REVIEW

Inspirations from Biological Optics for Advanced Photonic Systems

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Observing systems in nature has inspired humans to create technological tools that allow us to better understand and imitate biology. Biomimetics, in particular, owes much of its current development to advances in materials science and creative optical system designs. New investigational tools, such as those for microscopic imaging and chemical analyses, have added to our understanding of biological optics. Biologically inspired optical science has become the emerging topic among researchers and scientists. This is in part due to the availability of polymers with customizable optical properties and the ability to rapidly fabricate complex designs using soft lithography and three-dimensional microscale processing techniques.

Whether it is to search for nourishment, evade predators, or seek protection from the elements, unique biological optical systems are tailored for the individual needs of each organism. Among these, the mechanism of sight is perhaps the most varied in the animal kingdom. Eyes for different species are optimized for day or night vision, for near or far, for wide or narrow fields of view, and so on (*1*).

Biologically inspired optical science is a relatively new and expanding field. The recent development of reconfigurable soft lithography (*2*) using polydimethylsiloxane (PDMS) allows the creation of unconventional three-dimensional (3D) polymeric optical systems similar to biological ones, which are themselves constructed from biological polymers. Studies in developmental biology and molecular biology are examining how protein crystals form lenses and why biomolecular actuations are needed for the control of different optical systems. Man-made biomimetic systems can be grouped according to the biological designs they attempt to emulate, including camera-type eyes, compound eyes, and others.

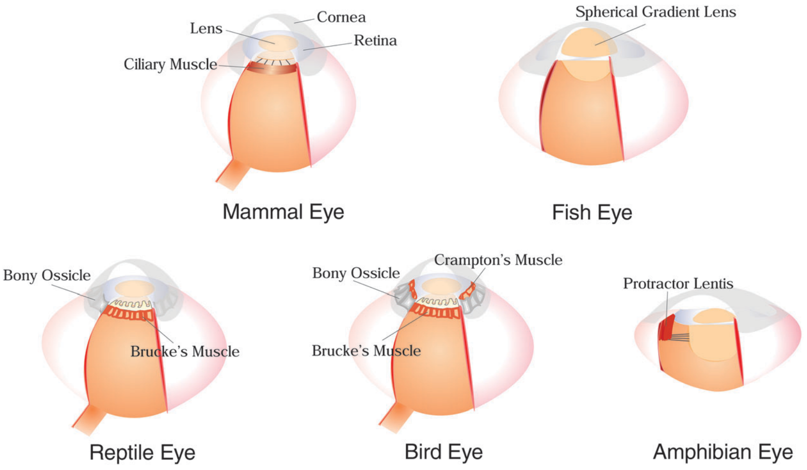

Fig. 1. Various types of camera-type eyes. **(A)** The arrangement of the mammalian ciliary muscle allows for passive changes in lens thickness. **(B)** The fish eye has a spherical gradient lens. **(C)** Brucke's muscles attached to bony ossicles in reptiles and birds, in contrast to the mammal and fish eyes, actively change the lens thickness. **(D)** Birds have an additional muscle, Crampton's muscle, which can alter the shape of the cornea. **(E)** The protractor lentis in some amphibian eyes moves a fixed-shape lens closer or farther from the retina for accommodation.

Eyes

The earliest scientific postulations of vision appeared during the time of the ancient Greeks, who described sight as elemental fire emanating from the eye (*3*). It wasn't until some fifteen hundred years later that al-Haytham accurately described how lenses can focus and magnify images (*4*), and the first accurate description of the human eye followed in 1604. Scientific fascination with eyesight has continued to the present day.

In its simplest form, sight requires that light rays be focused onto a light detector. The development of visual systems has been both convergent and progressive, with many species having accomplished similar functional goals through different paths. No fewer than 10 generalized optical mechanisms have been found in nature, each with its own variations (*5*). Two of the most prevalent are the camera-type eye and the compound eye.

Camera-Eye Systems

The human eye is the most familiar biological optical system. It is categorized as a camera-type eye (Fig. 1A), which generally relies on a single lens to focus images onto a retina. In the human eye, focusing at different distances is made possible by a flexible and controllable crystalline lens. The ciliary muscles alter tension on the lens, changing its curvature and therefore its focal length.

In the animal kingdom, there are diverse types of camera eyes. For example, fish eyes have a spherical gradient index lens (Fig. 1B). The bird eye has the added control of reshaping and deforming the cornea as well (*5*). Brucke's muscles attached to bony ossicles in reptiles and birds actively change the lens thickness (Fig. 1C). Birds have an additional muscle, Crampton's muscle, which can alter the shape of the cornea (Fig. 1D). In contrast, the whale eye uses hydraulics to move the lens itself closer or farther from the retina; a chamber behind the lens is filled or emptied with fluid depending on the focal length needed (*6*). This design allows for good vision in and out of the water, and compensates for increased pressure in deeper aquatic environments. The protractor lentis in some amphibian eyes moves a fixed-shape lens closer or farther from the retina for accommodation (Fig. 1E).

Using soft lithography techniques, which allow for the creation of unconventional 3D polymer structures, a few groups have used these principles in designing an adaptive fluidic lens (*7*–*9*). However, these designs use a homogeneous spherical lens which suffers because the peripheral light rays are more refracted than the axial ones, leading to a type of astigmatism.

In cephalopods such as octopi and squid, this spherical aberration is solved by a ball-shaped lens with a spherically symmetric refractive index gradient that decreases from the center outward. This arrangement is particularly well suited for a watery environment, where the cornea does not provide an appreciably refractory change. That is, both sides of the cornea consist of a watery medium, and the entire focusing power of the

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eye is within the lens itself. This mechanism also provides the shortest possible focal length, while allowing for a wide field of view in a compact form.

The necessary refractive gradient of this natural lens was first postulated in the 1800s (*1*), a precise mathematical description was achieved in 1944 (*10*), and a man-made equivalent was constructed in 1986 (*11*). However, creating a biologically faithful retina is equally challenging. The retina of the cephalopod, and in many animals, is a curved structure. This is noteworthy because conventional electronic processing techniques to create photosensor arrays (as in cameras) are planar. To remedy this, Hung *et al.* have fabricated photodetectors with flexible interconnects, allowing for a curved artificial retina (*12*).

Compound Eyes

Although commonplace, the insect compound eye has an allure that stems in part from it being so different than our own. Its complexity is notable at first glance, with up to 10 thousand lenslets in some species of dragonflies (Fig. 2A). Grossly, compound eyes are divided into two types, superposition and apposition. As we have come to expect, each type is well adapted to the needs of its owner.

In the apposition compound eye, the individual facets are optically isolated from one another, with each providing part of the total scene (Fig. 2B). This is analogous to having individual cameras arranged spherically. From an engineering perspective, the apposition eye has its advantage in that images are processed in parallel, with each facet sending signals simultaneously. This allows for fast motion detection and image recognition. The trade-off, however, is that the brightness of the image is substantially diminished, as each facet can only capture a small amount of light.

Replicating an apposition compound eye does not lend itself well to efficiency or compactness, as each optical unit requires its own image capture and processing module. Still, the design concept is a relatively simple one, and new micromachining technologies have miniaturized these devices to a scale never before possible. Ogata *et al.* fabricated an artificial compound eye and integrated retina in the 1990s using planar arrays of gradient refractive index (GRIN) rods to focus light through pinholes onto a photodetector array (*13*) (Fig. 2D). Their resolution was only 16 by 16 but has led to modern versions that have the ability to capture full color images (*14*, *15*).

Even newer examples of apposition eyes have ommatidia arranged normal to a sphere, more faithful to their natural counterparts. The first artificial ommatidia by self-aligned microlenses and waveguides were created by Kim *et al.* (*16*). This was followed by a 3D compound eye with self-aligned waveguides and individual microlens units on a spherical surface by Jeong *et al.* (*17*). The ommatidia are arranged along a hemispherical polymer dome such that each points to a different direction, allowing for a wide field of view, similar to that of the natural eye (Fig. 2E). The spherical configuration of the microlenses was accomplished by a polymer replication process with the use of the deformed elastomer membrane, which has microlens patterns. The formation of self-aligned polymer cones and waveguides with respect to microlenses on the hemispherical dome was also realized by a self-writing process in a photosensitive polymer resin (Fig. 2F).

In the superposition compound eye, the images from each facet are not optically isolated. That is, they are projected in overlapping fashion onto a common retina (Fig. 2C). This increases photosensitivity, but may lead to blurring at the image interfaces. In biomimetics, this type of compound eye is not as popular as the apposition type, but it does have unique applications.

Historically, one of the most famous examples of biomimetic optics was described in 1979, when Angel proposed that lobster eyes be used as x-ray telescopes (*18*–*20*). Lobster eyes are composed of an array of tapered tubes which bend light by reflection rather than refraction (Fig. 2F). The light follows a path as if striking a spherical mirror. The tubes also share a common retina, making a superposition compound eye.

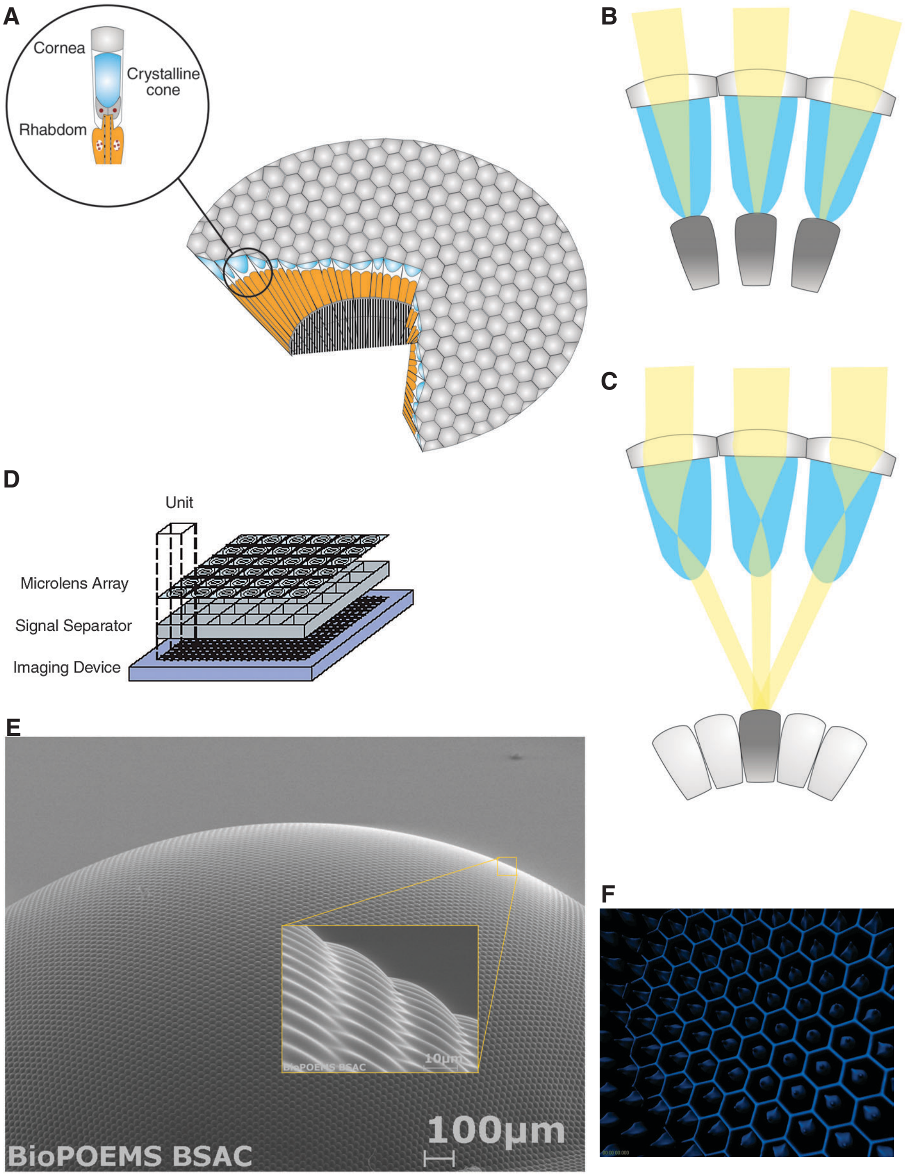

Fig. 2. Compound eye. (**A**) Schematics of compound eye. (**B**) Light flow through an apposition compound eye. (**C**) Light flow through a superposition compound eye. (**D**) Microlens array. [Image from (*13*)] (**E**) SEM image of an artificial compound eye fabricated by the biologically inspired 3D optical synthesis method. [Image from (*17*)] (**F**) Confocal micrograph of self-written cones under honeycomb-packed microlens array in the artificial compound eye. [Image from (*17*)]

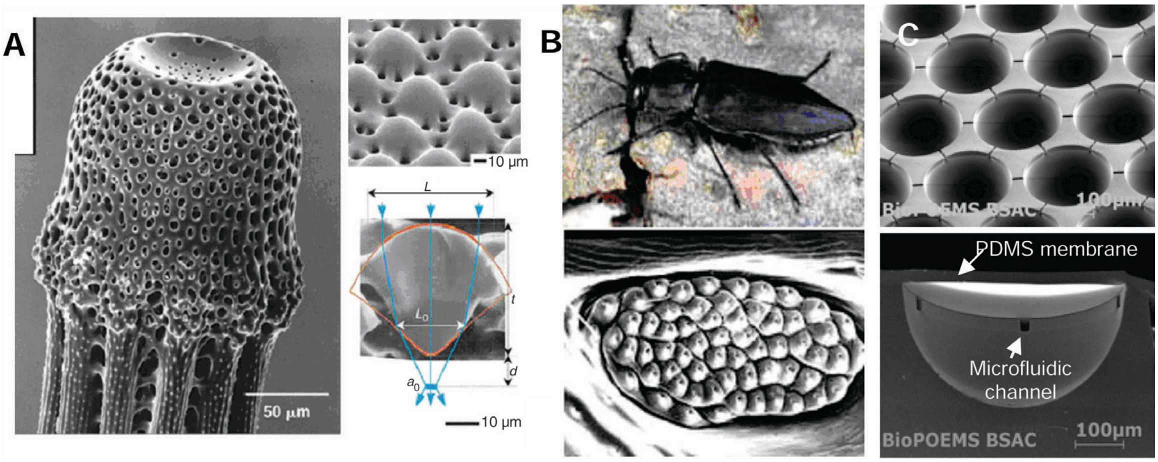

Fig. 3. Other biomimetic approaches. (**A**) SEM images of the brittlestar, indicating the focus of light rays at photosensitive locations beneath the surface. [Image from (*22*)] (**B**) An *M. acuminate* beetle with electron micrograph of its pit organ. [Image from (*24*)] (**C**) SEM images of biologically inspired microfluidic doublet lenses. (Top) Lens without thin PDMS elastomer. (Bottom) Cross-sectional image of the doublet lens with the thin PDMS elastomer membrane (*9*).

Traditional x-ray telescopes use concave mirrors to reflect x rays, but only a small percentage of rays are bent in this manner. X rays are only reflected at glancing angles, leaving a 1° field of view. Arranged spherically, a lobster eye has the potential for an unlimited field of view. Another use for the control of x rays is to invert the lobster eye such that parallel beams can be produced from a point source (*18*–*20*).

Finally, a hybrid apposition/superposition eye is under development by Szema *et al.* (*21*). Although its current form is not found in nature, this design draws its inspiration heavily from the biological world. Essentially, it involves a superposition eye with optical shutters attached to each of the facets of the eye. By opening one shutter at a time, images are retrieved from each facet individually, optically isolating each facet as in an apposition arrangement. However, these facets all project onto a common retina, mimicking the superposition compound eye. The advantages of this system are reduced processing requirements while maintaining separate, unblurred, images from each facet. The latter is particularly relevant given that the separated images can be used to determine distance to an object, much like humans use two eyes to perceive depth.

Other Systems in Nature

Commonly known as the brittlestar, the species *Ophiocoma wendtii* is able to evade predators and is sensitive to light, without obvious eyes or a brain. In 2001, Aizenberg *et al.* discovered that the calcite crystals throughout the brittlestar skeletal body were parts of an all-encompassing compound eye (*22*) (Fig. 3A). The crystals (40 to 50 μm in diameter) form doublet lenses which correct spherical aberration and birefringence. The focal point of the lenses matches nerve bundle locations beneath the crystal array. Commercial applications of such crystals have applications in optical networking and improved photolithography methods. They have been able to produce single calcite crystals with a defined crystallographic orientation by using micropatterned templates (*23*).

Jeong *et al.* have used this same design in a microfluidic doublet lens system capable of creating dual modes (*9*) (Fig. 3C). It can be tuned either by changing the shape of a fluidic lens or by changing the refractive index of the filling media. In this way, the system is able to minimize optical aberrations while maximizing the range of focal length or field of view.

The beetle *Melanophila acuminate* is another curious creature with the unique ability to detect forest fires some 80 km away. Female beetles lay eggs in burnt trees which no longer maintain their natural defenses. This is the only environment in which their larvae survive. They are directed to fires by specialized pit organs which are tuned to a specific infrared frequency (Fig. 3B). These organs hold 50 to 100 sensors, each 15 μm in diameter, which absorb the infrared light. Expansion of a cuticular apparatus is detected by mechanoreceptors which, in turn, direct the beetle (*24*).

Researchers are developing and characterizing new materials that behave similarly in response to heat (*25*). The expansion of these materials in response to various parts of the infrared spectrum allow for the detection of specific sources.

The Future

Imitating nature is a complex endeavor, and a blind biomimetic approach is not the best methodology. Instead, molecular-level studies of the biological development of natural vision systems are key. For example, current infrared sensors can distinguish more than what human eyes can see, but they require a sophisticated cooling system to work. Somehow, insects have this same ability without the limitation of temperature control. This is but one example of how it is primarily nature's designs that are superior to man-made equivalents. However, if we are able to decode the designs, then the combination of our creativity in materials and nature's wisdom is synergistic one with incredible potential.

References and Notes

1. M. F. Land, *Contemp. Phys.* **29**, 435 (1988).
2. Y. Xia *et al.*, *Science* **273**, 347 (1996).
3. C. Millerd, *On the Interpretation of Empedocles (Ancient Philosophy)* (Garland, New York, 1980).
4. A. Sabra, *The Optics of Ibn-Haytham: On Direct Vision (Studies of the Warburg Institute)* (The Warburg Institute, London, 1989).
5. M. Land, D. Nilsson, *Animal Eyes* (Oxford Univ. Press, Oxford, 2002).
6. R. Smythe, *Vision in the Animal World* (Macmillan Press, London, 1975).
7. D. Zhang, V. Lien, Y. Berdichevsky, J. Choi, Y. Lo, *Appl. Phys. Lett.* **82**, 3171 (2003).
8. N. Chronis, K. Jeong, G. L. Liu, L. P. Lee, *Opt. Express* **11**, 2370 (2003).
9. K. Jeong, G. L. Liu, N. Chronis, L. P. Lee, *Opt. Express* **12**, 2494 (2004).
10. R. K. Luneberg, in *Mathematical Theory of Optics* (Brown Univ. Press, Providence, RI, 1944), pp. 208–213.
11. Y. Koike, Y. Sumi, Y. Ohtsuka, *Appl. Opt.* **25**, 3356 (1986).
12. P. Hung, K. Jeong, G. Liu, L. P. Lee, *Appl. Phys. Lett.* **85**, 6051 (2004).
13. S. Ogata, J. Ishida, T. Sasano, *Opt. Eng.* **33**, 3649 (1994).
14. J. Tanida *et al.*, *Opt. Express* **11**, 2109 (2003).
15. J. Duparre *et al.*, *Proc. SPIE* **5346**, 89 (2004).
16. J. Kim, K. Jeong, L. P. Lee, *Opt. Lett.* **30**, 5 (2005).
17. K. Jeong, J. Kim, J., L. P. Lee, "Biologically inspired optical systems" (available at http://biopoems.berkeley.edu).
18. J. Angel, *Astrophys. J.* **233**, 364 (1979).
19. B. K. Hartline, *Science* **207**, 47 (1980).
20. M. Denton, *Nature's Destiny* (The Free Press, New York, 1998), p. 354.
21. R. Szema, J. Rastegar, L. P. Lee, *J. Med. Eng. Technol.* **28**, 117 (2004).
22. J. Aizenberg, A. Tkachenko, S. Weiner, L. Addadi, G. Hendler, *Nature* **412**, 819 (2001).
23. J. Aizenberg, D. Muller, J. Grazul, D. Hamann, *Science* **299**, 1205 (2003).
24. L. Sowards, H. Schmitz, D. Tomlin, R. Naik, M. Stone, *Ann. Entomol. Soc. Am.* **94**, 686 (2001).
25. J. Roach, "U.S. military looks to beetles for new sensors," *National Geographic News*, 8 March 2004 (available at http://news.nationalgeographic.com/news/2003/03/0314_030314_secretweapons3.html).

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