January 2004: Carbonic Anhydrase

Breathing In, Breathing Out

Breathing is a fundamental function in life - ever wondered what really happens when we breathe? The air we breathe in has precious oxygen that fuels the breakdown of sugars and fat in our cells. In our lungs, oxygen diffuses into the blood, binds to hemoglobin and is transported to all the cells of our body. Carbon dioxide is a byproduct of sugar and fat breakdown in cells and needs to be removed from our body. Again, blood acts as a transport medium. Carbon dioxide diffuses out of cells and is transported in blood in a few different ways less than 10% dissolves in the blood plasma, about 20% binds to hemoglobin, while the majority of it (70%) is converted to carbonic acid to be carried to the lungs. An enzyme present in red blood cells, carbonic anhydrase, aids in the conversion of carbon dioxide to carbonic acid and bicarbonate ions. When red blood cells reach the lungs, the same enzyme helps to convert the bicarbonate ions back to carbon dioxide, which we breathe out. Although these reactions can occur even without the enzyme, carbonic anhydrase can increase the rate of these conversions up to a million fold.

Green Plants and Corals

Plants also use oxygen for producing energy, and also release carbon dioxide. Green plants can convert water and carbon dioxide into sugars in the presence of sunlight. This process, photosynthesis, uses carbon dioxide from the atmosphere. Gaseous carbon dioxide is stored in plants as bicarbonate ions. In both land and water plants, carbonic anhydrase plays a role in converting bicarbonate ions back to carbon dioxide for photosynthesis. Another interesting biological phenomenon where this enzyme plays a role is the calcification of corals. Seawater calcium reacts with the bicarbonate produced by carbonic anhydrase from the coral polyps, forming calcium carbonate. This is deposited as the hard exterior of corals.

Carbonic Anhydrases

Carbonic anhydrase is an enzyme that assists rapid inter-conversion of carbon dioxide and water into carbonic acid, protons and bicarbonate ions. This enzyme was first identified in 1933, in red blood cells of cows. Since then, it has been found to be abundant in all mammalian tissues, plants, algae and bacteria. This ancient enzyme has three distinct classes (called alpha, beta and gamma carbonic anhydrase). Members of these different classes share very little sequence or structural similarity, yet they all perform the same function and require a zinc ion at the active site.

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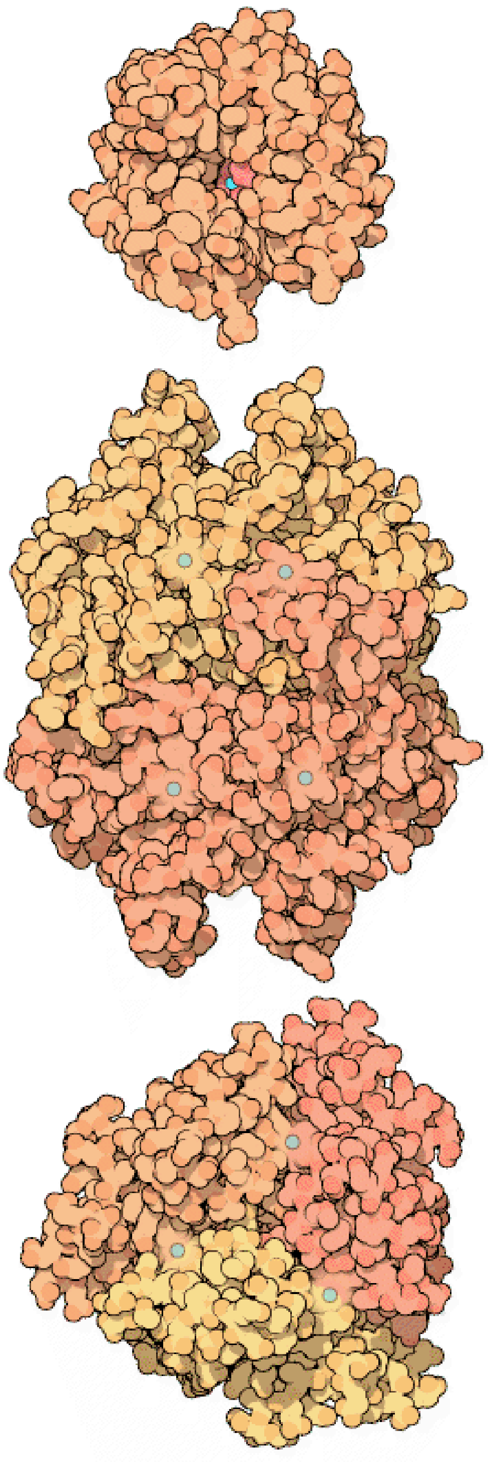

Carbonic anhydrase from mammals belong to the alpha class, the plant enzymes belong to the beta class, while the enzyme from methane-producing bacteria that grow in hot springs forms the gamma class. Thus it is apparent that these enzyme classes have evolved independently to create a similar enzyme active site. PDB entries 1ca2, 1ddz and 1thj, shown here from top to bottom, are examples of the alpha, beta and gamma carbonic anhydrase enzymes, respectively. The zinc ions in the active site are colored blue in these figures. Note that the alpha enzyme is a monomer, while the gamma enzyme is trimeric. Although the beta enzyme shown here is a dimer, there are four zinc ions bound to the structure indicating four possible enzyme active sites. Other members of this class form tetramers, hexamers or octamers, suggesting that dimer is probably a building block for this class.

Mammalian carbonic anhydrases occur in about 10 slightly different forms depending upon the tissue or cellular compartment they are located in. These isozymes have some sequence variations leading to specific differences in their activity. Thus isozymes found in some muscle fibers have low enzyme activity compared to that secreted by salivary glands. While most carbonic anhydrase isozymes are soluble and secreted, some are bound to the membranes of specific epithelial cells. For a deeper look at carbonic anhydrase from a genomic perspective.

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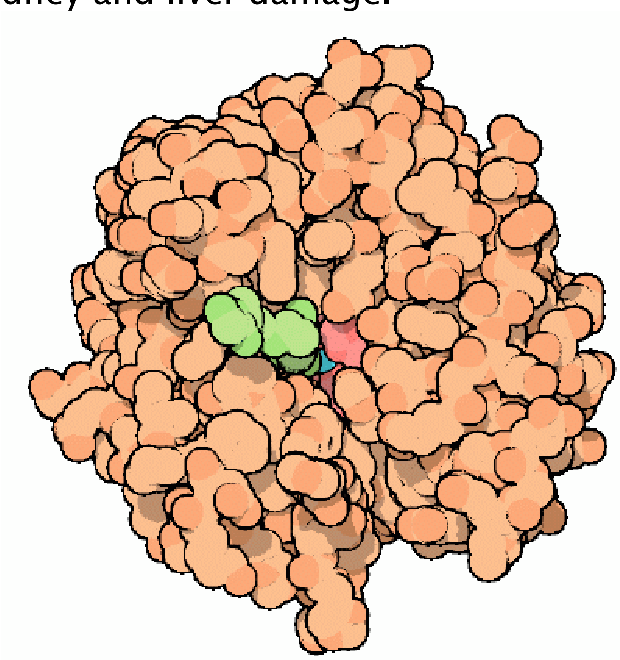
Carbonic Anhydrase in Health and Disease

Since this enzyme produces and uses protons and bicarbonate ions, carbonic anhydrase plays a key role in the regulation of pH and fluid balance in different parts of our body. In our stomach lining it plays a role in secreting acid, while the same enzyme helps to make pancreatic juices alkaline and our saliva neutral. The transport of the protons and bicarbonate ions produced in our kidney and eyes influence the water content of the cells at these locations. Thus carbonic anhydrase isozymes perform different functions at their specific locations, and their absence or malfunction can lead to diseased states, ranging from the loss of acid production in the stomach to kidney failure.

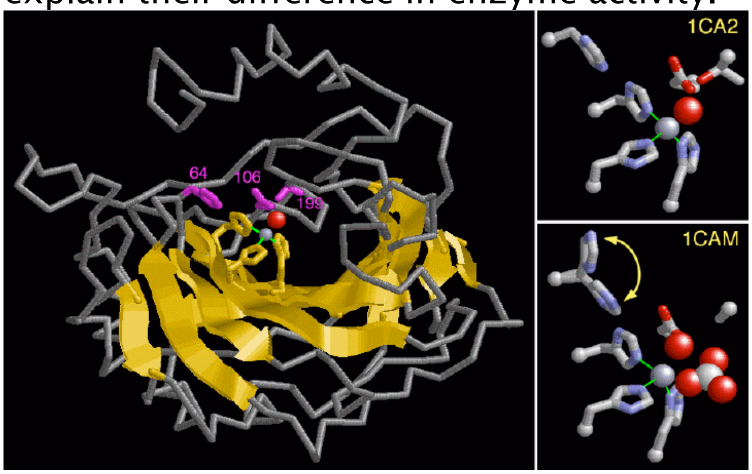
When there is a build up of fluid that maintains the shape of our eyes, the fluid often presses on the optic nerve in the eye and may damage it. This condition is called glaucoma. In recent years, inhibitors of carbonic anhydrase are being used to treat glaucoma. Blocking this enzyme shifts the fluid balance in the eyes of the patient to reduce fluid build up thereby relieving pressure. The structure of PDB entry 1cnw shows how one such inhibitor (a sulfonamide), colored green in the figure, is bound to human carbonic anhydrase (isozyme II). Note that this inhibitor binds near the active site and disrupts the interactions of the water bound to the zinc ion, blocking the enzyme action. Unfortunately, prolonged use of this drug can affect the same enzyme present in other tissues and lead to side effects like kidney and liver damage.



January 2004: Carbonic Anhydrase

Exploring the Structure

The alpha carbonic anhydrase enzymes have been well studied, leading to an understanding of how the enzyme works. The left hand figure shows the structure of carbonic anhydrase II from PDB entry 1ca2. Note the large beta sheet in the center of the structure colored in yellow. The active site lies at the bottom of a deep cleft in the enzyme where a zinc atom is bound, shown with a gray sphere. Nitrogen atoms of three histidines--numbered 94, 96 and 119 (colored in yellow)--directly coordinate the zinc. These amino acids are highly conserved in all isozymes. Atoms from threonine 199 and glutamate 106 (colored magenta) interact indirectly through the bound water, shown with a red sphere. Note that these residues in addition to the histidine 64 (also colored in magenta) help to charge the zinc with a hydroxyl ion. Some of the isozymes have differences in these and other residues, which may explain their difference in enzyme activity.



Zinc is the key to this enzyme reaction. The water bound to the zinc ion is actually broken down to a proton and hydroxyl ion. Since zinc is a positively charged ion, it stabilizes the negatively charged hydroxyl ion so that it is ready to attack the carbon dioxide.

A close up of the amino acid side chains in the active site and the zinc ion is shown in the two right hand figures. The top figure shows a hydroxyl ion, shown with a red sphere, bound to the zinc ion in PDB entry 1ca2. Zinc directs the transfer of this bound hydroxyl to carbon dioxide, forming a bicarbonate ion. The bottom figure shows an intermediate structure where the bicarbonate ion, shown with red and white spheres, has just formed and is still bound to the enzyme (PDB entry 1cam). Note that the side chain for amino acid 199 is modeled as an alanine in this structure. Histidine 64 swings towards and away from the zinc ion in each cycle of enzyme action while helping the zinc to recharge with a new hydroxyl ion. The two positions of this residue, shown in the bottom right figure, represent its movement during enzyme action. As soon as the zinc is reloaded with a new water molecule and the bicarbonate ion has been released, the enzyme will be ready for action on another carbon dioxide molecule