Tooth Decay: A Delicate Balance

By David Warmflash

WE ALL KNOW THAT EATING candy and other foods loaded with sugar causes tooth decay, but have you ever wondered why? We also know that brushing and flossing can prevent tooth decay, but how does this actually work? From the process that keeps your teeth hard as a rock to the decay that occurs in many people and the materials that dentists use to repair the damage, there are different types of chemicals and chemical reactions going on inside your mouth.

What's in a tooth?

Like bones, the hard parts of a tooth consist of a combination of mineral, proteins, and some water. Here, "mineral" means a compound that is solid and inorganic—not made of carbon-based molecules—with a definite chemical composition and an ordered atomic arrangement.

The white, outer layer of the tooth, or enamel, is 96% mineral (Fig. 1). This high fraction of mineral is what makes enamel the hardest substance in the body; it is basically a kind of rock. Known as hydroxyapatite ($Ca_5(PO_4)_3(OH)$), the mineral consists of calcium (Ca^{2+}) and phosphate (PO_4^{3-}) ions.

Hydroxyapatite also is present in dentin, the part of the tooth under the enamel and in the root of the tooth (Fig. 1), but hydroxyapatite makes up only about 70% of those tissues, the remainder being 20% organic material and 10% water. Because it is less mineralized, dentin is softer than enamel.

Despite their rock-hard texture, your teeth are alive, and the hydroxyapatite is dynamic. Small amounts of calcium and phosphate ions dissolve from enamel hydroxyapatite into the saliva—a process called demineralization (Fig. 2)—when the saliva's pH drops below 5.5. Normally, this happens when you eat acidic foods, such as pineapple and strawberries, which have a pH below 4.

Fortunately, the effect of those acidic foods is temporary. Saliva has a pH ranging from 6.2 to about 7.4, and it contains chemical compounds, called buffers, that resist pH change. So, the pH on the surface of the tooth quickly returns to normal, above 5.5, and once that happens, the calcium and phosphate ions that are present in saliva are remineralized back to hydroxyapatite.

When you don't eat food, mineralization and demineralization still occur, but at low rates—only relatively few ions form hydroxyapatite or separate from your teeth—and the rates of both mineralization and demineralization are equal (Fig. 3). This state of balance is an example of a chemical equilibrium, and it can be expressed as follows:

$$Ca_5(PO_4)_3(OH) \rightleftharpoons 5\,Ca^{2+} + 3\,PO_4^{3-} + OH^-$$

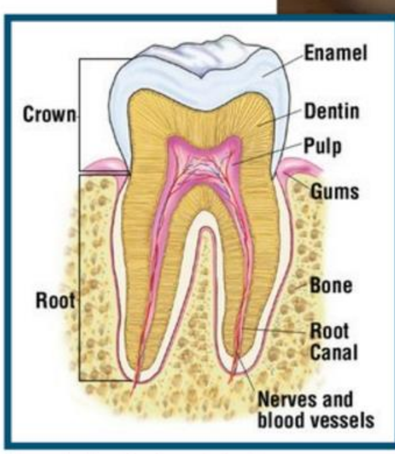

Figure 1. The structure of a tooth

But what if your teeth are not healthy? Tooth decay develops when hydroxyapatite's mineralization cannot keep up with demineralization. This is called an unstable equilibrium, because the number of calcium and phosphate ions that are released in the mouth from the dissolution of hydroxyapatite is higher than the number of calcium and phosphate ions that react with each other to form hydroxyapatite. Such an unstable equilibrium happens when teeth are exposed to low pH for extended periods of time.

Acids and bases in your body

The pH drop that occurs during tooth decay is confined to the mouth; it does not affect the body. Unlike the mouth, the body maintains a tight pH range; if it didn't, enzymes that catalyze biochemical reactions in the body would not work well. Throughout the body, blood is always slightly alkaline, with a pH of 7.4, a situation that is maintained by the lungs, kidneys, and several other organs that help keep the blood's pH constant.

The lungs and the kidneys, for instance, work together to help maintain a pH of 7.4 by keeping the following chemical reactions in the blood in a state of equilibrium:

$$CO_2 + H_2O \rightleftarrows H_2CO_3$$

$$H_2CO_3 \rightleftarrows HCO_3^- + H^+$$

In the first chemical equilibrium, carbon dioxide (CO_2) reacts with water (H_2O) to produce carbonic acid (H_2CO_3); and in the second chemical equilibrium, carbonic acid is ionized in the blood in the form of a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+).

Whether either reaction moves to the right or to the left depends on the relative abundance of carbon dioxide, water, and carbonic acid in the first chemical equilibrium and carbonic acid, bicarbonate ions, and hydrogen ions in the second equilibrium.

The two chemical equilibria above can be combined as follows:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows HCO_3^- + H^+$$

So, how can these equilibria shift? For example, when you exercise heavily, your muscles produce lactic acid (CH_3CHOH-$COOH$), so hydrogen ions are added to the blood. When this happens, the concentration of hydrogen ions increases, which disturbs the two chemical equilibria above. To reestablish them, the concentration of hydrogen ions needs to decrease.

In general, a chemical equilibrium is reestablished according to a principle called Le Châtelier's Principle, which states that a system that is shifted away from equilibrium acts to restore equilibrium by reacting in opposition to the shift. For a chemical equilibrium (shown as $A \rightleftarrows B$ in Fig. 3), this means that if the concentration of either reactants or products is changed, the additional reactants or products will cause the equilibrium to shift left or right until a new equilibrium is established (but for which the concentrations of the reactants and products will be different than the original ones).

In the case of the two equilibria described before, some of the excess hydrogen ions will react with bicarbonate ions to form carbonic acid, and the additional carbonic acid will be converted into carbon dioxide and water. So, the equilibria shift to the left and, in time, new equilibria are formed.

If not for this shift in equilibria, the pH would drop dramatically, which could seriously damage the lungs, heart, and other organs. Instead, the pH drops slightly, generally to 7.36.

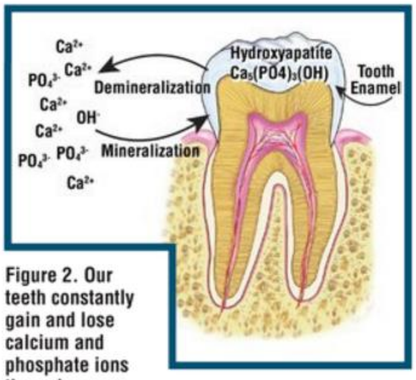

Figure 2. Our teeth constantly gain and lose calcium and phosphate ions through processes called mineralization and demineralization, respectively, which occur at equal rates in our mouths and result in no net loss of these ions from our teeth. But if acidic food leftovers bind to our teeth and are not cleared, they increase the rate of demineralization, which can lead to tooth decay.

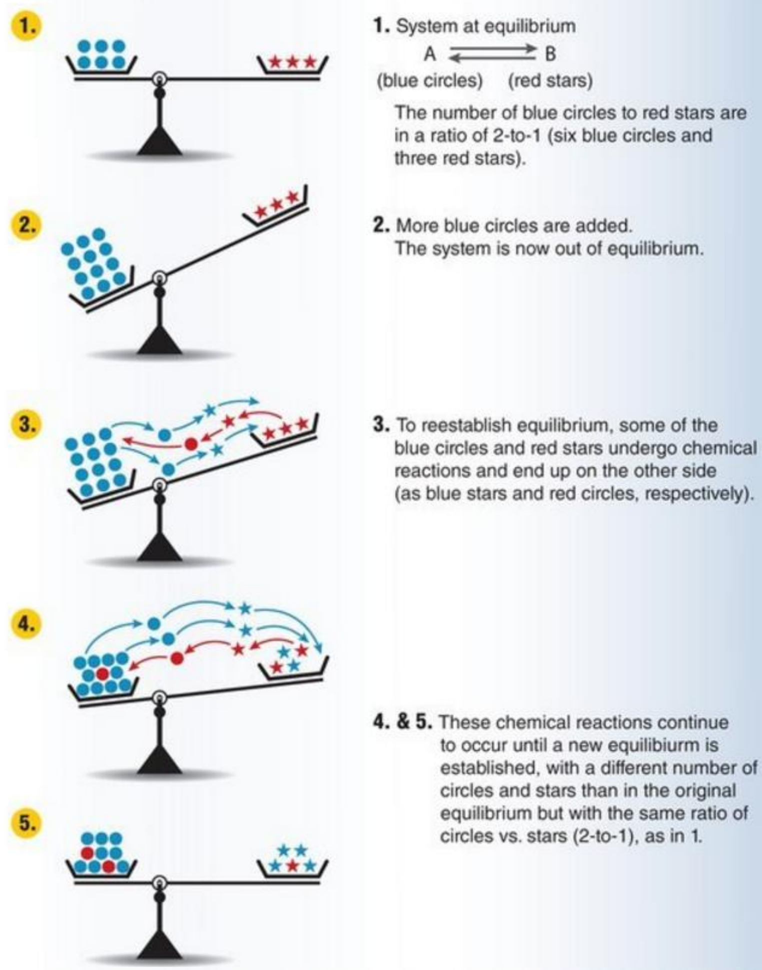

Figure 3. Schematic representation of Le Châtelier's Principle in the case of a chemical equilibrium between a reactant (A) and a product (B). When more reactant A is added to the solution, it disturbs the equilibrium. To restore the equilibrium, the additional reactant causes the forward reaction to occur, resulting in more product, and some of the additional product to decompose into the reactant. Ultimately, a new chemical equilibrium is established.

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Acids and bases in your mouth

Even though the pH of blood throughout your body is constant, it can change more significantly in some parts of your body. In the mouth, saliva has a pH ranging from 6.2 to about 7.4, and, as mentioned earlier, it contains chemical compounds, called buffers, that resist pH change. The carbonic acid (H_2CO_3)/bicarbonate (HCO_3^-) buffer is the major buffer in saliva.

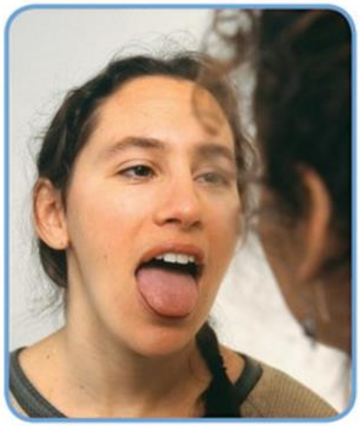
When food enters the mouth, it is accompanied by a subsequent decrease in pH. The drop in pH is caused by increased concentrations of hydrogen ions, due to lactic acid being produced by bacteria when they ferment carbohydrates. To counter this drop in pH, the salivary ducts secrete more bicarbonate ions, which help neutralize the increased amount of hydrogen ions produced by the bacteria. In saliva, as in the body, the following equilibria exist:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows HCO_3^- + H^+$$

A rise in bicarbonate ion concentration conveniently removes the increased amounts of hydrogen ions produced by bacteria, so the above equilibrium ($H_2CO_3 \rightleftarrows HCO_3^- + H^+$) shifts to the left to produce more carbonic acid. But the concentration of carbonic acid in the mouth is maintained at a nearly constant level, so the excess carbonic acid needs to be removed. To make this happen, the other equilibrium ($CO_2 + H_2O \rightleftarrows H_2CO_3$) shifts to the left, and more carbon dioxide is produced. Ultimately, this excess carbon dioxide diffuses out from the saliva.

In this way, excess hydrogen ions are effectively neutralized and removed and, over time, new equilibria are established. So, the pH on the surface of the tooth quickly returns to normal, above 5.5, and once that happens, the calcium and phosphate ions that are present in saliva are remineralized back to hydroxyapatite, reducing the risk of erosion of the teeth.

The problem occurs when the pH at the tooth surface falls to 5.5 or below and stays that way for a while. This causes holes to form in the enamel, eventually exposing the underlying dentin to the acidic environment. Being only about 70% mineral, dentin is less resistant to acid than enamel and demineralizes at a pH of 6.2 or lower. Once there is a hole in the enamel, the dentin and the rest of the tooth are in a lot of trouble.



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Treating tooth decay

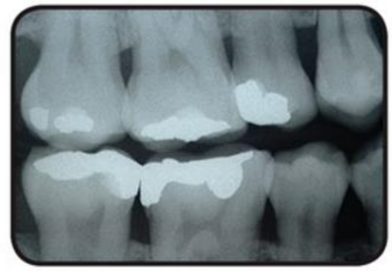
When tooth decay has advanced too far to be reversed, the decayed, infected part of the tooth needs to be removed, and the remaining hole needs to be filled. If you have had any cavities, you may know that dentists usually fill them with something called composite resins. This substance is composed of chain-like molecules, called polymers, which are made of many similar units, called monomers, which are linked together.

Left: Tooth decay, which is due to bacteria, caused a hole, or cavity, to form in the tooth. Right: A resin filling plugs the hole and prevents the tooth from further decaying.

Composites have been around since the mid-20th century. However, for decades, dentists preferred to fill teeth with a metal alloy, called an amalgam, which is made of mercury, silver, tin, copper, and tiny amounts of other metals, because the early composites did not bond well to dentin.

But there are some problems with amalgam. One of them is that sometimes dentists remove not only the damaged part of the tooth, but also some healthy material along with it, because the place for the filling has to be shaped just right so that the packed amalgam cannot move.

Another problem is that because metal blocks X-rays, having amalgam fillings in your mouth can make it difficult for a dentist to get a useful 3-dimensional panoramic X-ray picture, in contrast to composite fillings which the X-rays can penetrate. Also, amalgam needs to be disposed of properly, because it contains mercury. So, today, most dentists use composite resins instead of amalgams.



This X-ray image shows resin fillings (white) that filled cavities in three top teeth and two bottom teeth.

Precipitation and dissolution of minerals, buffers, ions, and polymers—these topics are probably part of your chemistry curriculum in school. Now, you can tell your friends and teachers how they are also at work inside your mouth. *CM*

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