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Looking – into the future

Having to wear reading glasses as you get older may soon be a thing of the past. **Helen Gleeson** describes her team's research into liquid-crystal contact lenses that will be able to switch focus and restore youthful vision

We're often told that with age comes wisdom. Unfortunately, this virtue also comes hand-in-hand with various downsides, notably our bodies no longer functioning as they used to (as much as we may not want to admit it). And as we reach middle age and lose count of the grey hairs, there is the inevitable prospect of having to put on a pair of glasses.

Over the course of your life, it becomes ever harder to focus on objects closer to you because the crystalline lens in the human eye becomes more rigid. This means the lens can no longer change shape as readily as it used to, so cannot focus on nearby objects – to use the technical term, the lens can't "accommodate". This condition, known formally as presbyopia and informally as not-having-arms-long-enough-to-hold-text-far-enough-away-to-see-properly, affects everybody over the age of 50. A few people don't think it has affected them, but in truth their distance vision was already imperfect and presbyopia just makes everything a little bit better.

But imagine if we could magically get rid of these vision problems and you never had to wear glasses again? Is there a way to restore the vision of your youth so it is no longer a thing of the past?

Imperfect solutions

There are several existing solutions for presbyopia, but all are compromises and none fully restores youthful vision. The most common approach is to use spectacles with different focal regions, known as bifocals or varifocals. The spectacle lenses are shaped differently in the regions associated with distance compared to those linked with reading, thereby forming different focal lengths.

Bifocal contact lenses also exist and, as with glasses, these work by having different focal regions in different parts of the lens. Selecting the right part of the contact lens relies on the brain distinguishing between in-focus and out-of-focus images, together with the pupil generally being smaller in conditions

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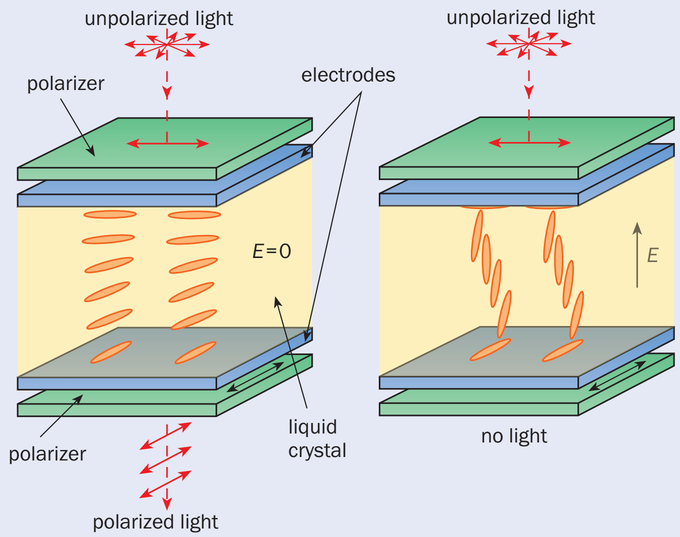
Inside an LCD



Liquid-crystal displays (LCDs) contain a thin film of a nematic liquid crystal roughly 5 μm thick, held between two transparent electrodes, which are themselves sandwiched between two polarizers. The liquid crystal molecules have a specific geometry depending on the type of device, but in the most common arrangement, known as a "twisted nematic" device, the "director" – the average direction in which the nematic liquid-crystal molecules point – is aligned to the polarizers, which are at 90° to each other. This means the director rotates through an angle of 90˚ across the layer. In the absence of an electric field (E), unpolarized light becomes polarized as it enters the LCD. Its axis of polarization gets rotated 90° by the liquid crystal and the light then passes through the second polarizer, causing a bright state. When a sufficiently large electric field is applied across the electrodes, however, the liquid-crystal molecules align perpendicular to the plane of the device, changing its effective refractive index and suppressing the twisted arrangement. The light therefore gets completely absorbed by the second (crossed) polarizer, creating a dark state.

where we read. This clever solution works well for some people, but it is, again, a compromise.

In particular, reading in the dark is a problem with bifocal contact lenses. That's because when it's dark, your pupil is wide open to try and let in as much light as possible. But the dilation of the pupil exposes the outer edges of the contact lenses – the parts usually associated with focusing on distant objects. There's also a lack of contrast as not all of the light passing through the lens is focused on a single image, making it difficult to distinguish small text.

Another common solution is so-called "monovision". This corrects one eye for good distance vision and the other for good near vision and can be done via contact lenses or laser surgery. Once again, however, this solution doesn't work for everyone as some people feel disoriented by having different foci associated with each eye and the approach falls short of restoring our vision to that of our youth.

We're working on another possible solution. The aim is to develop liquid-crystal contact lenses with variable focus. Our team, which we set up a few years ago with staff at the UK-based firm Ultravision, brings together optometrists and experts in optics and liquid crystals. We wanted to see if liquid crystals could be used to make "switchable" contact lenses by virtue of them having a refractive index that varies with applied voltage. At first glance, our approach may seem more rooted in science fiction than reality, but we believe it could offer the eyesight of youth to older generations.

From TVs to eyes

Nowadays, liquid crystals are a massive part of everyday life, as they are used in the flat-panel liquid-crystal displays (LCDs) of billions of mobile phones, televisions and laptops. These fascinating "soft" materials are characterized by the fact they are ordered fluids. There are many variants of liquid crystal because there are many ways of achieving order in a fluid, but it's the so-called "nematic phase" used in LCDs that is of interest to us.

The molecules that form nematic liquid crystals are usually rod-like and orientated such that their long axes point, on average, in the same direction – this is defined by a unit vector called the "director". Liquid crystals have long-range orientational order, so many of a nematic liquid crystal's physical properties, such as its refractive index, are anisotropic, which means that the value of those properties varies from one region to another, depending on the local value of the director.

But because liquid crystals are fluids, the director is extremely responsive to external stimuli, such as electric and magnetic fields, temperature and pressure. Applying a voltage above a particular value, for example, orients the director either parallel or perpendicular to the electric field's direction, depending on whether the dielectric anisotropy is positive or negative respectively. As the system's optic axis (i.e. the direction of optical symmetry) is defined by the director, it also reacts to the applied voltage. These are the properties any LCD devices rely upon (see box, left).

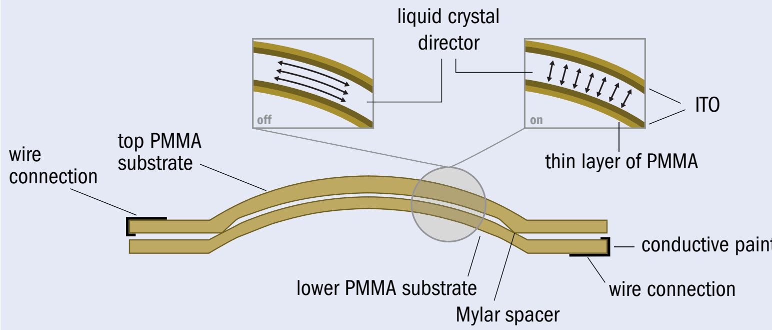
Eye on the challenge

Based on the voltage-dependent refractive index, researchers have been suggesting liquid-crystal lenses since the 1970s. But making a liquid-crystal contact lens that can be placed on the eye is not easy. The overall device must be curved and less than 300 μm thick – anything chunkier would not be comfortable to wear. The change in focus must be around +2.0 dioptres, which is the measure of focus in optometry; most people with presbyopia need an additional +1.5 or +2.0 dioptres. The lens needs to change focus faster than the eye can blink, meaning less than a second in practice. Ideally, it shouldn't be too expensive either, which means that a simple manufacturing process is important. And, somehow, the lens needs to have a source of power so it can change focus. Indeed, to make a device that stands a chance of being used in the eye, it's important that the lens can stay powered for at least a day.

We decided to use polymethylmethacrylate (PMMA) as the base for the lens as this is a material commonly used for contact lenses. We then came up with a simple – and in our view elegant – solution based around "balanced optics". It involved forming a contact lens with three layers (figure 1), each of

> There are still some challenges to be overcome before we get close to a commercial switchable contact lens

1 Layered lenses



The liquid-crystal contact lenses rely on balancing three layers that act as lenses in their own right.

which is a lens in its own right. The bottom layer, a substrate of PMMA, follows the curvature of the eye and is coated on the surface adjacent to the liquid crystal with a transparent indium-tin-oxide (ITO) electrode and a polymer that aligns the liquid crystal when in the "off" state. Next comes the liquid-crystal layer, topped with another layer of ITO-coated PMMA. Together, these three lenses are balanced. Their curvature, the PMMA refractive index and the "off"-state refractive index of the liquid crystal are designed to provide either no vision correction or distance vision correction, depending on what is needed by the individual. When a voltage is applied, producing an electric field across the electrodes, the refractive index of the liquid-crystal layer changes (by an amount that depends on the voltage, the lens geometry and the liquid-crystal material). As a result, the focal power of the lens changes too.

We have now demonstrated several geometries with different kinds of liquid-crystal alignment, all of which rely on the liquid-crystal refractive index changing between ~1.5 and ~1.7. This switching starts at voltages as low as ~0.7 V_{rms}, which at the moment is simply applied with wires attached to the electrodes. The response time is well under 1 s. Our design allows us to do better than mimic putting on reading glasses that give a change of ~2.0 dioptres, while also variably changing the focus so that we can correct for intermediate vision too (e.g. for viewing a computer screen).

One potential drawback of using a liquid crystal is related to its anisotropy. We need the property of having two refractive indices (birefringence) to achieve a voltage-dependent refractive index – but unless we design our lens carefully, the focusing power would depend on the polarization of the light and so would suffer from similar drawbacks as some of the other technologies. The problem is that the refractive index experienced is also polarization-dependent (remember it is polarized light that interacts with the liquid-crystal layer in an LCD). Our solution has been to develop a lens with two chambers for the liquid crystal, oriented orthogonally with respect to each other, to ensure that the whole lens operation is polarization-independent.

Ever closer future

Although a switchable spectacle lens is far easier to make and power, using liquid-crystal contact lenses has many advantages. First, we can ignore any chromatic aberration in the contact lens, which is caused by the fact that the refractive index in any material is wavelength-dependent and leads to different wavelengths being focused at slightly different points. That's because the aberration in the lens is less than the aberration of the cornea and the brain just sorts it out. Second, we don't need to be concerned about off-axis rays that would experience a different focus because of the liquid-crystal geometry. Again, the contact-lens geometry helps as it restricts vision to mostly the axis of the lens.

There are still some challenges to be overcome before we get close to a commercial switchable contact lens. The first is to determine how the lens will be powered. One reason LCDs are so successful is that they are inherently low-power devices, meaning they can run for a long time on a small battery. This helps us, as there are several possible solutions to powering the lens. Indeed, we have a strong patent in the area of liquid-crystal contact lenses and our first investment will allow us to make an eye-ready wireless lens that has the power source on the lens itself.

Another major challenge is how the lens will know when to change the refractive index. The simplest way to do this is to have the lenses communicating with, say, a smart watch. However, many other possible control mechanisms have been proposed, for example blinking. Of course, in such a case, a longer than normal blink would be needed, or perhaps a specific sequence of blinks.

It might still seem like science fiction to have batteries or other power technologies mounted on a contact lens, but a contact lens containing a light-emitting diode powered from an induction coil was demonstrated a few years ago (*J. Micromech. Microeng.* **21** 125014). There are several other examples of "smart contact lenses" including ones containing glucose sensors for monitoring diabetes, such as that announced by Google in 2014. The challenge of powering such devices is a hot topic, with wide-ranging suggestions including one where the lenses might be powered by tears. There is also increasingly simple technology that could be used to trigger the change in focus – something that users would want to be simple and, if possible, automatic.

As all of these technologies come together, contact lenses that have variable and controllable focus are no longer science fiction – but could become reality within the next five years. ■