

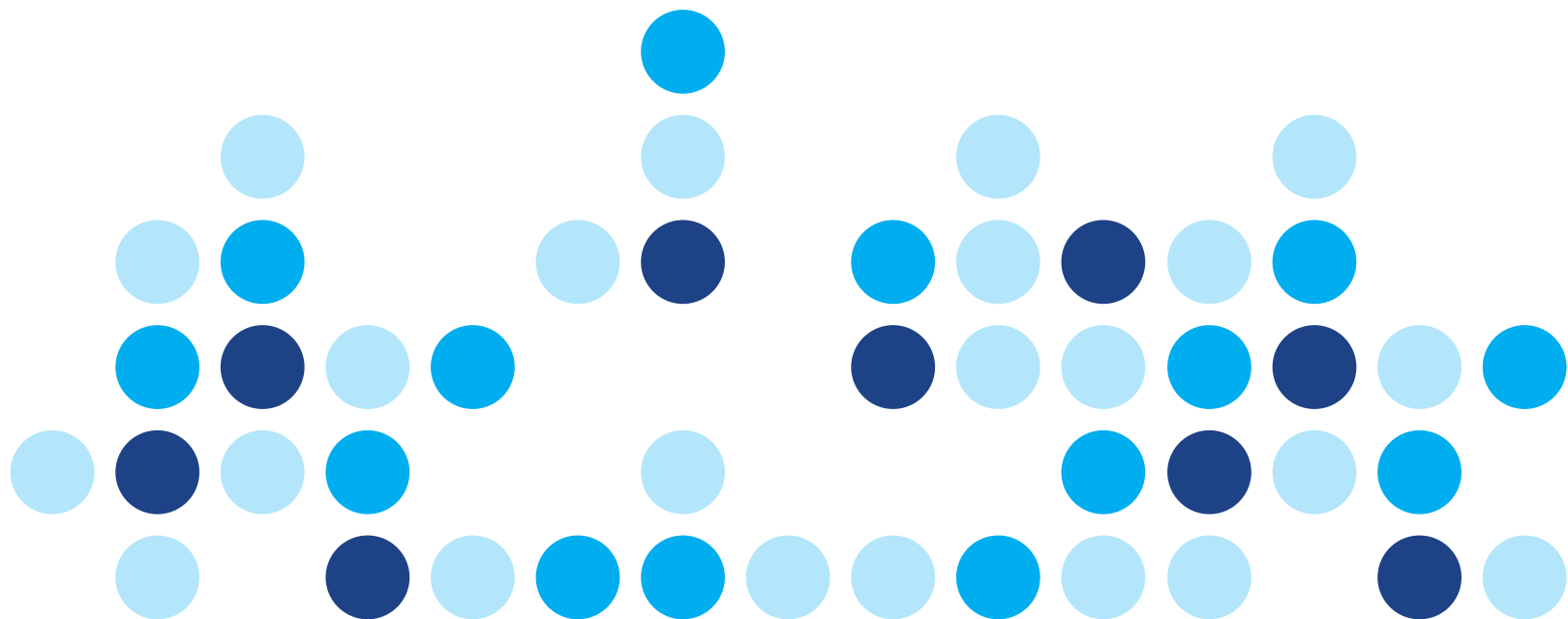
Refractive and Diffractive Principles in Presbyopia-Correcting IOLs — An Optical Lesson

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Key Take-aways:

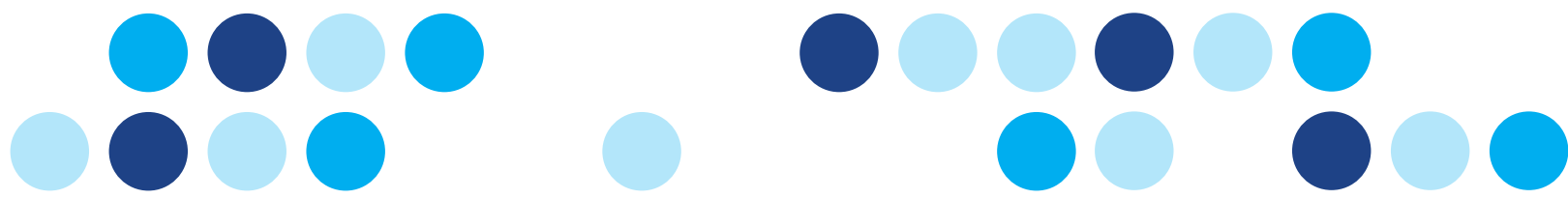
- Multifocality in IOLs is achieved through refractive or diffractive optical approaches.
- Diffractive multifocal IOLs intentionally induce diffraction so that the waves exiting the lens will have constructive interference at two or more distinct foci at different distances.
- Zonal refractive multifocal IOLs shape the waves exiting the lens from different annular regions shape that they converge to two or more foci.
- The main distinction between the different optical approaches to achieve multifocality is that the out-of-focus light in the diffractive multifocal tends to be spread out uniformly over a larger area and is thereby less noticeable. The out-of-focus light in zonal refractive multifocal lenses is concentrated into rings around the objects and cannot be easily suppressed. Consequently, diffractive multifocal IOLs have replaced zonal refractive multifocal lenses as the treatment for presbyopia.
- Trifocal IOLs are an emerging technology that offer intermediate vision in addition to distance and near. Trifocal IOLs can use traditional diffractive optics or a unique diffractive optical approach.

Introduction

The human eye is a dynamic system, enabling good vision under a wide range of conditions. The eyes have sophisticated mechanisms to adapt to various lighting conditions and to adjust power to focus on objects at different distances. In the young eye, accommodation can focus from distant objects to objects as near as 4 cm. However, the aging process causes the magnitude of accommodation to progressively decrease. By the age of 50, most people are fully presbyopic, meaning they have minimal ability to accommodate.¹

Aside from the aging process, accommodation is also lost when traditional intraocular lenses (IOLs) are implanted after cataract surgery. Traditional IOLs have a fixed power and remain in a stable position within the eye following implantation. In most cases, this effect is moot since the typical patient receiving IOLs have already become presbyopic due to their age. However, younger recipients, perhaps from congenital or traumatic cataracts, are made presbyopic with traditional IOLs. Regardless of the conditions, IOL implantation guarantees presbyopia and the need for additional correction to perform near and intermediate vision tasks such as reading or computer work.

To help alleviate pseudophakic presbyopia, the ideal situation would be to implant an IOL that had the capability to change its power as the young crystalline does. Such accommodating IOLs are being aggressively pursued, but this technology is still evolving. Multifocal IOLs, on the other hand, have found widespread clinical success at addressing the impact of presbyopia. Multifocal optics have two or more distinct powers within their aperture. While being able to provide benefits for near vision, multifocal optics may also induce some visual artifacts. The technology represents a tradeoff between an improved range of vision and visual artifacts such as reduced contrast, halos and glare. An overview of the evolution of multifocal optics utilized in IOLs is provided here along with a description of the techniques used to help minimize the visual artifacts associated with these lenses.



Multifocal IOLs

Multifocal IOLs incorporate multiple powers within the same lens, enabling different focal points at different distances. IOLs with optical designs that create 2 distinct focal points are clinically described as multifocal IOLs, and this paper will use that terminology instead of bifocal IOLs.

Multifocal IOLs take advantage of the principle of simultaneous vision, where both in-focus and out-of-focus images are simultaneously presented to the retina. The role of the visual-neural system is to filter out or ignore the blurred component and enhance the sharp component providing acceptable vision for the distinct distances. Figure 1 illustrates the effect of simultaneous vision on the retinal image quality from a monofocal and multifocal IOL. The power of a monofocal IOL is typically chosen to provide crisp distance vision as it only contains one power. Figure 1 shows high contrast, sharp imagery for the monofocal distance vision, but the words become blurred and unreadable for near vision. Alternatively, a multifocal IOL can have 2 powers where a) the distance power creates a sharp image of distant objects, but a blurred image of near objects and b) the near power creates a sharp image of near objects and a blurred version of distant objects. In the figure, the multifocal IOL distance image demonstrates slightly reduced contrast and small halos around each of the letters in comparison to the monofocal IOL distance image, however the text is still resolvable. The multifocal IOL also demonstrates a significantly better near image quality compared to the monofocal IOL where the near image is unresolvable. The goal of multifocal IOL designers is to minimize contrast loss and halos for the various object distances, while providing improved range of vision.

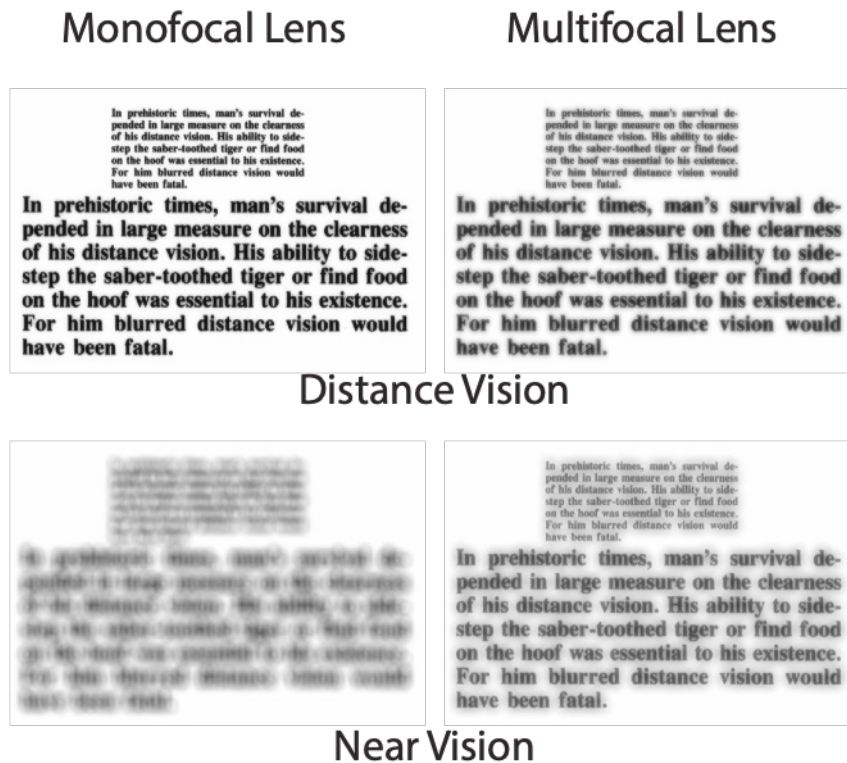
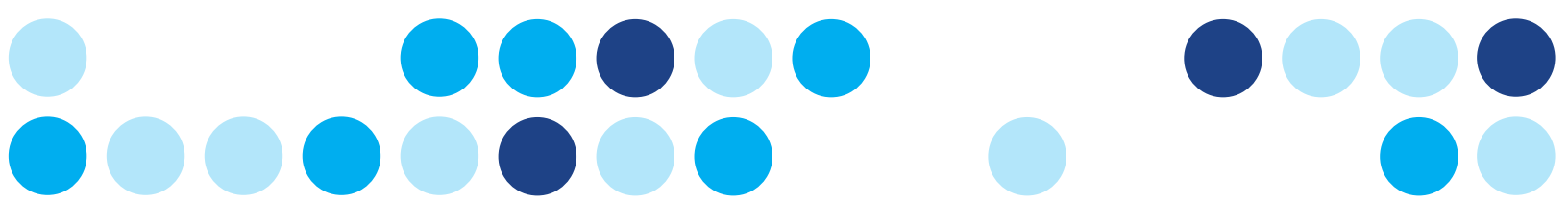


Figure 1. Simultaneous vision. Examples of a simulated view of a text equal to a VA of 20/20 (small font) and 20/40 (larger font) at distance (6 m or 20 feet) and near (33 cm or 13 in). The Multifocal lens allows for distance and near vision while the single vision lens only provides clear vision at distance.



Historically, multifocal IOLs have been predominantly bifocal, meaning they provide 2 distinct focal points. This can be achieved through a variety of optical principals, but two broad categories of multifocal IOLs can be defined: refractive multifocal and diffractive multifocal IOLs. There are also hybrid diffractive-refractive lenses in which typically the center of the lens has a diffractive structure and the periphery of the lens is purely refractive. For the purposes of this description, hybrid lenses are classified as diffractive lenses and the refractive portion is simply a design feature that helps to mitigate the visual artifacts.

Early multifocal IOLs employed refractive principles to create multiple powers. Refractive principles rely on Snell's law to refract or bend rays of light to the desired focal range. These early lenses are known as zonal refractive lenses which had distinct regions or annular zones that refracted light into different foci.²⁻⁵ Figure 2A illustrates a zonal refractive type lens. The central circular region has a power corresponding to distance vision. The surrounding annular regions alternate between near and distance powers to achieve the multifocal effect. When properly designed, both near and distance regions are present for various pupil sizes. As a result of these large zones, the bending of the light rays is determined strictly by refraction. Figure 2B illustrates an alternative form of a refractive multifocal lens where the upper portion of the of the lens is designed for distance vision and the lower portion contains a higher-power sector that provides near vision. The two regions are connected by a rapid but smooth transition denoted by the horizontal lines in the figure.

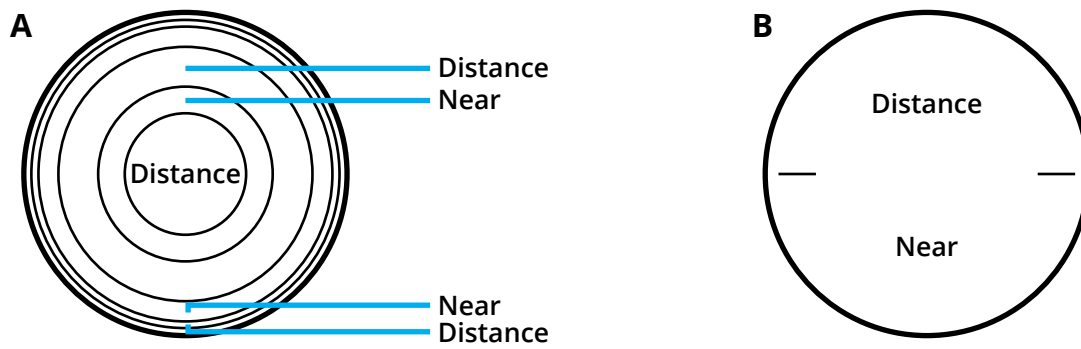


Figure 2. Examples of refractive multifocal optic design. (A) Alternating zones of varying refractive power (zonal refractive lens). (B) Radial sectors that provide near and distance (sector refractive lens).

Figure 3A shows the profile of a zonal refractive lens and the wavefront passing through the lens. The wavefront is continuous, but locally curved so that different portions of the wavefront converge to one of the two focal spots. Figure 3B shows the profile of a sector multifocal lens. The wavefront from the upper portion of the lens converge to the distance focus, while the wavefront from the lower portion converges to the near focus.

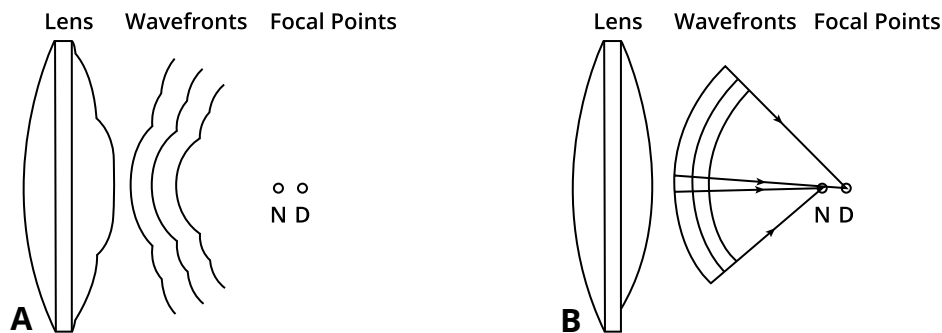


Figure 3. A continuous, but locally curved wavefront passing through (A) a zonal refractive lens and (B) a radial sector refractive lens with waves converging to two focal points (N - near, D - distance).

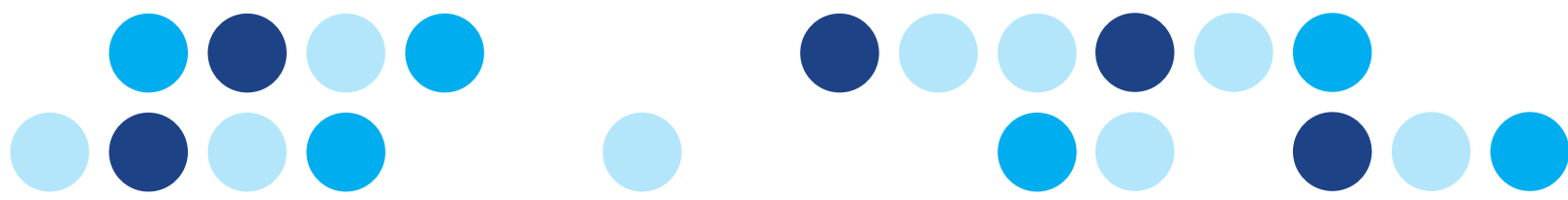


Figure 4 illustrates the simultaneous vision aspects of these lenses. In Figure 4A, the distance power portions of the zonal refractive lens create a sharp image of distant objects on the retina. The near power regions create a blurred image of the trees and this blur tends to be concentrated into rings around the sharp image. For near objects, the situation is reversed. In Figure 4B, for distant objects the upper portion of the sector lens focuses to the retina, while the lower portion of the lens focuses early and then is blurred by the time it reaches the retina. For near objects, the roles of the upper and lower portions of the lens are reversed. Zonal refractive IOLs are rarely used mainly due to the haloes created by the concentrated rings associated with the out-of-focus components of the lenses, and have been replaced by diffractive multifocal IOLs as the dominant paradigm for mitigating presbyopia for the past 10 years in the United States.⁶ Sector-type lenses are available internationally.

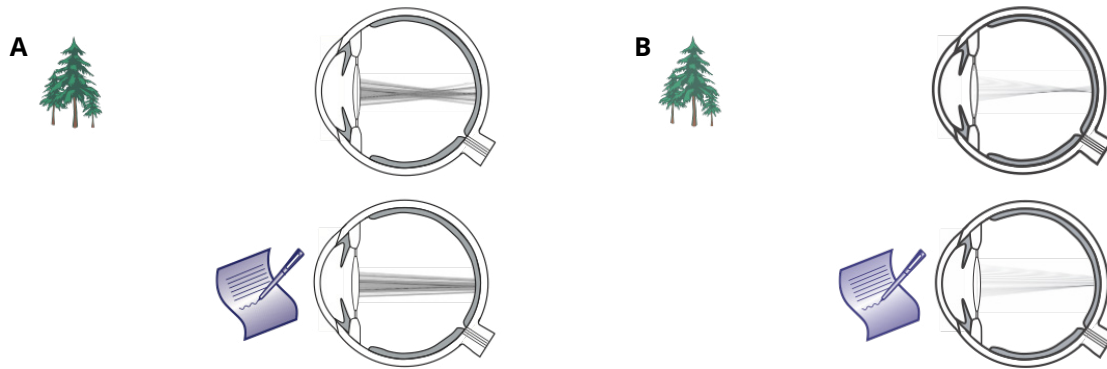


Figure 4. Refractive Multifocal IOL light distribution. (A) Alternating zones of varying refractive power. (B) Radial sectors to provide near and distance.

These diffractive multifocal IOLs use diffraction and interference to create their multifocality.⁷⁻¹⁰ Diffractive multifocal lenses are often misunderstood because they move away from the more easily described geometrical picture of light rays bending at the surface of the lens. Instead, these lenses take advantage of the wave nature of light. Waves, in general, have the ability to interfere with one another. Consider two waves moving towards each other, as shown in Figure 5. Each wave is made up of peaks and troughs. When the waves overlap, if their peaks line up, then the waves combine to have peaks that are twice as high. This process is called constructive interference. Similarly, if the peaks of one wave line up with the troughs of another wave, then the combined wave is neutralized, resulting in a wave with zero height. This process is called destructive interference. These effects are similarly used for sound waves in noise-cancelling headphones. The headphone “listen” to the ambient noise and create a sound wave that destructively interferes with the noise, effectively canceling it out.

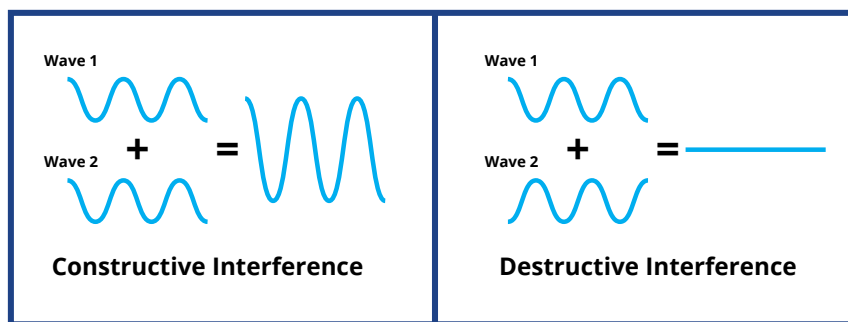
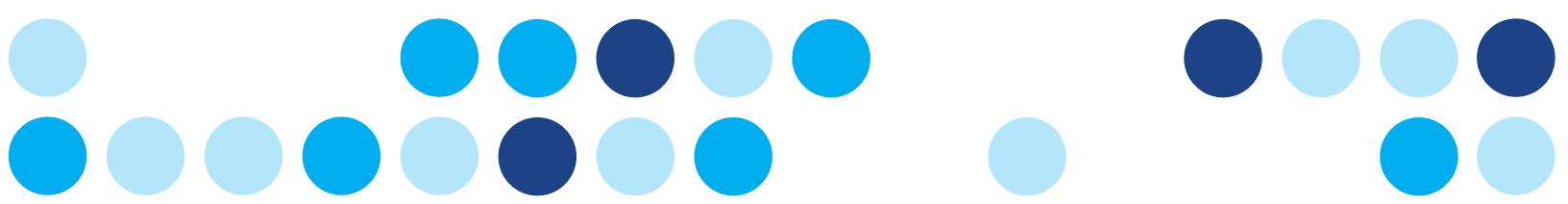


Figure 5. Constructive interference is additive, resulting in a higher amplitude of the combined wave. In constructive interference, two waves need to meet and their troughs line up together. Destructive interference is subtractive, resulting in a lower amplitude of the combined wave. In destructive interference, two waves meet and the trough of one wave lines up with the trough of the other wave. A combination of constructive and destructive interference may also occur.



Waves can also undergo diffraction when they interact with boundaries and sharp edges. Figure 6 illustrates diffraction effects. From a geometrical optics point of view, light passing through a single slit would just propagate unaffected through the region of the opening. However, diffraction is caused by the interaction of the light with the boundary of the slit and this causes the light to bend around the edges and travel off into a different direction. Putting light through two small slits causes the light to be bent further and now the waves emanating from the slits can overlap and undergo constructive and destructive interference.

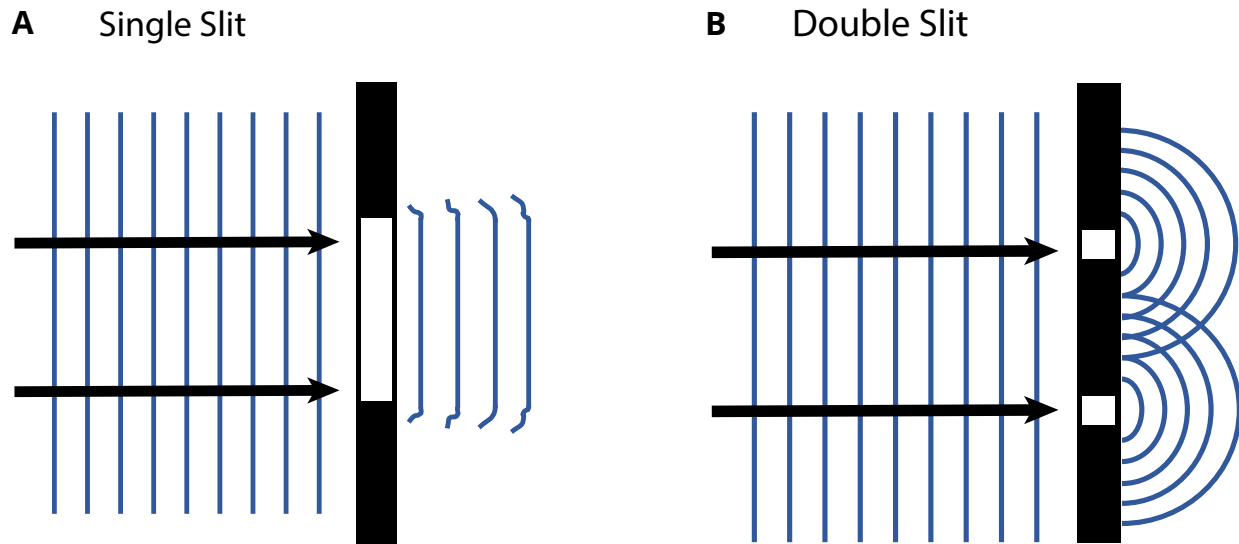
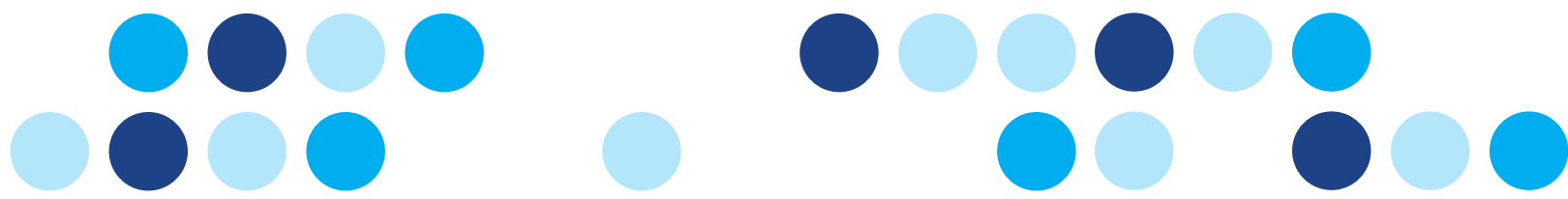


Figure 6. Diffraction. A) Light passing through a single wide slit propagates unaffected through the region of the opening. B) Light passing through two small slits bends and waves emanating from the slits can overlap and undergo constructive and destructive interference.

In diffractive multifocal IOLs, a structure is placed on the lens surface where the shape of the structure is chosen to intentionally induce diffraction so that the waves exiting the lens will have constructive interference at two distinct foci. A typical diffractive multifocal lens consists of concentric annular zones created on the surface of the lens. The surface areas of the zones are equal, which means the separation between or width of each zone gets progressive smaller towards the edge of the lens. At the junction of each zone, an abrupt step appears (Figure 7B). The area of each zone dictates the add power of the lens and the height of the step determines the relative amount of energy that goes into each focus. The dimensions and step heights of the diffractive zones are chosen so that as the waves passing through the lens propagate to the retina, the waves from the various diffractive zones mix and there are two distinct regions of constructive interference that correspond to the two main foci of the multifocal lens. A basic diffractive multifocal targets having equal energy in the distance and near portions. In such a lens, the step heights are chosen such that roughly 40.5% of the incident light goes to the add portion, 40.5% of the incident light contributes to the distance portion and the remaining light goes into other diffractive foci. Alternative step heights can be used to shift more energy to either the distance or near focus. Furthermore, apodization, which is discussed in more detail below, can be used to further tailor the energy distribution between the two foci. Figure 8 illustrates the profile of a diffractive multifocal lens. The discrete steps in the lens introduces discontinuities in the wavefront emerging from the lens. As this disjointed wavefront propagates to the retina, the various pieces begin to overlap, leading to constructive interference in the neighborhood of the two foci.



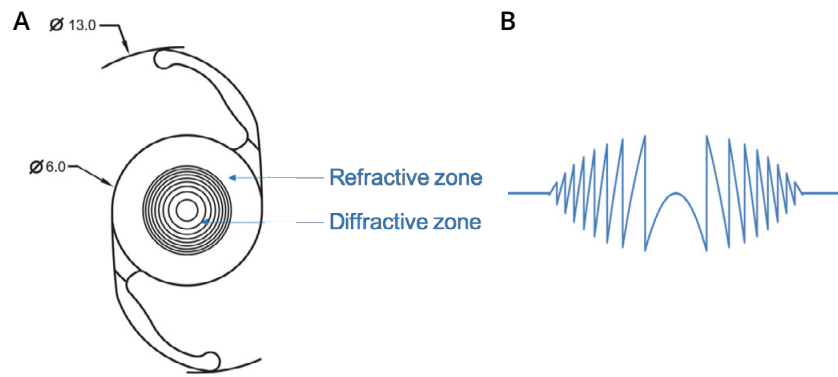


Figure 7. (A) Example of a hybrid diffractive-refractive lens. (B) Cross-sectional view of a sample diffractive structure.

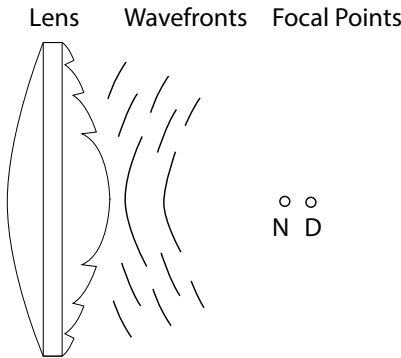


Figure 8. The discrete steps of a diffractive lens create discontinuities in the wavefront emerging from the lens. Various pieces of the disjointed overlap, leading to constructive interference in the neighborhood of the two foci. (N - near, D - distance).

An alternative means for understanding the effects of a diffractive multifocal lens is through an understanding of a diffraction grating. Diffraction gratings are routinely used in optics to split light into multiple beams. Gratings are created by etching an array of linear grooves into a glass surface. The most basic grating is a square wave grating shown in Figure 9. The square wave causes light to split into multiple beams or sequentially numbered "diffraction orders." The 0th order beam passes straight through the grating. The +1st order beam travels at an angle θ_1 and the -1st order beam travels at an angle $-\theta_1$. Higher order beams make larger and larger angles. In general, the angles of the diffracted beams are dependent upon the spacing between the squares of the square wave pattern. A smaller spacing leads to a larger angle. A disadvantage of the square wave grating is that the energy is distributed to many diffraction orders and often only two orders are desirable.

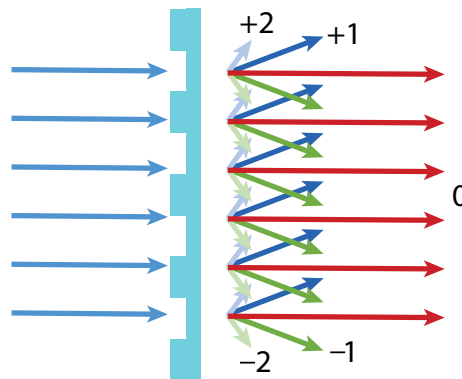
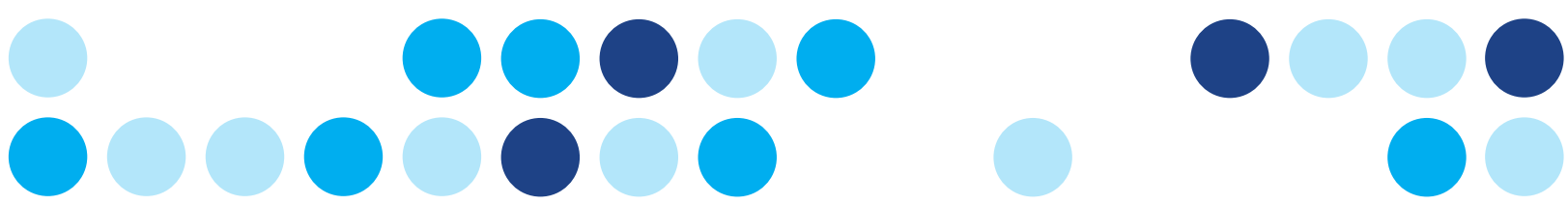


Figure 9. Square wave grating with multiple diffraction orders.



A blazed grating is often used to concentrate most of the light into two diffraction orders. A blazed grating is created by replacing the square wave pattern with a triangular pattern. This shape causes most of the energy to go into the 0th and +1st diffraction orders as shown in Figure 10A. The height of the steps in the triangle pattern determines the relative amount of energy in the 0th and +1st diffraction orders. The height of the step is chosen to equally split the amount of energy in the 2 diffraction orders. A chirped grating makes the spacing between the patterns get closer together. As mentioned previously, the smaller the spacing between the patterns, the larger the angle of the diffracted beam as shown in Figure 10B.

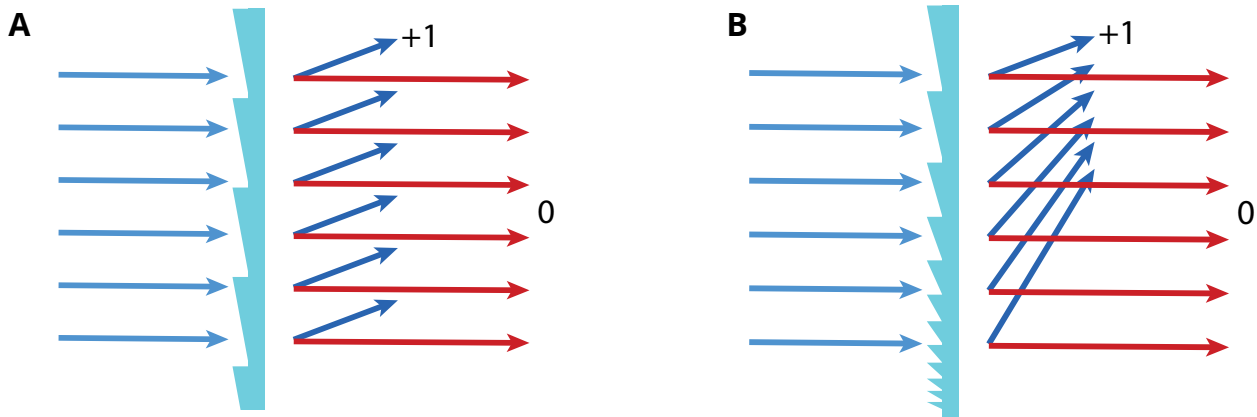


Figure 10. A) Blazed grating with a triangular pattern. B) Chirped grating with a progressively smaller triangular pattern.

A diffractive multifocal lens is the two-dimensional rotationally symmetric analogue to the linear gratings. Figure 11 shows a diffractive multifocal IOL, where the diffractive pattern has the triangular shape as described above, so the incoming light is predominantly split into two diffraction orders. The spacing between the diffractive zones becomes progressively closer together towards the edge of the lens, so the diffracted light bends at an increased angle. Finally, the diffractive structure is superimposed onto a refractive base lens which causes the two beams to focus to two distinct points. The 0th order in this case corresponds to the distance focus and the +1st order corresponds to the near focus.

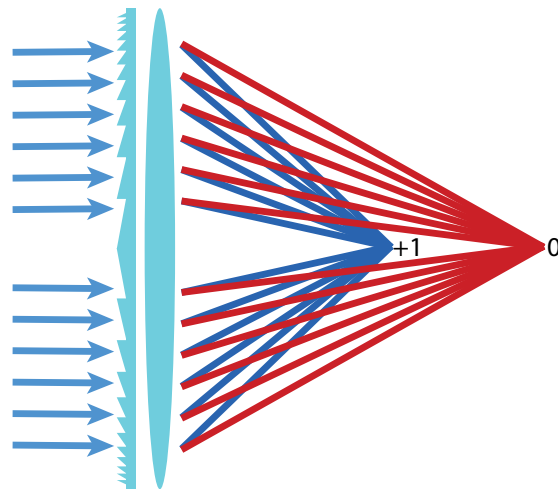
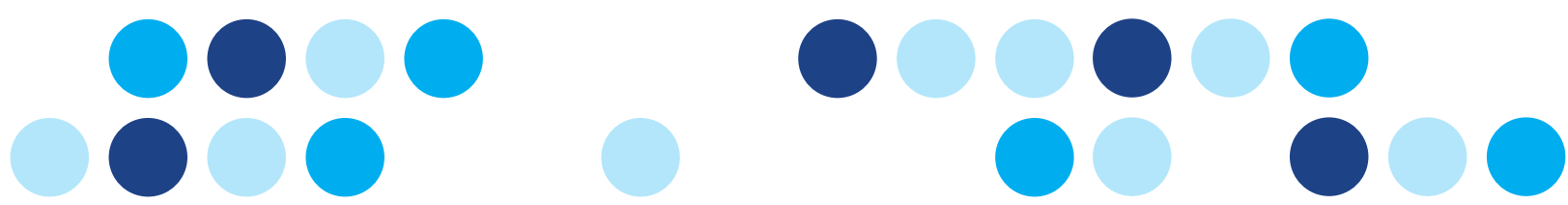


Figure 11. The diffractive structure, superimposed onto a refractive base lens, focuses the light in two distinct points: the 0th order corresponding to the distance and the +1st order corresponding to the near.



As with refractive multifocal lenses, diffractive multifocal IOLs rely on simultaneous vision. Figures 12 and 13 show the effects of different object distances for diffractive multifocal optics. The main difference between simultaneous vision with diffractive multifocal lenses when compared to their refractive predecessors is that the out-of-focus light in the diffractive multifocal tends to be spread out uniformly over a larger area, whereas for the refractive multifocal lenses, the out-of-focus light is concentrated into rings around the objects. The broader spread of the blurred diffractive IOL component makes it far less noticeable and easier for the visual system to suppress.¹⁰ Consequently, diffractive multifocal IOLs have replaced zonal refractive multifocal lenses as the choice for presbyopia mitigation.

Viewing distant objects in bright light - Two images simultaneously projected on the retina

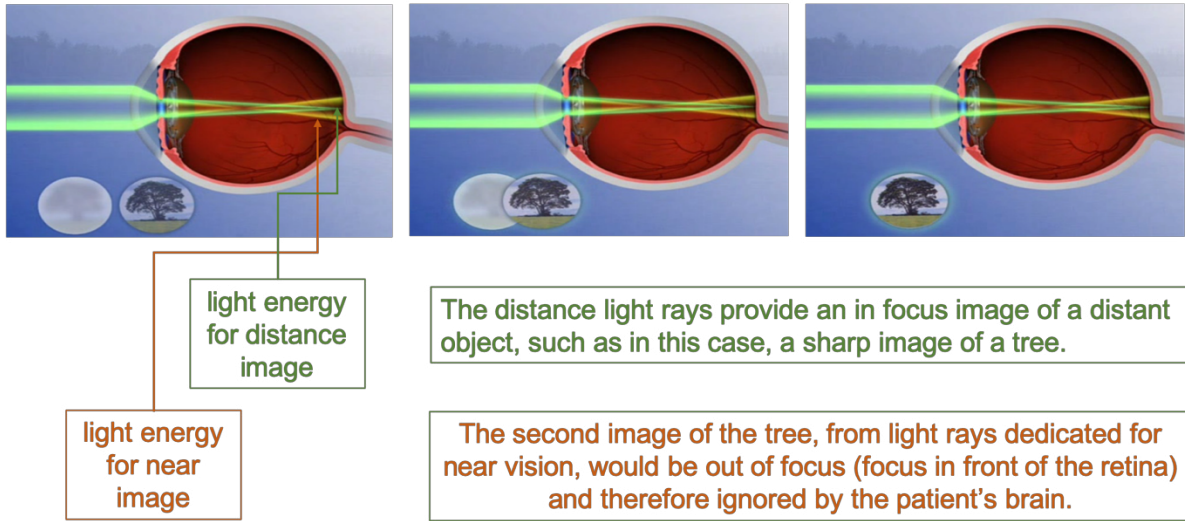


Figure 12. Diffractive Multifocal IOL and distant object in a bright lighting condition.

Viewing close up objects in bright light – Two images are simultaneously projected on the retina

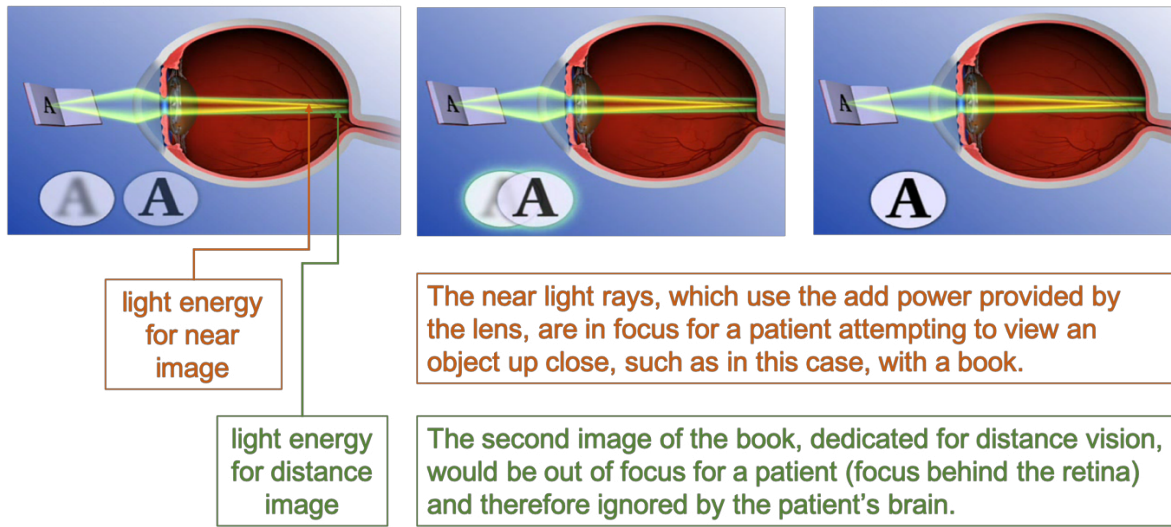
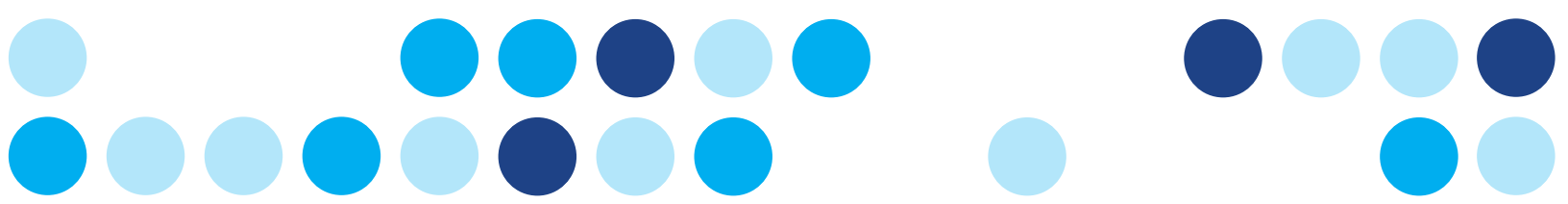


Figure 13. Diffractive Multifocal IOL and close up object in a bright light condition.



Apodization refers to an optical change in the diffractive zone and assists in light energy distribution, especially for larger pupil sizes. Apodized diffractive IOLs modify the step height so that the steps gradually reduce to zero towards the periphery of the lens (Figure 7). The lower step height shifts energy from the near foci to the distance foci. The energy becomes more biased towards distance for larger pupil sizes. The apodization follows the dynamics of the eye, where under bright conditions the pupil size is small and both distance and near vision are needed. Under darkened conditions, the pupil size expands and distance vision is more important. People do not need to read in the dark. Figure 14 shows an example of an apodized diffractive lens.

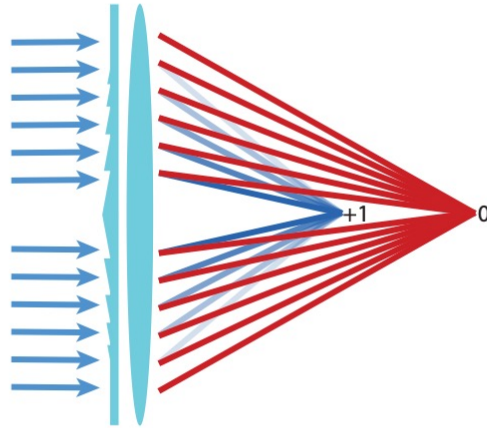


Figure 14. Apodized diffractive lens to progressively direct light energy to distance with larger pupils.

Trifocal IOLs

Trifocal IOLs are an emerging technology to provide an intermediate focal point in addition to near and distance foci. Trifocal technology still relies on the diffractive multifocal effect, but now adds one more variation to the step heights. In this case, the heights of the steps are varied in an alternating fashion from diffraction zone to diffraction zone. The simplest example of a trifocal diffractive IOL alternates between high and low steps as shown in Figure 15. This pattern has the effect of creating three diffraction orders, the 0th, +1st and +2nd, corresponding to distance, intermediate and near foci. More complicated alternating patterns can be used to tailor the amount of energy in each of the foci, as well as the location of the intermediate foci.

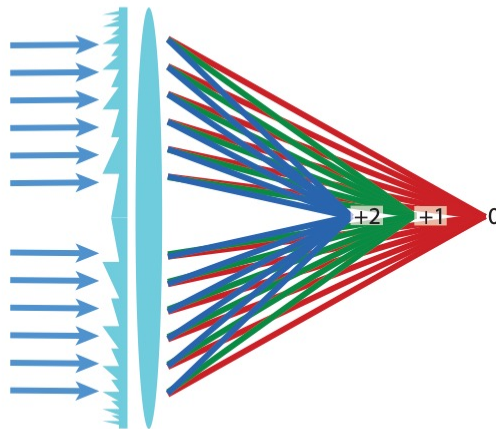
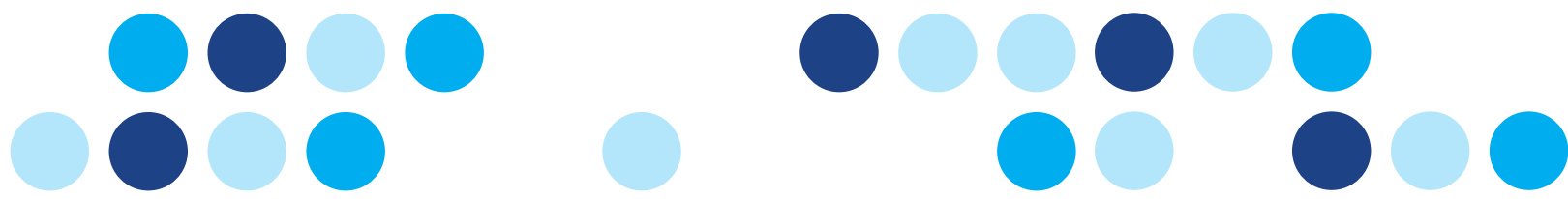


Figure 15. The diffractive structure with alternating step heights creates a trifocal effect. When superimposed onto a refractive base lens, the light focuses to three distinct points: the 0th order corresponding to the distance and the +1st order corresponding to the intermediate and the +2nd corresponding to near.

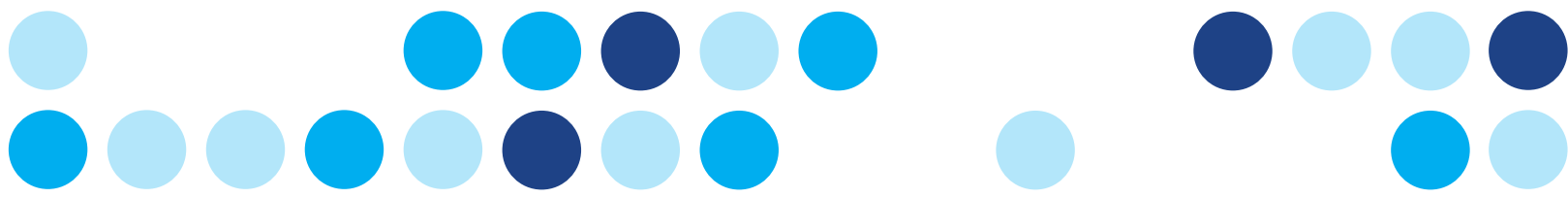


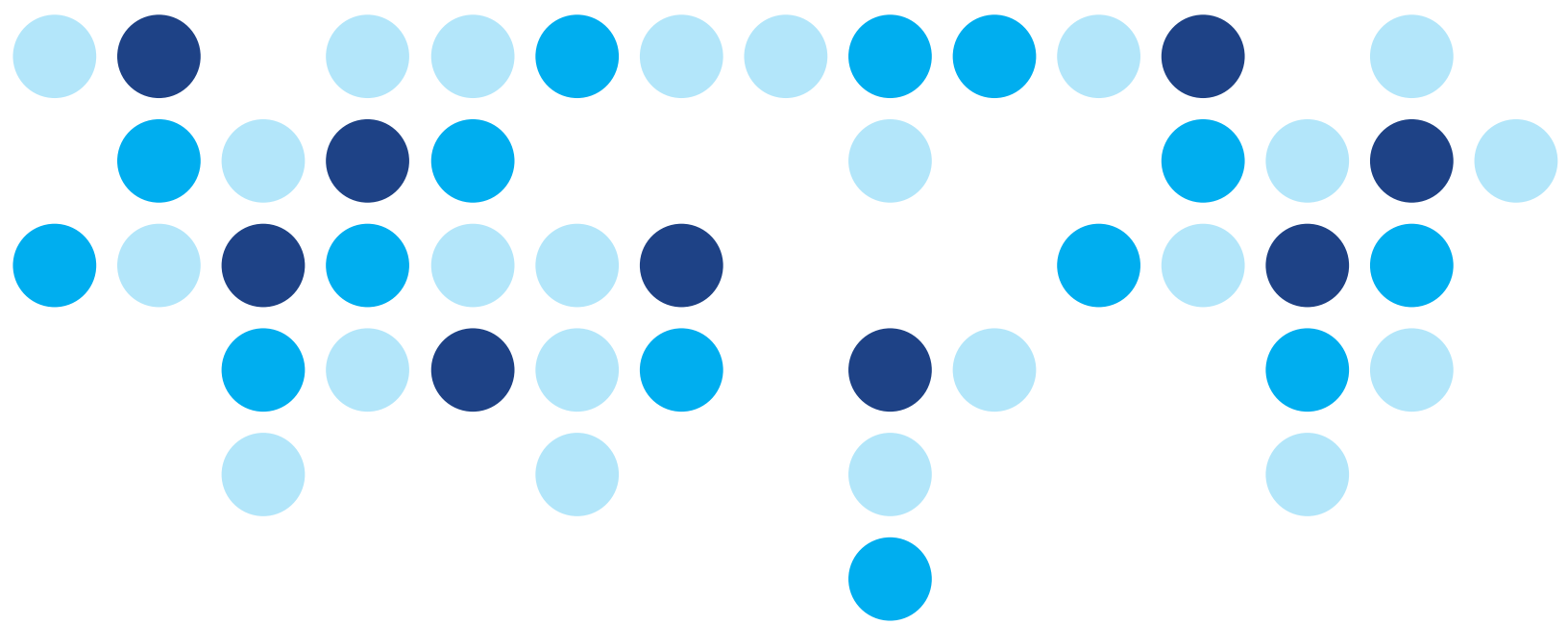
Summary

Multifocal IOLs are used to treat presbyopia following cataract surgery. These lenses contain two or more powers within the lens, which leads to multiple distances that can be in focus on the retina. Multifocal optics rely on simultaneous vision to achieve their beneficial effect of increasing the range of vision, but can also reduce contrast and introduce visual artifacts such as haloes. Refractive multifocal lenses tended to suffer from strong halo artifacts. Diffractive multifocal lenses have largely supplanted the refractive-base technologies since they reduce unwanted artifacts. Techniques such as apodization further reduce the unwanted artifacts for diffractive multifocals. Diffractive multifocal IOLs have been a highly successful means for mitigating presbyopia and novel designs continue to evolve to provide excellent vision at multiple distances.

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