AN EXCERPT FROM...

The Physics of Superheroes: Spectacular Second Edition

By James Kakalios

Fresh Air Underwater

The most striking ability of Aquaman, as well as that of Marvel Comics Prince Namor, the Sub-Mariner, and all the other denizens of comic books' many distinct underwater cities of Atlantis, is the ability to extract oxygen directly underwater. Without this superpower, there doesn't seem to be much point to being a water-based superhero. It turns out that this is the one special power that requires the smallest miracle exception from the laws of nature. Why shouldn't Aquaman breath through water — after all, we do!

Everyone knows that drowning results when the lungs fill up with water. What is less commonly recognized is that normal breathing would be impossible without a small amount of water in the lungs. Fresh air comes in through the nose, and travels down the bronchial tube, where it is warmed to the body's temperature and pre moistened. In fact, the air has to be at 100 percent relative humidity as it moves down the ever more finely branching tubes on its way to the alveoli — small little spherical buds where the exchange of oxygen and carbon dioxide occurs. These pockets are roughly 0.1 to 0.3 mm in diameter, smaller than the period at the end of this sentence. On the other side of the walls of the alveolar bud are the capillaries — very narrow blood vessels in which plasma and red blood cells flow to drop off carbon dioxide molecules and pick up oxygen molecules on their way to the heart. The capillaries are narrow for the same reason that the alveolar spheres are so small — to maximize the ratio of surface area to volume. Since the gas exchange takes place only through the walls of the alveoli and the capillaries, the more surface area there is, the more regions there are for possible gas diffusion to occur.

There has to be some transition for these gas molecules between the interior of the alveoli— which are connected through the bronchial tubes to the outside world — and the capillaries that carry the blood. This is provided by a thin coating of water on the interior of the alveolar surface. This water layer facilitates the transfer of gases by ensuring that the inner cell walls of the alveoli do not become dried out by direct contact with air, which would cause them to lose their functionality. Only after it is has dissolved from the gas phase to the liquid phase can an oxygen molecule diffuse through the two cell walls and get picked up by speeding red blood cells. The alveoli can be considered air bubbles in water, and we could not breathe without (a little) water in our lungs, though, just as so often in life, too much of something turns a necessity lethal. Aquaman, who lacks the gills of a fish that facilitate our finny friends' oxygen extraction directly from the surrounding water, must have some sort of super power adaptation that enables him to continue breathing even when completely underwater.

But even this very thin water layer in the alveoli should be physically capable of causing asphyxiation. The same physics responsible for glistening dewdrops should produce acute shortness of breath, or worse. The magnitude of surface tension in the water layer is sufficient to cause the small alveolar buds to close up entirely, so that even deep breaths would not be enough to provide the necessary pressure to drive the oxygen molecules into the bloodstream. What saves us from choking on an amount of water that could not fully fill a thimble? Soap!

Surface tension is the name given to the pulling force that results from the attraction of molecules in the fluid (let's say water) to each other. Such an attractive force must of course exist — or else the atoms or molecules in the liquid would fly away from each other as they return to the vapor state. For most liquids, this force is a relatively weak electrostatic cling (called the van der Waals attraction) that arises from fluctuating charge distributions in the molecule. The force can't be too strong, for the water molecules must be able to move past each other and flow through hoses or fill up the volume of a container in exactly the manner that a solid doesn't. We'll discuss van der Waals later on, when we consider the physics that enables gecko lizards and Spider- Man to climb up walls and across ceilings

This attractive force tends to pull the water molecules equally in all directions— it is not stronger in the up- down direction than it is in the left- right direction. For water molecules in the middle of a liquid, the pull is balanced on all sides. A molecule on the surface of the liquid only feels an attractive pull from the water molecules beneath it, as the air above does not exert an upward attractive pull. These surface molecules therefore experience a net downward pull that curls the water into a perfectly spherical drop in the absence of gravity. For water on a blade of grass at dawn, condensing from the atmosphere owing to the lower temperatures in the absence of sunlight, the water adheres to the surface of the grass, and surface tension curves the top layer of the morning dew into a hemisphere. This curved surface of water acts as a lens, concentrating the early-morning sun's rays and accounting for the glistening light of dawn before the sun rises higher in the sky and the more intense sunlight evaporates the water droplets.

This tendency of water to curve is less charming when it forces the walls of our alveoli to constrict, requiring extreme pressures to keep the air buds open. When faced with the problem of decreasing the surface tension in alveolian water in the development of our physiology, natural selection chose the same solution we employ when washing our clothing. The cells in the alveolar walls generate a substance known as "pulmonary surfactant." The first term just refers to the lungs, while a "surfactant" is a long, skinny molecule with different chemical groups at either end. Electrostatic interactions result in one end of this molecule being attracted to the charge distributions in water molecules, while the other end is repelled by those same charges. If the long skinny molecule is fairly rigid, like a spine, then a large collection of such molecules will orient themselves so that all of the regions that are repelled by water are pointing in one direction (typically where there is a low concentration of water), while those ends that are attracted to water will extend into the fluid. The region where the surfactant molecules can satisfy both ends at the same time is at the water- air interface, with the water-attracting end inserted into the water and the water- avoiding end protruding out into the air. In such a configuration, the surfactant interferes with the water- water bonding at the surface of the water layer. This reduces the cohesive force between water molecules that was the source of the surface tension. Without pulmonary surfactants, the alveoli — essentially air bubbles in water — are unable to effectively facilitate gas exchange with the bloodstream. These crucial surfactants do not develop in the fetus until late in gestation, which is why premature babies may suffer from respiratory distress syndrome, an often-fatal condition prior to the development of effective artificial surfactants.

A moment ago I referred to the reason why surface tension arising from even a thin layer of water in the lungs does not kill us as “soap.” While not technically correct, in that pulmonary surfactants are not soaps, the converse is true, in that soaps are surfactants, with water-attracting and water-repelling chemical groups at either end of long skinny, chain-like molecules. Soap helps one clean up by reducing the surface tension of water, so that it can make direct contact with the dirt. That is, surfactants make water wetter, and help us breathe easy as well.