COMPETENCIES COVERED

Dispensing opticians: Standards of practice, Optical appliances, Refractive management
Optometrists: Standards of practice, Optical appliances

STANDARDS OF PRACTICE | OPTICAL APPLIANCES | REFRACTIVE MANAGEMENT | STANDARDS OF PRACTICE | OPTICAL APPLIANCES

Adaptive spectacle lenses: part one

by Professor Mo Jalie SMSA, FBDO(Hons), Hon FCGI, Hon FCOptom, MCMI

An adaptive spectacle lens is a lens whose power can be made to change by applying some sort of effort to the lens. Unlike the usual power variation lens (i.e. a progressive or degressive power lens), the power of an adaptive lens can be changed, either across the whole lens aperture, or over just a selected area of the lens, for example, just the near portion.

Adaptive optics are employed in many optical instruments, for example, to create changes in some areas of the primary objective lens of a telescope in order to control aberrations, which have been caused by changes in the surface geometry, or by disturbances in the object space. Needless to say, an aberration can be looked upon as an alteration in power from the desired value. In the case of the spectacle lens, an adaptive lens can be adjusted to produce just the correct power necessary to correct a given degree of ametropia or presbyopia.

Currently, variable power can be produced by four different methods:

1) Systems which depend upon a variable axial separation of its components.
2) Systems which depend upon adjustable sliding contact between the components.
3) Lenses whose surfaces can be deformed by alterations in the volume of the lens.
4) Lenses whose refractive index can be altered by applying a small electric current to the lens.

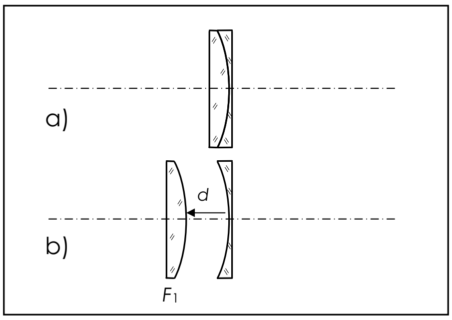

Figure 1: Variable power by varying the separation of the lens components

In each of the first three cases, the change can be altered and reversed by the wearer as many times as required. In the fourth case, it is an on-off change, depending upon whether the current is being applied or has been switched off. The following sections describe the theory of these methods in detail[1].

VARIABLE POWER FROM SYSTEMS WITH A VARIABLE SEPARATION OF THE LENSES

Consider the two optical components, +20.00D and -20.00D illustrated in **Figure 1(a)**. When placed in close contact as shown in the Figure, they neutralise one another and the result is a parallel sided afocal block.

Now suppose that the lenses are separated by 2.4mm as shown in **Figure 1(b)**, the power of the system measured at the concave surface of the -20.00D component is given by:

$$\frac{F_1}{1-dF_1} + F_2 = \frac{20}{1-0.0024 \times 20} - 20.00 = +1.00\text{ D}$$

Shifting the +20.00 Dlens forwards by a further 2.15mm produces +2.00D and a shift of 10mm from the zero position produces a power of +5.00D. Clearly, such a combination of lenses can be used to obtain a variable power system.

The change in effective power measured at the concave surface is:

$$\frac{F_1}{1-dF_1} - F_1 = \frac{dF_1^2}{1-dF_1}$$

Since d is small when expressed in metres, the denominator is not very different from unity, and we can express the change in power, A, as:

$$A = \frac{dF_1^2}{1000}$$

where *d* is expressed in millimetres. Note that since the numerator of this expression is always positive, it does not matter whether the front moveable lens is the plus component or the minus component.

To produce an adaptive optical system which could provide variable power from,

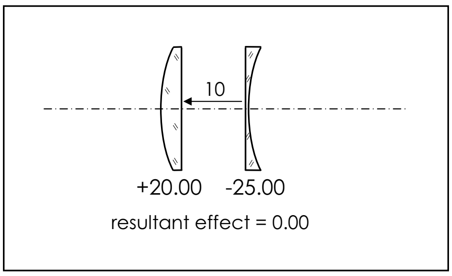

Figure 2: Variable power system designed to produce range +5.00D to -5.00D

This article has been approved for 1 CET point by the GOC. It is open to all FBDO members, and associate member optometrists. The multiple-choice questions (MCQs) for this month's CET are available **online only**, to comply with the GOC's Good Practice Guidance for this type of CET. Insert your answers to the six MCQs online at www.abdo.org.uk. After log-in, go to 'CET Online'. **Questions will be presented in random order.** Please ensure that your email address and GOC number are up-to-date. The pass mark is 60 per cent. The answers will appear in the August 2016 issue of *Dispensing Optics*. The closing date is 12 July 2016.

C-51040

say, +5.00D to -5.00D, we could choose a -25.00D rear component and a +20.00D front, moveable component as shown in **Figure 2**. When the lenses are in contact the power of the combination is -5.00D. If the front lens is then moved forward by 2.4mm, the power of the combination becomes -4.00D.

The components have been reversed from those shown in **Figure 1** in order to provide a better optical performance over a wider field with fewer off-axis aberrations, so the front surface of the plus lens must be compensated for the lens thicknesses.

In order to produce a variable power, *ready-to-wear* spectacle lens designed for reading purposes only, whose power covered the full permissible range suggested in BS EN ISO 14139 – Ophthalmic Optics – Specifications for ready-to-wear spectacles, of +1.00D to +3.50D, a back element of -19.00D could be combined with a front moveable lens of power +20.00D. Then, when the lenses are in contact they will provide a power of +1.00D and the movement required to obtain a lens of power +3.50D would be just 5.55mm.

Requiring such a small movement of the components, a device of this nature would be very simple to construct with the front lens mounted in, say, a screw threaded cap which would not have an unusual appearance or be too cumbersome. Bennett has recorded that adaptive spectacles of this nature were patented by H. Dixon[2] of London as long ago as 1785.

VARIABLE POWER FROM SLIDING COMPONENTS

Adaptive prism systems are well known, the rotary prism. Such a device employing two 15Δ components can produce any resultant prism power from zero to 30Δ by rotating the two prisms in relation to one another. The rotary prism not only forms a useful trial case accessory, but is also used as a prism compensator in the focimeter, either to extend the measuring range of the instrument or to neutralize prism in a lens before power readings are taken.

THE STOKES' LENS

Another accessory which may be found in the trial case is the Stokes' lens, which is an adaptive cylinder that can produce any cylinder power from zero up to twice the value of either component. However, the Stokes' lens also has a residual spherical power which is always half the value of the resultant cylinder power.

Consider the pair of ±6.00D plano-cylinders illustrated in **Figure 3**. When placed together as shown in **Figure 3(a)**

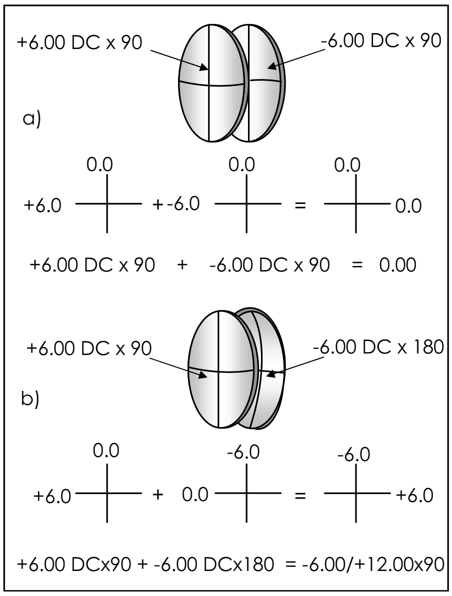

Figure 3: Stokes' lens made with ±6.00D cyls in minimum and maximum configurations

they neutralise one another and the resultant effect is zero. This effect is confirmed by the optical cross representations of the principal powers shown in the Figure, and the fact that they neutralise along every meridian is obvious since the absence of material from the convex cylinder is replaced by the presence of material from the concave cylinder.

If the -6.00DC component is now rotated through 90° as shown in **Figure 3(b)**, the combination becomes -6.00DC x 180/+6.00DC x 90, which is equivalent to -6.00DS/+12.00DC x 90.

Suppose now that the -6.00DC x 90 shown in **Figure 3(a)** was rotated through 30° from the zero position. The resultant, found by summing the obliquely crossed cylinders, -6.00DC x 60/+6.00DC x 90, is found to be -3.00DS/+6.00DC x 120.

This result can be found as follows. If we have two equal but opposite powered cylinders, F_1 DC / $-F_1$ DC with an angle α between their axes, we find from the theory underpinning Stokes' construction that the axis of the resultant cylinder lies at α/2 from either axis, i.e. midway between their

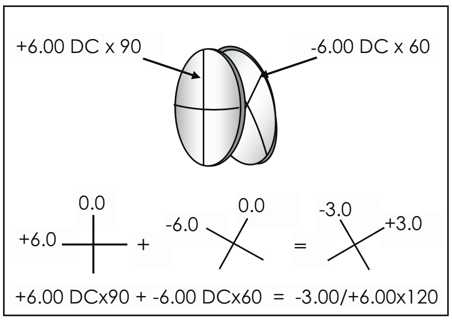

Figure 4: Stokes' lens with acute angle of 30° between the axes; +6.00DC x 90/ -6.00DC x 60

two plus axis meridians, and that the power of the resultant cylinder is given by

$$\begin{aligned} C &= \sqrt{(F_1^2 + F_2^2 + 2F_1F_2 \cos 2\alpha)} \\ &= \sqrt{(2F_1^2 - 2F_1^2 \cos 2\alpha)} \\ &= \sqrt{(4F_1^2 \sin^2 \alpha)} \\ &= 2\,F_1 \sin \alpha \end{aligned}$$

and

$$\begin{aligned} S &= (F_1 + F - C) / 2 \\ &= -C / 2 \\ &= -F_1 \sin \alpha. \end{aligned}$$

For the example shown in **Figure 4**, -6.00DC x 60/+6.00DC x 90, α = 30°

$C = 2\,F_1 \sin \alpha = 12 \sin 30 = +6.00$DC

$S = -F_1 \sin \alpha = -6 \sin 30 = -3.00$DS

So the resultant is -3.00/+6.00 x 120.

If the minus cylinder is rotated through 60° from the zero position, the two components now being +6.00DC x 90/ -6.00DC x 30 the angle between the axis meridians, α, = 60°.

$C = 2\,F_1 \sin \alpha = 12 \sin 60 = +10.40$ DC

$S = -F_1 \sin \alpha = -6 \sin 60 = -5.20$ DS

(i.e. half the value of the resultant cylinder) and the combination is equivalent to -5.20/ +10.40 x 105.

If it is required to produce variable cylinder power but to maintain a fixed axis direction, then the components must be arranged to rotate through equal angles, one clockwise and the other, anti-clockwise from the zero position, and this must lie at 45° to the required axis direction. For example, if it is required to maintain an axis direction of 45° then the cylinders shown in **Figure 3(a)** would be orientated so that their common axis meridian for the zero position lay along 180˚ and, using the same mechanism as that found in the rotary prism, when one cylinder is rotated anti-clockwise, through 15°, so that its axis lay along 15°, the other cylinder would rotate clockwise through 15°, so that its axis lay along 165°.

The Stokes' lens is used in some automatic refractometers when it is usually combined with an adaptive spherical lens to neutralise the spherical component, which results from the variable cylinder.

ALVAREZ-LOHMANN LENSES

An adaptive lens which can provide both variable spherical and cylindrical power was described by Luis W. Alvarez[3] in 1967. Three years later, an adaptive lens of similar construction was described by A. Lohmann[4] and lenses of this type are often referred to as Alvarez-Lohmann lenses. Here, for brevity they will be called simply, Alvarez lenses.

Consider the parallel-sided block of optical material, say a block of CR39, illustrated in **Figure 5(a)**. Clearly, there would be no movement of objects viewed through the block depicted in **Figure 5(a)**, under the transverse test. On careful

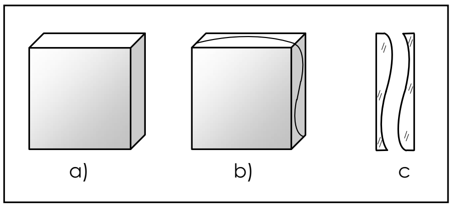

Figure 5: Components of the Alvarez lens
a) block of optical material, e.g. CR39
b) block sliced into two as indicated
c) cross-section of the two components

inspection of the block, it is seen that the block is actually made from two separate components, which have been put together as shown in **Figure 5(b)**.

A cross-sectional view of the two separated components is shown in **Figure 5(c)**. Like the plano-convex and plano-concave cylinders, which make up the Stokes' lens, the absence of material from one component is entirely replaced by the presence of material from the second component

Figure 6(a) shows that provided that the two components are sufficiently thin, despite its peculiar shape, the Alvarez lens would still be afocal if its two components were placed together, with their plane surfaces in contact. Once again, the absence of material from one component is precisely compensated for by the presence of material from the second.

Now consider the cross-sectional shapes of the resulting element when the two components are separated by sliding the two components along their plane surfaces, as shown in **Figure 6(b)**. In **Figure 6(b)** the components have been separated by sliding the second component downwards in relation to the first, the plane surfaces remaining in contact. It can be seen that an optical element is formed, which has two convex surfaces and it will be seen that the thickness of this element varies in every meridian in exactly the same way as the thickness of a bi-convex spherical lens.

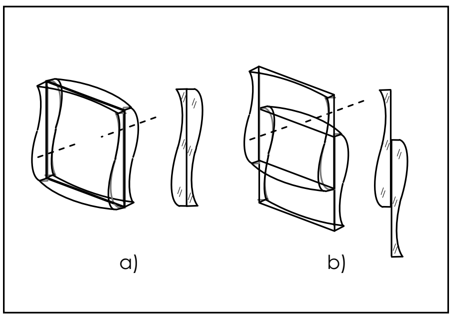

Figure 6: Alvarez lens arranged to form a positive lens
a) components in afocal position
b) components slid apart to form a plus lens

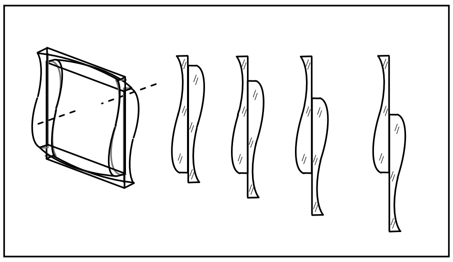

Figure 7: Increasing the separation of the elements increases the power of an Alvarez lens

Furthermore, as can be deduced from **Figure 7**, the greater the separation of the components, the greater becomes the thickness difference across the components so the greater becomes the power of the resulting spherical lens. In **Figure 8**, the two components of the Alvarez lens have been slid in the opposite direction, when the resulting optical element is seen to possess two concave surfaces forming a negative lens. Once again, the further the movement of one component in relation to the other, the greater the increase in the minus power of the lens.

Now consider how the thickness of the Alvarez lens changes when, starting from the afocal position of the elements, the components are slid horizontally in relation to one another (**Figure 9**). It can be seen that along the vertical meridian of the combination the thickness does not change, the Alvarez lens remains afocal in the vertical meridian. Along the horizontal meridian, however, as the separation increases from the zero position shown in **Figure 9(a)**, the thickness of the combination starts to increase. It will be seen that this movement produces a plano-cylinder with its axis at 45°. The Alvarez lens now behaves like a plano-cylinder whose cylindrical effect increases as the separation of the components is increased along the horizontal meridian.

It follows that if the two components are separated in both the vertical and

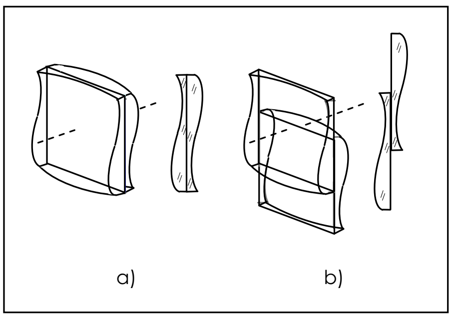

Figure 8: Alvarez lens arranged to form a negative lens
a) components in afocal position
b) components slid apart to form a minus lens

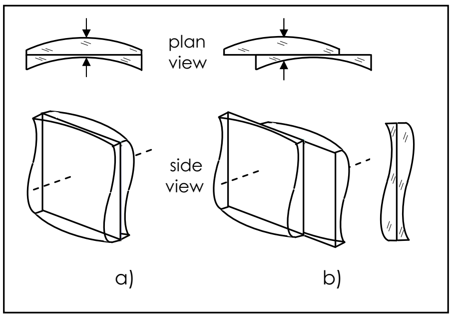

Figure 9: Alvarez lens arranged to form a plano-cylinder
a) components in afocal position
b) components slid apart to form a plano-cylinder

horizontal meridians the resulting Alvarez lens will possess both spherical and cylindrical power, i.e. it has become a variable power sphero-cylindrical lens. As stated above, the axis of the cylinder will lie along the 45° meridian of the elements shown in **Figures 6 to 9**.

The contact surface between the two elements does not need to be a plane surface as can be seen in **Figure 10**, which shows a cross-sectional view of a curved form of Alvarez lens. However, in designing a curved interface, sufficient space must be allowed between the two sliding components to enable them to slide without making contact with one another.

VARIABLE POWER FROM FLUID-FILLED LENSES

If a hollow, parallel-sided, plate of glass with very thin, flexible walls is attached to a reservoir containing some transparent liquid, when the space between the walls is just filled with the liquid the filled plate will act like a parallel-sided plate of glass with no power, as illustrated in **Figure 11(a)**.

If a further volume of liquid is now forced into the plate, the flexible walls will bulge outwards under the pressure of the liquid to form a bi-convex lens. Assuming the walls of the deformable plate to be thin and remain parallel-sided, they play no part

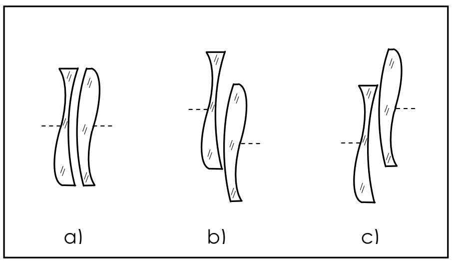

Figure 10: Alvarez lens with a curved contact surface
a) elements in afocal position
b) arrangement for plus lens
c) arrangement for minus lens

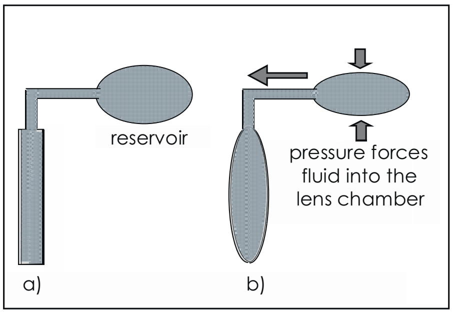

Figure 11: Fluid-filled adaptive lens
a) chamber filled with fluid
b) pressure forces fluid into the chamber to produce a bi-convex lens

in the power of the resulting lens which is due entirely to the shape of the liquid lens of refractive index, *n*. On the other hand, if fluid is withdrawn from the sealed chamber it will suck the thin walls towards one another to produce a bi-concave lens as illustrated in **Figure 12**.

The power of the resulting lens will depend upon the change in volume of the liquid. Since there is greater pressure exerted at the centre of the bi-convex lens where the thickness of fluid is greatest, the form of the convex surfaces will be paraboloidal. In the case of the withdrawal of fluid to produce a minus lens, once more, the change in thickness of the fluid will produce a pair of concave paraboloidal surfaces.

Consider the paraboloidal cap illustrated in **Figure 13**, whose radius at the vertex is r_0, and whose sag at the diameter, 2*y*, is *z*. The volume, *V*, of the paraboloidal cap is given by $\pi z^2 r_0$ and since for a paraboloid,

$$z = \frac{Y^2}{2r_0} = \frac{d^2}{8r_0}$$

where, $d = 2y$, on substituting 100(n - 1)/F for r_0 the volume of the cap is given by

$$\frac{\pi d^4 F}{6400(n-1)} \text{ cm}^3,\ d \text{ in cm.}$$

The relationship between the power, *F*, and the volume of the lens, *V*, is therefore,

$$F = \frac{6400(n-1)}{\pi d^4} V,$$ *V* being expressed in cm³.

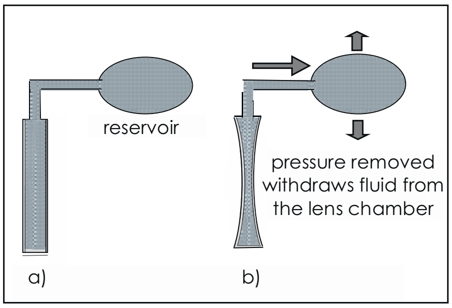

Figure 12: Fluid-filled minus adaptive lens
a) chamber filled with fluid
b) pressure removed draws fluid out of chamber to produce a bi-concave lens

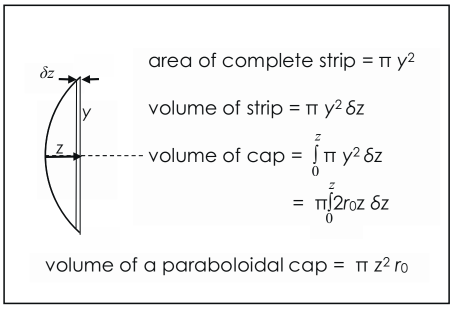

Figure 13: Volume of a paraboloidal cap

Suppose that the fluid contained between the walls is an oil of refractive index 1.586, and that the fluid lens is circular of diameter 42mm, i.e. 4.2cm. When the cavity contained by the hollow parallel-sided walls, t_E, is 3mm thick, as shown in **Figure 12(a)**, the volume of the cylindrical plate formed by the oil is simply

$$V_0 = \frac{\pi d^2 t_E}{4} \text{cm3} = \pi \times 4.2^2 \times 0.3 / 4 = 4.156 \text{ cm}^3.$$

In order to induce a change in power of +1.00D, the volume of the plate must be increased by, *V*,

$$= \frac{\pi d^4}{6400(n-1)} \text{ cm}^3 = \frac{\pi \times 4.2^4}{6400(0.586)} = 0.261 \text{ cm}^3$$

when its total volume becomes $V + V_0$

$= 4.156 + 0.261 = 4.417 \text{ cm}^3$

The power of the lens, *F*, can then be expressed as

$$F = \frac{6400(n-1)}{d^4} (V - V_0).$$

It can be seen from this expression that the power increases linearly with the volume of the lens.

The graph in **Figure 14** shows a plot of the necessary change in volume against the power of the lens. In real terms, the amount of fluid which has to be injected to increase the power of the lens by +1.00D, or to remove from the lens to obtain a change of -1.00D, is just a little over 0.25 cm³.

Bennett records that the first known deformable lens produced by inducing a change in the power of a lens by changing

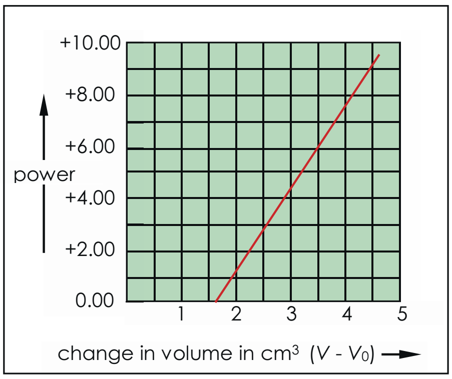

Figure 14: Graph to show the relationship between the power and the volume of a lens

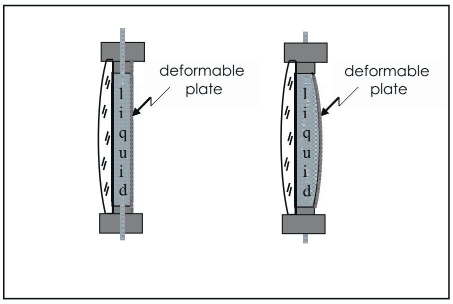

Figure 15: Dr Cusco's deformable lens

its volume, was thought to have been used as an objective for a long-focus telescope, made in 1747 by a Dresden instrument maker named Grummert. A patent was granted to the French ophthalmologist Dr Cusco[5] for the use of such a lens in a binocular optometer, used to study accommodation. The detail of one of his lenses is shown in **Figure 15** where it can be seen that one surface of the lens is rigid, only the right-hand surface being deformed when liquid is pumped into the system. The power of the variable focus lenses could be controlled to 0.01D by an elaborate hydraulic system. The chief problem in designing a deformable lens is that of ensuring that the hydraulic system forms a liquid-tight cavity.

A suggestion made by Dr B.M. Wright was to employ a triple-layer construction the three components being laminated together to form the lens. The front component is a glass (or plastics lens) made to the distance prescription, with any astigmatic correction on the convex surface of this component. The central layer is a

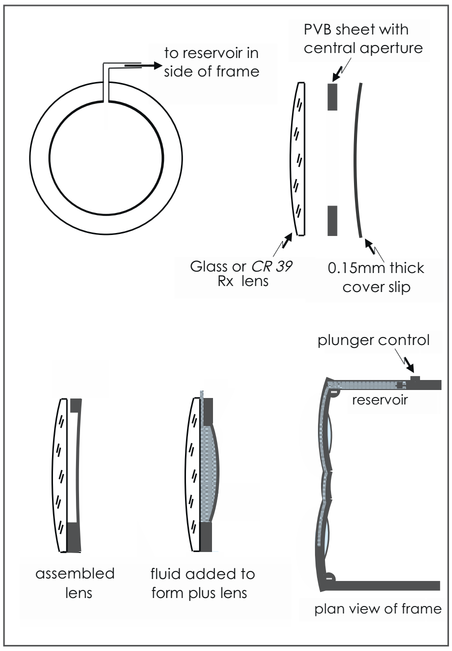

Figure 16: Dr Wright's deformable lens

circular sheet of polyvinyl butyral, 0.37mm thick, with a central circular hole some 25mm in diameter to serve as the liquid chamber. The rear component is a cover slip of glass, 0.15mm thick, capable of flexing to the extent required under pressure (**Figure 16**).

A duct 0.75mm in diameter was drilled downwards through the upper edge of the lens, opening into the liquid chamber via a short horizontally drilled hole. The fluid supply is kept in a reservoir in one of the sides and supplied to each lens cavity via a duct in each frame rim, linked via the bridge of the frame. Sliding a plunger on the reservoir side of the frame forces more fluid to enter the cavities, causing the cover slip to flex into a convex cross-section. Sliding the plunger on the side of the frame in the opposite direction withdraws fluid from the lenses the cover slip resuming its unstressed form and the lens power to reduce.

The search for a method of providing a fluid-tight seal which could withstand the pressure from the liquid passing through such narrow ducts was unsuccessful and the design was eventually abandoned.

The second part of this article, to be published later in the year, will deal with recent versions of fluid-filled lenses which have solved the problems of providing fluid-tight sealed units and electro-active lenses.

REFERENCES

1. More historical information is given in Bennett AG (1972) Variable and progressive power lenses. Manufacturing Optics International, IPC Science & Technology Press, Guildford.
2. Brit. Patent 1515. Dixon H (1785) Telescopes, microscopes spectacles etc.
3. US Patent 3305294. Alvarez LW (1967) Two-element variable-power spherical lens.
4. Lohmann A (1970) A new class of varifocal lenses. *Applied Optics* 9: 1669–71.
5. Fr. Patent 129293. Dr Cusco (1879) Système de lentille à foyer variable sans déplacement.

PROFESSOR MO JALIE is Visiting Professor in Optometry at the Ulster University and to the educational facility in Paris, Essilor Academy Europe. He also works as a consultant to the ophthalmic industry. He was the Head of Department of Applied Optics at City & Islington College from 1986 to 1995 where he taught optics, ophthalmic lenses and dispensing from 1964. He has written several books and educational CDs, holds four patents and runs a web-based course in Spectacle Lens Design, which is reviewed each year, leading to FBDO(Hons) SLD.