorax;
2. the tissue planes within the lung itself (interstitial space), from where it may travel into the space around the heart, the tissues of the neck and the larynx (mediastinal emphysema); or
3. the blood.

In this latter condition (arterial gas embolism, or AGE), gas bubbles can pass from the pulmonary capillaries via the pulmonary veins to the left side of the heart, and then to the carotid or basilar arteries (cerebral arterial gas embolism, or CAGE). While this explanation appears reasonable, it is not completely satisfactory. Since lung tissue is extremely compliant, one would expect the interstitium of the lung and the vessels within it to be subjected to the same increase in pressure as the alveoli. The vessels might therefore be expected to collapse, preventing gas from entering. Probably gas enters blood vessels at "corners" of the lung – for example, between the lung and the mediastinum, where pressure differentials may cause disruption (tearing), allowing extra alveolar gas to enter. It is important to note that a

breathhold ascent from a depth as shallow as four feet of sea water(fsw)/1.2 meters (msw) may be sufficient to tear alveoli sacs, causing lung tear and one of these three ailments. For a fixed quantity of gas, the relationship between its volume and the external pressure is provided by Boyle's law. In essence, Irish physicist/chemist Robert Boyle discovered that at a constant temperature and mass, the volume of a gas is inversely proportional to the pressure exerted on that gas. When the pressure is doubled, the volume is reduced to one-half of the original volume. Conversely, when the pressure is reduced by one-half, the volume doubles. For a diver at 15 fsw/4.6 msw, the total pressure acting on his body is 1.5 atmospheres (one atmosphere at the surface, plus an additional 0.5 atmospheres exerted by the water column). A sudden ascent to the surface would therefore result in a 30 percent pressure reduction, and assuming a compliant chest wall, a volume increase of 50 percent. Lung injury may result. Actual volume changes may be less than this because of the effect of the surrounding chest wall to provide some rigidity and protection for the lung. However, if the same vertical change occurred from a depth of 66 fsw/20 msw, the 0.5 atmosphere of depth change would only result in a 16 percent reduction in pressure and a 20 percent increase in lung volume, and would be less likely to cause lung injury. Boyle's law thus explains why abrupt changes in depth while in shallow water can be far more hazardous than equivalent changes of depth in deep water.