The Cutting Edge: Sharp Biological Materials*

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Through hundreds of millions of years of evolution, organisms have developed a myriad of ingenious solutions to ensure and optimize survival and success. Biological materials that comprise organisms are synthesized at ambient temperature and pressure and mostly in aqueous environments. This process, mediated by proteins, limits the range of materials at the disposal of nature and therefore the design plays a pivotal role. This article focuses on sharp edges and serrations as important survival and predating mechanisms in a number of plants, insects, fishes, and mammals. Some plants (e.g., Pampas grass and Cortaderia selloana) have sharp edges covered with serrations. The proboscis of mosquitoes and stinger of bees are examples in insects. Serrations are a prominent feature in many fish teeth, and rodents have teeth that are sharpened continuously, ensuring their sharpness and efficacy. Some current bioinspired applications will also be reviewed.

INTRODUCTION

Many biological systems have mechanical properties that are far beyond those that can be achieved using the same synthetic materials. This is a surprising fact, considering that the basic polymers and minerals used in natural systems are quite weak. This limited strength is a result of the ambient temperature, aqueous environment processing, and the limited availability of elements (primarily C, N, Ca, H, O, Si, P). Biological organisms produce composites that are organized in terms of composition and structure, containing both inorganic and organic components in complex structures.[1–3] They are hierarchically organized at the nano-, micro-, and meso-levels.

The complexity and uniqueness of biological materials is well illustrated in the Arzt[4] pentahedron, which has five components: ambient temperature and pressure processing, self assembly, functionality, hierarchy of structure, and evolution/environmental effects. The components of the E. Arzt pentahedron shown in Figure 1 of the commentary on page 18 are indicative of the complex contributions and interactions necessary to fully understand and exploit (through biomimicking) biological systems. These components are prominent in all biological systems, all the way from the molecular, cellular, organ, and organism levels. The limited scarcity of materials available to nature because of the restrictions in synthesis and processing shifts the focus on the design of these materials. In a sense, and paraphrasing M.F. Ashby,[5] materials and design are inseparable in nature.

This article illustrates these unique aspects by focusing on one characteristic of biological materials: their ability to puncture, cut, and shred. The fact that serrations and needles are present in many species and in diverse configurations is direct evidence that they developed independently, by a mechanism that anthropology calls convergent evolution.

How would you...

...describe the overall significance of this paper?

...describe this work to a materials science and engineering professional with no experience in your technical specialty?

...describe this work to a layperson?

PLANTS: RAZOR GRASS

Figure 1 shows a blade of pampas grass (Cortaderia selloana) with serrations along its outer edge. Each serration is in the shape of a thorn protruding upward along the side of the blade. They extend approximately 50 μm from the body of the leaf and form sharp points with an apex angle of roughly 20°. This sharp cutting edge was evolutionarily designed as a defense mechanism against grazing animals. This feature is also prominent in other grasses, such as Hypolitrium Shraderenium. Other examples can be found in cactuses, which have their bodies covered in sharp needles for protection.

INSECTS: MOSQUITO AND BEE

Figure 2 shows the proboscis of the mosquito (Culex pipiens). The proboscis is composed of an outer sheath that is used to detect the surrounding environment such as temperature and chemical balance. Inside this sheath there are two tubes which enter the mosquito's unsuspecting prey. One of the sheaths is terminated with an inner stylet that is used to pierce through the skin and draw blood while the other injects an anticoagulant into to keep the blood flowing. Figure 2 shows three

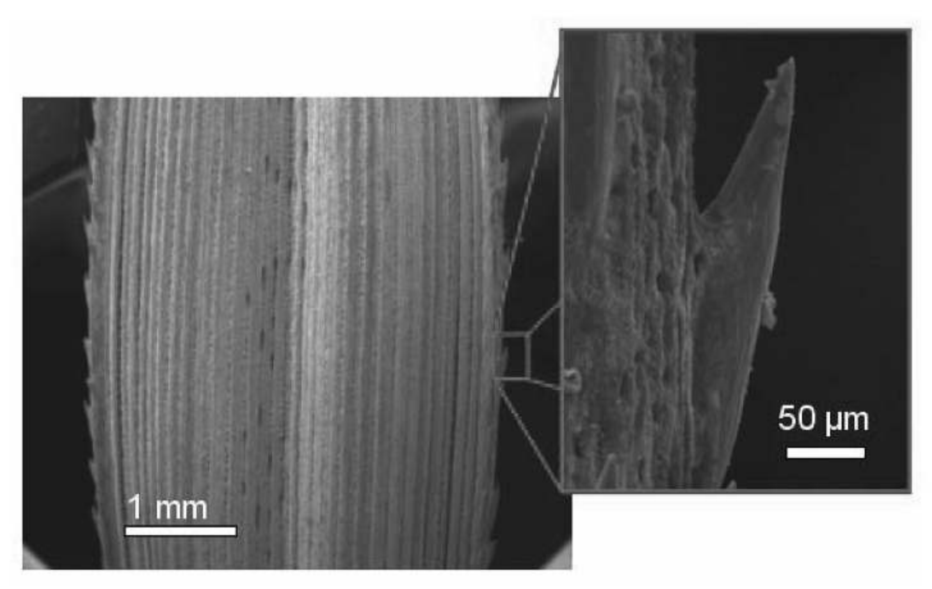

Figure 1. Pampas grass (*Cortaderia selloana*); note serrations at edges.

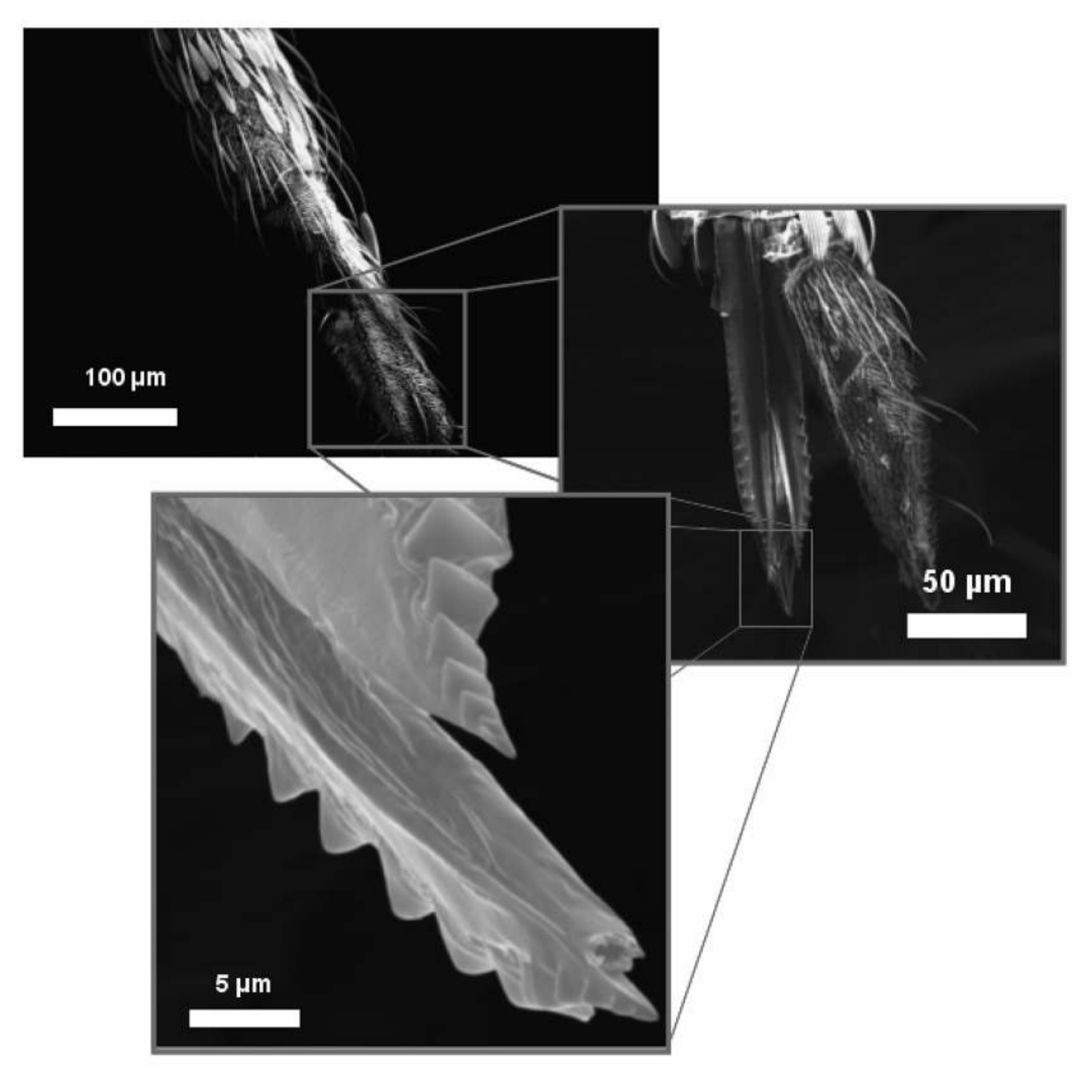

Figure 2. Scanning-electron micrographs of mosquito (Culex pipiens) proboscis; top: proboscis covered with hairy sheath; middle: partially exposed stylet extremity; bottom: exposed serrated stylet designed to section tissue for dual needle penetration.

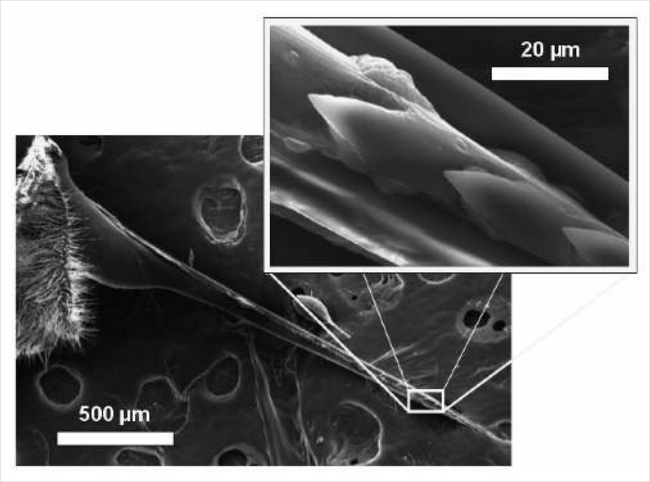

Figure 3. A bee (Apis mellifera) stinger; notice directional barbs that ensure retention of stinger in tissue of prey.

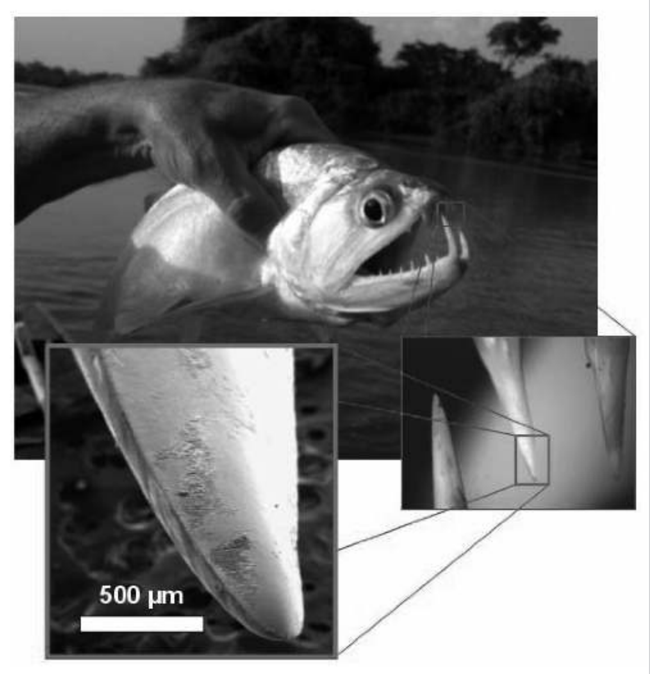

Figure 4. A dogfish (Hydrolycus scomberoides) and teeth.

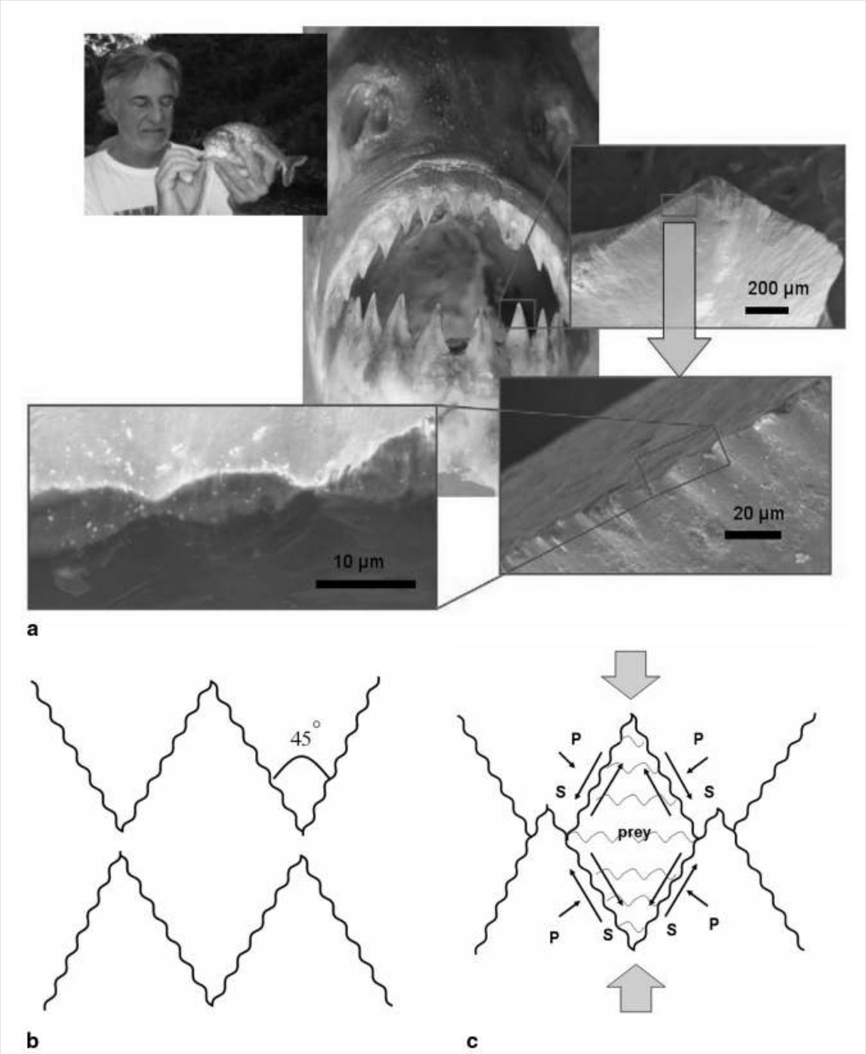

Figure 5. A piranha (Serrasalmus manueli) teeth: (a) hierarchical structure from jaw to single tooth to micro serrations; (b) and (c) diagrams of guillotine-like confinement of material during the biting action of a piranha.

scanning-electron microscopy (SEM) images at increasing magnifications; the top micrograph shows the sheath, covered with hair; the middle micrograph shows the tip of the stylet protruding from the sheath; and the bottom one, at the highest magnification, shows the serrations on the edge of the stylet. There are two rows of serrations, one on each side. They are designed to reduce compression and nerve stimulation during a bite by increasing the efficiency of the cutting edge. This is in congruence with K. Oka et al.[6] and T. Ikeshoji,[7] who concluded that the initial bite of a mosquito is painless because of the highly serrated proboscis. They used this as inspiration for a novel syringe.

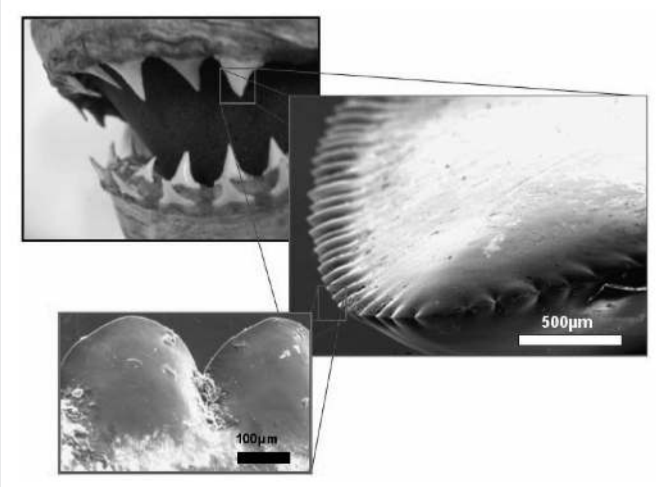

Figure 6. Great white shark (Carcaradon carcharinus) teeth.

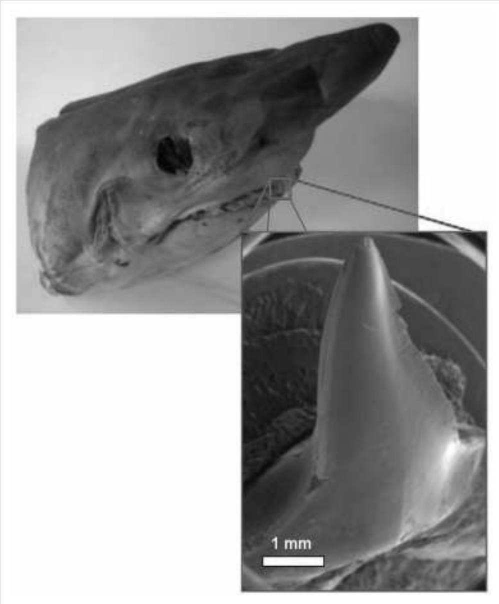

Figure 7. A Mako shark and tooth.

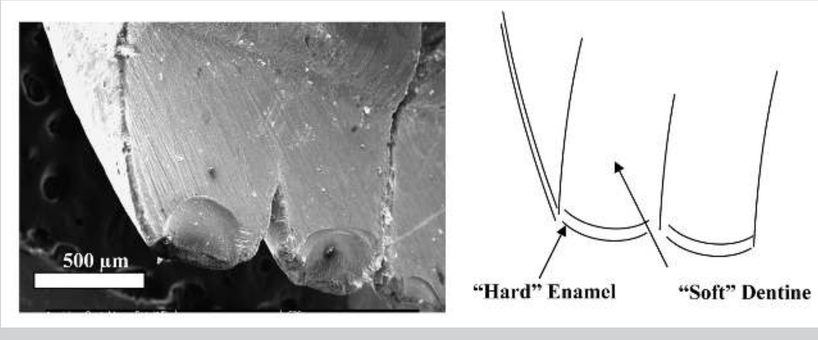

Figure 8. A rabbit tooth (incisor).

The stinger of the common bee (Apis mellifera), shown in Figure 3, is yet another example of functional serrations; in this case they are reverse-facing barbs that help to propel the needle deep into the tissue of its prey. These barbs are on the scale of 10–20 µm in gauge length and run along the shaft of the stinger. When the insect has used the stinger it stays embedded in the skin and therefore the delivery of poison is ensured.

FISH

The function of the fish teeth examined here are of particular interest. There is a great variety of teeth that are evolutionarily adapted to the diet and predation habits. The long sword-like teeth of the Amazon dogfish (Hydrolycus scomberoides) are a good example of extreme piscivorous evolutionary design. They are used to puncture and hold prey and are thus designed in a hook-like fashion facing inward toward the mouth of the fish. They actually are so long that they protrude through the head once the mouth is closed. This can be seen in Figure 4. They also have sharp lateral edges that cut through the flesh of other fish.

The piranha (Serrasalmus manueli) is quite different, although living in the same Amazon basin. Figure 5a shows the structural hierarchy of the cutting mechanisms found in the jaw of a piranha. The jaw is designed with sharp triangular teeth aligned so that as the mouth of the fish closes the tips of the teeth of both the lower and upper jaw are superimposed and puncture the prey. As the jaw further closes any tissue caught in the trough of the aligned teeth is severed in a guillotine-like action. This is shown in Figure 5b. There are superimposed compression and shear forces which effectively cut through skin and muscle. Each tooth exhibits micro-serrations along its cutting edge, seen in the detail of Figure 5a. These serrations, approximately 10–15 µm in wavelength, are used to create a highly efficient cutting effect which converts some of the dragging force into normal force at localized points.

The sharks evolved teeth from the scales of their ascendants. There is considerable variation[8–12] in the configuration and morphology of shark teeth, which is illustrated here by two examples: the great white shark and the Mako shark.

The great white shark (Carcaradon carcharinus) uses sharp teeth to perform a very specific killing action. To avoid self-injury the great white shark takes one efficiently large bite into its prey then retreats and waits for its victim to undergo shock or hemorrhaging before final consumption. The prey is very often a mammal such as a seal or a sea lion. This bite takes only one second to complete[8] and thus extremely sharp teeth are required. Each tooth is outfitted with a line of large serrations, with up to 300 µm between points. The serrations are perfectly aligned along the cutting edge of the tooth, each creating a mini tooth on the side of its parent tooth. Similar to the piranha tooth the serrations on this edge maximize the efficiency of the drag force and convert it into points of normal force summed along the side of each serration. This configuration of serrated teeth is favored when the diet consists of tougher flesh. Indeed, the Tyranosaurus[13] teeth have serrations with spacing of approximately 200 µm, very close to the great white shark. Figure 6 shows (a) an optical image of the overall jaw of a great white shark, with multiple rows of teeth, (b) a scanning-electron micrograph of the cutting edge of the tooth with large serrations, (c) a side view of serrations, and (d) a top-down view of serrations.

Compared with the great white shark, there are no serrations on the edge of the shortfin Mako shark (Isurus oxyrinchus) tooth. The teeth are slender and slightly curved in a hook-like fashion. The function of these teeth is primarily to puncture and capture prey[10] while in the great white shark the teeth are used more as cutting tools. It is clear in Figure 7 that the angle of the apex of the tooth of a Mako is much smaller then that of the great white. This sharp angle, similar to that of the dog fish, is used to puncture and swallow prey in one bite; the sides of the teeth have sharp edges to slice through the tissues that were perforated.

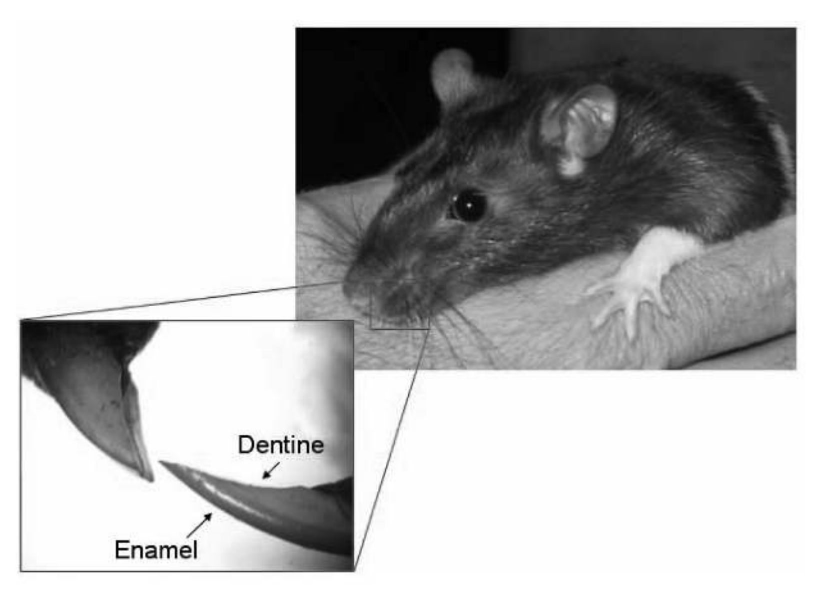

Figure 9. Self-sharpening rat incisors.

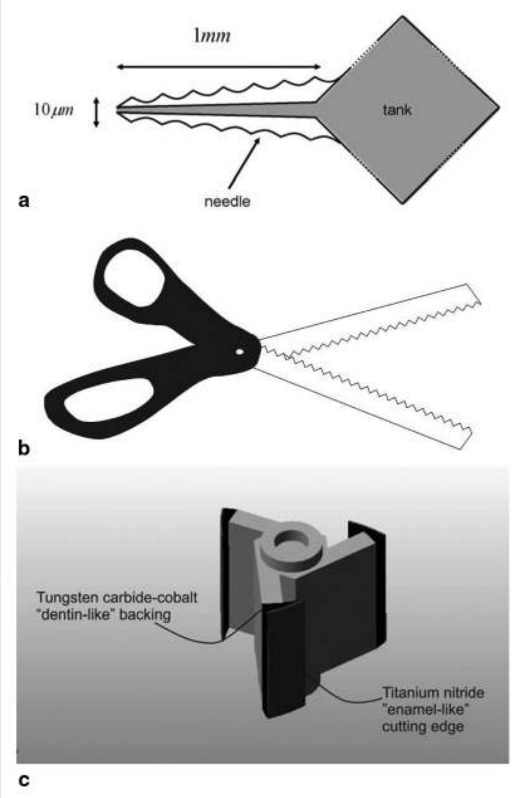

Figure 10. Possible biomimetic devices: (a) syringe inspired by mosquito proboscis; (b) scissors inspired by piranha teeth; (c) shredder cutting blades inspired by rabbit incisors.

RODENT INCISORS

The incisor teeth of rodents such as the rabbit and rat (Figures 8 and 9, respectively) have been evolutionarily designed to "self-sharpen" through a process that takes advantage of natural wear and difference in wear rates depending on the hardness of certain materials. These teeth are designed in such a way that a softer dentine backing is worn away at a faster rate then the hard enamel cutting edge. This action continuously exposes new sections of the enamel material, as the rodent periodically self-sharpens its teeth. In Figure 9 the enamel and dentine of rat incisors are shown.

BIOMIMETIC DEVICES

Figure 10 shows schematic representations of some possible and successful biomimetic approaches to devices inspired from the sharp objects described. Figure 10a represents a hypodermic needle inspired by the proboscis of the mosquito which was first developed by Oka et al.[6] This hypodermic needle has dimensions comparable with the mosquito proboscis but, more importantly, uses the serrated edges (one on each side) to slice through the tissue. The syringe manufactured by Oka et al.[6] has a built-in reservoir and is equipped with jagged edges that mimic the mosquito stylet. It is made from SiO_2 using a silicon micromachining technology.

Figure 10b represents a possible design of scissors inspired by the mouth of a piranha. The angle, spacing, and configuration of the scissor serrations match those of the piranha. This conceptual design is ideally suited to cut through tissue having the approximate mechanical resistance of flesh.

Figure 10c is a schematic drawing of a cutting tool which was designed to self-sharpen using the same mechanisms as the rodent tooth. This equipment, inspired on the rat and rabbit incisors, was successfully manufactured in Germany by Jürgen Berling and Marcus Rechberger from the Fraunhofer Institute UMSICHT.[14] They used a hard titanium nitride ceramic reinforced with nanoparticles as the hard 'enamel' portion of the cutting blade. The soft 'dentine' part of the knife was made by a tungsten carbide-cobalt alloy. The titanium nitride layer was twice as hard as the alloy. In Figure 10c the inner regions of the three blades of the shredder rub against the materials to be cut and wear out, keeping the outer layer, (the hard titanium nitride) exposed and sharp.

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