Optical Principles

Kerstin Petermann and Lisa Hinzelmann

Light is an electromagnetic radiation. It can be perceived by the human eye in the range of 380–780 nm. It has properties of both particles and waves and it's dual character becomes easier to understand when looking at the human eye. Light is refracted at the cornea and lens where it acts as a wave. When reaching the retina however, it acts as a particle, a photon, which activates the photoreceptor layer and leads to a biochemical reaction that ultimately results in light perception.

Radiation Optics or Geometrical Optics (GO)

The description of imaging, i.e. the projection of an object point to an image point by means of an optical system, is done in Geometrical Optics (GO) via a simplified notion of light rays, which in turn are the normals of the wave fronts. These are unaffected by diffraction, and propagate in homogeneous media with the same refractive index termed n. The refractive index n is defined as the speed of light in vacuum divided by the speed of light in the medium. For the representation of the imaging ratios, a theoretically, infinitely small space around the optical axis is assumed. In this paraxial Gaussian space, the actually thick lens is simplified to a thin lens with infinitely large radius. The optical axis of imaging systems runs in the GO always as a straight line through the center of curvature. In the eye, this assumption no longer applies, since the center of curvature of the cornea and the

K. Petermann (✉) · L. Hinzelmann
Department of Ophthalmology, Goethe-University, Frankfurt, Germany
e-mail: kerstin.petermann@kgu.de

L. Hinzelmann
e-mail: lisa.hinzelmann@kgu.de

M. Shajari et al. (eds.), *Cataract and Lens Surgery*,
https://doi.org/10.1007/978-3-031-05394-8_5

front and back surfaces of the lens are not located on a straight line. Therefore, only an approximate determination of the optical axis and the application of the optical laws can be made.

Refraction

When light passes between media of different densities, there is a change of direction, which is known as refraction. Refraction always occurs towards the incidence slot of the optically denser medium (Snell's law of refraction).

In order to distribute the incident light to different focal points, a refractive optical system, such as the intraocular lens, either consists of zones with different refractive indices or a surface with different radii of curvature that merge smoothly into one another. In the ocular system, the incident light is projected onto the retina as an image point by changing the refractive power of the natural lens.

Refractive Power D

The refractive power D is defined as the reciprocal of the focal length f and is expressed in diopter [D, dpt], which corresponds to m^{-1}.

$$D = \frac{1}{f}$$

At optically interfaces in paraxial space, the refractive power is calculated from the ratio of the refractive indices (n) of medium 1 in front of the interface (n_1) and medium 2 behind the interface (n_2) as well as the angle of incidence of the light, which in the case of lenses results from the given radius of curvature (r).

$$D = \frac{n_2 - n_1}{r}$$

The refractive index depends on the speed of light as it varies in different media. For the cornea, a refractive index of $n = 1.3672$ is most frequently used but as the cornea is a human tissue there is no standardized n. It is important to acknowledge this fact when working with different devices as they might use different values for n. An adjustment is therefore necessary when using keratometry values of different devices.

Aberration

Aberrations (lat. aberratio meaning deviation) occur outside of paraxial space and depend on the wavelength of light. They prevent a complete unification of rays radiating from the object point into the conjugate image point and impair a true-to-scale, true-color image. A distinction must be made between chromatic aberrations, which are caused by the wavelength dependence of the refractive index, and monochromatic aberrations, in which only one wavelength is considered.

Chromatic aberration occurs because, in most media, short-wavelength light is slowed down more than long-wavelength light, meaning that long-wavelength (red; 640–780 nm) light is refracted less than short-wavelength (blue; 430–490 nm) light. As a result, light is separated and becomes visible in its spectral colors.

Monochromatic aberrations are again divided into lower-order aberrations (spherical and astigmatism) and higher-order aberrations (for example coma, spherical aberration, secondary astigmatism). Lower-order aberrations can be corrected by spectacle lenses which higher-order aberrations cannot.

For refractive procedures and lens surgery, spherical aberration, coma, and astigmatism of oblique bundles are particularly important, as they can significantly influence the image quality (Fig. 1).

One of the most influential higher-order aberrations on image quality is *spherical aberration* (SA). As the height of incidence of a parallel incident light beam increases, the angle of incidence changes. Rays far from the axis are refracted more strongly (positive SA) or more weakly (negative SA) than rays close to the axis, resulting in a circle of confusion instead of a sharp image point. The larger the

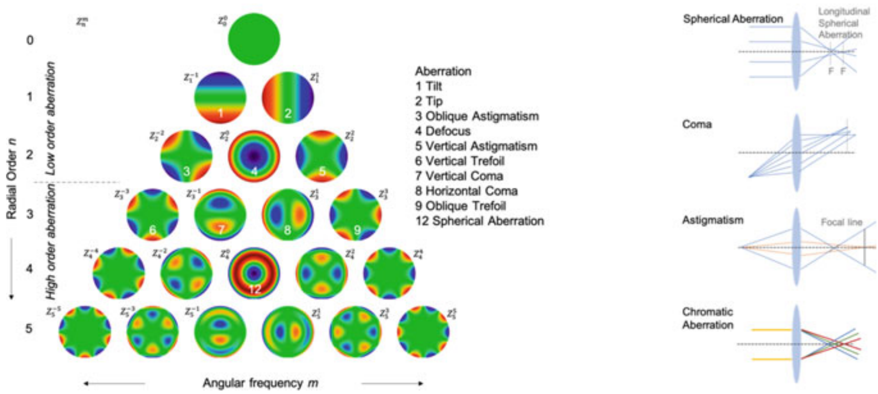

Fig. 1 Representation of the imaging errors: schematically on the right and as Zernike polynomials up to 5th order on the left. The values are given as Z_n^m, where m is the meridional frequency (number of oscillations when orbiting the center) and n is the radial (Zernike) order. With increasing order, the influence on the quality of vision decreases

aperture of the incident beam, the greater the effect of spherical aberration. Aspherical lenses can counteract this as they provide a different radius peripherally than centrally. They can also be used simultaneously to focus an extended depth of field. Their effectiveness here is highly dependent on pupil size and centration of the intraocular implant in the capsular bag.

Coma is perhaps the second most important of the higher order aberrations. It arises at object points that do not lie on the optical axis as an image-side ray bundle with a comet-tail-like, asymmetrical appearance. It is the asymmetric portion of the image superimposed with spherical aberration. Coma is especially seen in eyes with keratoconus, corneal scars after keratoplasty, radial keratotomy or decentered excimer ablation. In astigmatism of oblique bundles, the object point is also located outside of the optical axis and is imaged in two perpendicular image areas, for example due to tilted optics or oblique incident light.

Wave Optics

Light is described in wave optics by a transverse wave with wavelength, amplitude and phase. Since light is an electromagnetic wave, the model of geometrical optics cannot explain all effects. A wave arises when a locally occurring oscillation continues via the coupling of neighboring boundary elements.

Diffraction and Interference

When a wave is deflected by an obstacle, diffraction occurs and new waves are created. The wave can also spread behind the obstacle. According to the Huygens–Fresnel principle, every point of the wave front is a starting point for a new elementary wave. If the oscillations of several waves overlap at a single point, interferences occur. Interference between different elementary waves results in intensity distribution of diffraction, as the amplitudes are enhanced or cancelled. Interference distributions of light can be used to create multifocal optics. In this process, concentric rings with different step heights and distances from each other act on as phase gratings on the intraocular lenses for diffraction of the incident light rays. The light is focused to different focal points for distance, intermediate, and near, with some of the light lost as scattered light. Diffractive systems act independently of the aperture and as a results are not pupil-dependent.

Zernike Polynomials

The description of a wavefront and its aberrations is often done by using Zernike polynomials (Fig. 1). This is a set of polynomials defined on a unit circle. Each polynomial describes the characteristic shape of the error component, and together they represent the total wavefront error. Using polar coordinates, the polynomials result as the product of the angular function and radial polynomials. An infinite number of Zernike polynomials can be used to describe higher order aberration. For the eye, however, only the first twenty (thus up to the 5th order) are really clinically relevant. Aberrations of the 1st and 2nd order are correctable with spectacle lenses and as mentioned previously are often called aberrations of lower order. Accordingly, all aberrations of the 3rd order and higher, such as coma, spherical aberration and trefoil, are considered higher order aberrations.

Lens Design

A greater understanding of these optical principles have resulted in Intraocular lenses (IOL) becoming available in different optical designs. They differ in the number of focal points and the surface progression. The breakdown of lens options can be described as follows: spherical, aspheric and toric mono- and multifocal lenses. Multifocal lenses can be additionally differentiated into rotationally symmetrical refractive or diffractive lenses.

Intraocular lenses are implanted as part of cataract surgery or refractive lens exchange in the capsular bag and replace the natural lens or as a phakic lens in addition to the natural lens. They refract the incident light in one or more focal points.

Monofocal intraocular lenses correct the spherical equivalent (lower order aberrations) and refract the incident light so that it is imaged onto a single focal point. The postoperative target refraction can be set to either distance, intermediate, or near. For example, if distance is selected, the patient will require spectacles lenses for the intermediate and near ranges.

Aspheric intraocular lenses are modified and correct the spherical aberration of the eye. By correcting the aberration, better vision is made possible, especially in twilight when the pupil is wider. The wider the pupil the more of the corneal spherical aberrations influence the image so aspheric lenses can mitigate this effect.

Toric intraocular lenses are used to correct astigmatic eyes. These correct the corneal radii, which are strongly curved at different angles to each other, and thus reproduce the incident light in a pixel on the retina. Toric lenses are available as monofocal or multifocal lenses.

Multifocal IOLs are usually rotationally symmetric and use refractive and/or diffractive optics to image objects at different distances on the retina.

Bibliography

1. Bass M, Decusatis C, Enoch JM et al. Handbook of optics, third edition volume I: geometrical and physical optics, polarized light, components and instruments. New York: McGraw-Hill, Inc;2009.
2. Haferkorn H. Optik: Physikalisch-technische Grundlagen und Anwendungen. Hoboken: Wiley;2008.
3. Hecht E. Optics, global edition, 5th ed. Harlow: Pearson Education Limited;2017.
4. Liftin G. Technische Optik in der Praxis, 3. aktualisierte und erweiterte Aufl. Berlin: Springer Berlin Heidelberg;2005.
5. Velzel C. A course in lens design. Dordrecht: Springer;2014.
6. Yanoff M, Duker J. Ophthalmology. 5th ed. Philadelphia: Mosby, Elsevier;2019.