Spectacles: Past, Present, and Future

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Spectacles probably have a longer history than any other optical device, apart from magnifiers, and their development has continued throughout the era of The Optical Society (OSA). A fascinating aspect of this history is that spectacle lens design and technology involve not only optical solutions to the visual needs of the wearer but also considerations of comfort, fashion, and appearance. In particular, the diameter of lens required to fit any frame may put serious constraints on the optical characteristics of the lens.

The optics of the human eye should form an image of the outside world on the light-sensitive retina. Since objects of interest may lie anywhere between distant and relatively close distances of the order of arm's length or less, either the depth of focus of the eye must be very large or, more realistically in view of the eye's relatively large maximal numerical aperture, ~0.25, an active focusing mechanism is required. Focusing is achieved by active changes in the shape of the elastic crystalline lens, a process known as accommodation. With accommodation relaxed, the eye ought to be focused for distance, when it is called emmetropic.

Unfortunately, our evolutionary development has left us with two problems. First, the ocular dioptics may not form a sharply focused image of distant objects, so that the eye suffers from ametropia. If the optics are too powerful, the image lies in front of the retina, and the eye is myopic ("short-sighted"); if too weak, the image lies behind the retina and the eye is hyperopic (often erroneously called "long-sighted"). Evidently the myopic eye can focus clearly on near objects and the hyperopic eye may be able to increase its power by accommodation to focus both distant and some near objects. The second problem is that while accommodation was adequate to the needs of our short-lived ancestors, most of us are now living too long for accommodation to remain effective in the later part of life. The objective amplitude of accommodation (i.e., the maximum change in ocular power) for each of us declines steadily from the early teenage years to reach zero at about 50, when the individual becomes fully presbyopic. Thus, older uncorrected emmetropes and hyperopes inevitably have poor near vision, although myopes have less difficulty. Almost all older individuals need some form of optical assistance if they are to see both distant and near objects clearly, the only exceptions being a few happy anisometropic individuals, having one near-emmetropic eye and one mildly myopic eye.

By 1916, at the time when the OSA was founded, basic spectacle lens design was reasonably well understood. A variety of types of bifocals were available, including the fused form, where the bifocal near segment was made of flint glass and the distance carrier was made of crown so that the "add" effect could be obtained with a lens having no surface discontinuities. Prisms had been introduced by Von Graefe and Donders to help those with convergence problems. Tints of various colors and transmittances were available (indeed, as early as Christmas Eve 1666, the great diarist Samuel Pepys was writing "I did buy me a pair of green spectacles, to see whether they will help my eyes or no"). After seven centuries of development, could spectacle lenses be improved further?

Spectacle lens design and the materials used have, in fact, advanced to a surprising degree during the "OSA century." The earliest relevant paper in the OSA's brave new flagship publication, *Journal of The Optical Society of America*, appeared in the first volume under the title "The reflected images in spectacle lenses" [1]. These reflections may interfere with the wearer's vision but are generally considered to be most important from the cosmetic point of view. Since for normal incidence the reflectance at the surface of a lens of refractive index n is $(n-1)^2/(n+1)^2$, the problem increases as the lens index is raised. Single-layer and multi-layer coatings have, in recent decades, provided a solution, but questions remain on the optimal coating characteristics, since under conditions of spectacle use fingerprints and other dirt may, on the lens, be more obvious on the coated lens, and regular cleaning is required. It is, incidentally, of interest that as late as 1938 Tillyer, in a discussion on optical glasses given at an OSA symposium on optical materials, still thought it worth commenting "more light gets through the lens when it is tarnished slightly"—an earlier, less controlled form of lens coating!

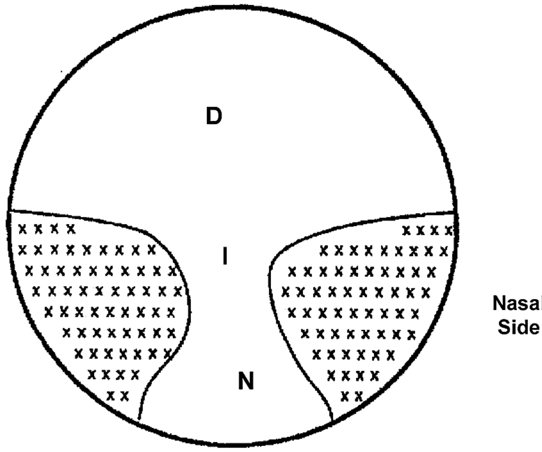
The question of lens index is also, of course, of great importance in relation to lens thickness and the consequent appearance of the spectacles when worn. Surface power is given by $(n-1)/r$, where r is the surface radius. Thus, for any required corrective power, the difference between the two surface curvatures of a meniscus spectacle lens will be reduced if its index is increased. This means that a positive lens can have smaller central thickness and a negative lens will have reduced edge thickness for any given lens diameter. This is of particularly cosmetic value for high myopes wanting a frame that demands a large lens diameter. Depending upon the material density, the weight of the thinner lens may also be reduced. Thus, over recent decades there have been continuing and successful attempts to produce materials of higher refractive index, in both glass and plastic. Whereas traditional crown and flint glasses had indices of 1.52 and 1.62, respectively, materials are now available with indices up to 1.9.

Refractive index and density are, however, not the only consideration with lens materials. Dispersive characteristics are also important, since when directing the visual axis away from the lens center the wearer is effectively looking through a prism, resulting in transverse chromatic aberration and color fringing around objects. Thus, as well as having high index and low density, the ideal lens material should have as high a constringence (Abbe number, V-Value) as possible. Currently glasses of refractive index 1.8 have a constringence of about 35.

A major advance in materials was the appearance of plastic lenses. Although polyethyl methacrylate (PMMA, Plexiglass, Perspex) had been introduced before the second world war, it was relatively soft and easily scratched. The breakthrough came with a wartime development, CR39, a polymerizable, thermosetting plastic with a refractive index (1.498) similar to that of crown glass and a V-value of 58. Importantly, it had better scratch resistance than PMMA, a high impact resistance, and half the density of crown glass. The first ophthalmic lenses in the material were produced by Armorlite in 1947. Lenses can be either surfaced or molded. Demands for still higher impact resistance led to the introduction of polycarbonate lenses in the late 1950s, first for safety eyeware and later, as optical quality improved, for all powers of ophthalmic lens. Polycarbonate is a thermoplastic, and lenses can again be made by either molding or surfacing techniques. Its index (1.586) is a little higher than crown glass but its V-value (30) is lower: since the scratch resistance is not high, the surface is usually protected by a hard coating, such as thermally cured polysiloxane. The specific gravity and UV transmittance are low. Other higher index plastics are now available. Various hard and anti-reflection coatings can be applied to all these plastic lenses, whose many attractive features have given them a dominant position in the spectacle market. Ultimately gradient-index media may find a role in spectacle lens design [2].

From the design point of view, the advent of computers has allowed the impact of aspherization on the performance of single-vision lenses to be explored in considerable detail [3]. Such work has revealed that aspherization widens the range of lens forms that yield zero oblique astigmatism as compared to those lying on the Tscherning ellipse. Modern ray-tracing techniques have also greatly benefited the design of progressive addition (varifocal) lenses. These are lenses for presbyopes in which the discrete power zones of traditional bifocals and trifocals are replaced by a smooth variation in power across the lens surface, from that appropriate for distance vision to that for near, with good vision for intermediate distances between the distance and near zones and an absence of visible dividing lines on the lens surface. First proposed by Aves in 1907, with his "elephant's trunk" design, the first successful lenses of this type were the French Varilux designed by Maitenaz (Essilor) and, in the U.S., the Omnifocal (Univis). Since then numerous variations have been produced. Optically, the challenge is that the shorter the progressive corridor between stable distance and near corrections, the narrower the corridor and the greater the unwanted astigmatism in neighboring lens areas (Fig. 1). Since the visual axes converge during near vision, separate right and left eye lenses are required. Moreover the "ideal" lens depends on such factors as the extent to which the individual patient moves the eyes or the head when changing fixation. Thus, the concept of "customized" lenses has been introduced, where details of the design depend upon the characteristics of the individual wearer and the frame used. The manufacture of such lenses is only possible through the recent availability of digital surfacing or "freeform" technology. An obvious downside is that the advantages of customization may be destroyed if the lenses are in the incorrect position as a result of frame movement or distortion.

While neutral and color-tinted lenses have been available for many centuries, with progressive refinement in bulk, coated, or laminated forms, one striking innovation in the OSA era was the introduction, by Corning in the mid-1960s, of photochromic lenses. These actively change their transmittance in response to the ambient light level, obviating additional prescription sunglasses. The original glass-based photochromics relied on silver halide, in which electron exchange under the influence of high levels of short-wavelength light yielded opaque colloidal metallic silver. The resultant loss in transmittance was reversed when the light levels lowered, with transition times of the order of a few minutes. Subsequent advances have resulted in more stable lenses with shorter transition times and photochromic plastics using organic dyes.



▲ **Fig. 1.** Zones of a progressive addition lens (PAL). The distance D and near N zones are connected by a progressive intermediate zone (I). Areas of poor vision because of unwanted surface astigmatism are shown by shading. (Reproduced with permission of [4]. Copyright 1993, The Optical Society.)

One specialized area of spectacle use is for low-vision patients, who require magnification for either distance or near tasks. Ellerbrock [5] gave a valuable account of the aids available at that time, and the OSA later honored an outstanding practitioner in the field, Louise Sloan, by the award of its Tillyer Medal in 1971 [6] (Fig. 2). The question of whether wearers of bioptic spectacles, with their limitations on field of view, should be allowed to drive remains controversial. "Press-on" plastic Fresnel lenses and prisms have found application in patients with binocular vision problems such as squint.

▲ **Fig. 2.** Louise Sloan receiving the Tillyer Medal in 1971.

What does the future hold? One challenge is the search for a full-aperture lens of variable power for the correction of presbyopia, so that the accommodational ability of the young eye can be mimicked. While multi-lens "zoom" spectacles exist, their appearance makes them unacceptable to all except a minority of presbyopes. Variable-power lenses with a fluid reservoir enclosed by a flexible membrane, so that the surface curvature can be varied by pumping liquid in or out, have a long history but have so far found only a limited market. Alvarez lenses, consisting of two closely spaced component lenses with surfaces following a cubic equation that are translated laterally with respect to each other, have found some application recently. Like membrane lenses they are difficult to incorporate into standard frames. Possibly more promising are electrically switched devices, such as liquid-crystal refractive or diffractive lenses, but the latter suffer from the problem of large amounts of transverse chromatic aberration. The search continues.

Finally, there is continuing interest in the interaction of spectacles with the growth of the eye and the development of refractive error. In recent decades the prevalence of myopia has increased, particularly in many Asian countries, presumably associated with lifestyle changes for those involving near work or outdoor activity. Can a child's wearing of suitable spectacles eliminate, or at least reduce, these myopic changes? Animal experiments suggest that the axial length of the growing eye is affected by lens wear and that peripheral as well as axial imagery are of importance. Thus current studies are exploring the possible beneficial effects of bifocal or other lenses to relieve accommodation demand and lenses that modify the pattern of peripheral refraction.

Many spectacle challenges remain for future members of the OSA!

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