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THEORETICAL PRINCIPLES OF REFRACTIVE & DIFFRACTIVE MULTIFOCAL & EDOF IMPLANTS

In recent years, the range of optical technologies for the correction of presbyopia during cataract surgery has expanded considerably and is therefore more complex. At the same time, a consensus has yet to be reached regarding the terminology used to differentiate between the various categories (e.g. "EDOF"). Implants tend to be identified in terms of their viewing distance or degree of multifocality (bifocal, trifocal and even quadrifocal lens using a suppressed diffractive order) rather than by their technology. However, recognising and understanding the optical principles used in implant design is a key asset in understanding the benefits as well as the risks and limitations associated with various intraocular implants for a given patient.

In this paper, we therefore propose to review the main optical technologies used in intraocular implants alongside potential adjustment variables to alter the optical outcome. We will then focus on phase and contrast concepts. These are extremely useful mathematical tools for comparing the optical performance of the different intraocular implants.

• PRINCIPLES & GEOMETRIC PARAMETERS OF MULTIFOCAL & EDOF OPTICS

>>> Refractive intraocular implants

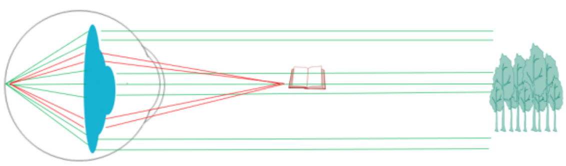

Figure 1 – Example of a refractive multifocal implant

Refractive multifocal and EDOF implants are based on the Snell-Descartes law according to which light is seen as a set of optical rays deviated by implant geometry.

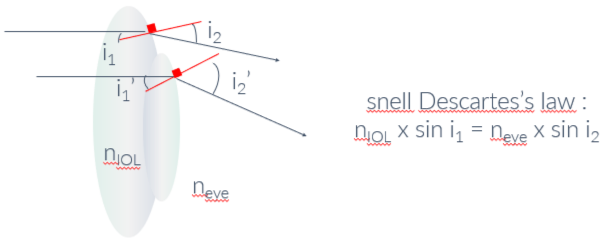

Figure 2 – Snell-Descartes law

Historically, the first refractive multifocal implants were based on an optic comprising several concentric zones with variable powers (Fig. 3 - A) followed by several sector-shaped power zones (Fig. 3 - C) in order to reduce dependency on pupil diameter.
More recently, the majority of extended depth of focus implants are based on a variation in spherical aberration (SA) (Fig. 3 - B) such that the total spherical aberration of the implanted eye (i.e. cornea + implant) is either positive (by adding to the positive SA of +0.27 µm of the patient's cornea), or negative (by over-correcting the patient's positive SA). The outcome will therefore depend primarily on the SA of the patient's cornea, which, in practice, can vary considerably from one case to the next [1].

The results obtained with this type of implant will also be strongly impacted by corneas with a more atypical SA following corneal surgery.

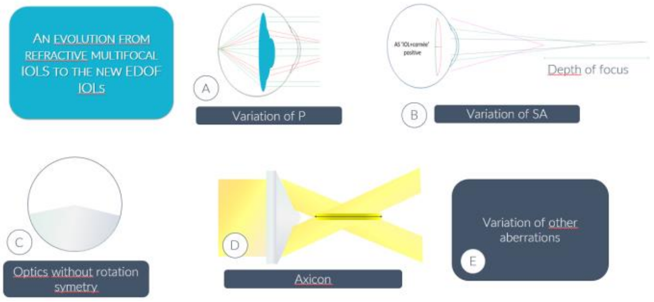

Figure 3 – The main categories of refractive multifocal implants

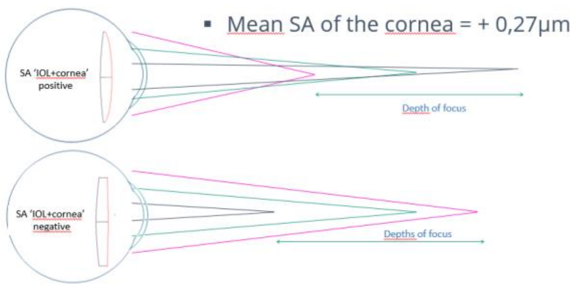

Figure 4 – Positive and negative total "implant+cornea" spherical aberration.

Other technologies such as Axicon (Fig. 3 - D) or other wave—front modifications (by experimenting with higher order spherical aberrations, for instance) can stretch the depth of focus by limiting sensitivity to corneal SA.
As a general rule, refractive multifocal and EDOF implants offer a range of solutions to increase the depth of focus whilst maintaining good distance vision contrast and, overall, milder halos and glare compared to implants based on diffractive technologies. This benefit comes at the cost of more frequently limited near vision addition (no real multifocality) and an sensitivity of results that may be significant in relation to the patient's physiological parameters (corneal SA, pupil dependence).

>>> Diffractive intraocular implants

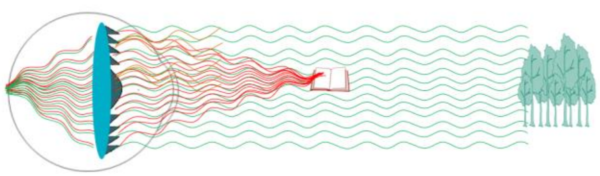

Figure 5 – Example of a diffractive multifocal implant

Diffractive multifocal and EDOF implants are based on the laws of diffraction. Light forms a set of waves that are diffracted in all directions by echelettes/steps/rings. Carefully chosen steps geometry allows sharp images to be selected at the desired focal points.

Ring width is the crucial parameter for near and/or intermediate vision addition: The closer the rings, the greater the addition.
Ring height defines the energy devoted to close vision (near and/or intermediate vision): The higher the rings, the more energy is devoted to near vision (and even less to distance vision). Conventional bifocal implants have a typical profile height of around λ/2. A diffractive, albeit monofocal implant can even be obtained by doubling the typical ring height of a bifocal implant (λ)!

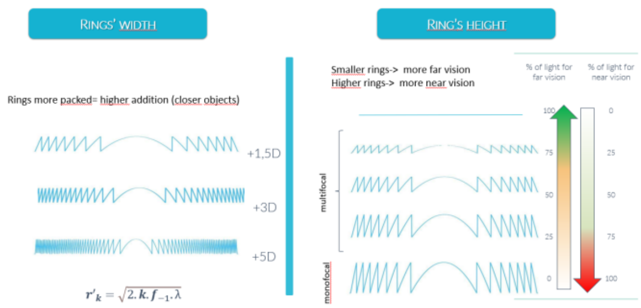

Figure 6 – Impacts of diffractive ring width and height (r'_k = the radius of the k ring, f_{-1} = the near focal length, λ_0 = the design wavelength at 546 nm)

A bifocal echelette implant with **higher order diffraction** is obtained by further increasing ring height to approximately 1.5 λ. It should be noted that this technology is associated with strong dissymmetry in energy distribution between distance and intermediate vision depending on the wavelength. A typical result is a virtually monofocal implant for distance vision in the red (and virtually no intermediate vision) and a virtually monofocal implant for intermediate vision in the blue (with no distance vision).

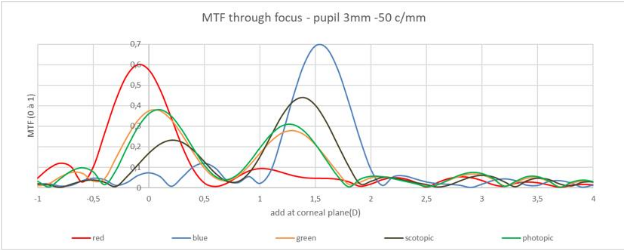

Figure 7 – MTF for the different wavelengths of a diffractive multifocal implant using higher orders

Whilst the benefit of diffractive versus historical refractive implants was pupil independence, this directly resulted in increased halos and glare. To limit this inconvenience, many diffractive implants are now designed with **apodization.** This involves a gradual reduction in diffractive ring height on the implant periphery such that, in night vision, i.e. with dilated pupils, light energy is mainly directed towards distance vision (as opposed to near vision which causes halos).

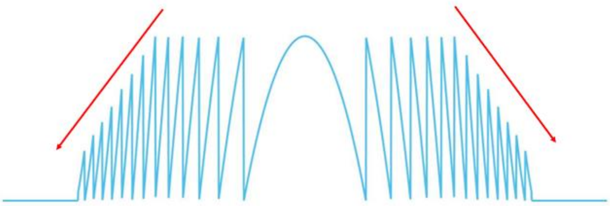

Figure 8 – Principle of apodization

Finally, despite greater visibility, the geometric shape of the steps in the diffractive profile has only a very moderate impact on outcome with diffractive multifocal implants in reality [2].

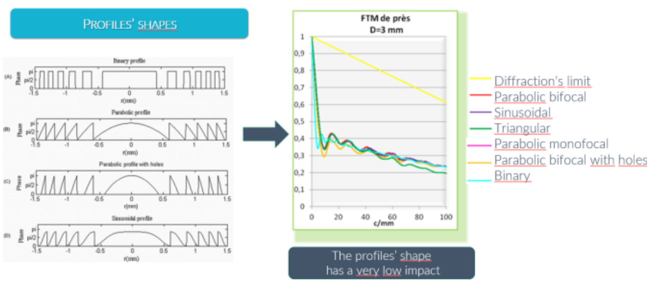

Figure 9 – Frequency MTF in near vision for various diffractive profile geometries

The commercially available diffractive multifocal and EDOF implants often use a combination of the parameters discussed here. This sometimes involves superimposing several diffractive profiles (for trifocal or quadrifocal implants, for example) and/or modulating the diffractive profile with various parameter combinations from one "step" profile to the next.

Overall, diffractive optics are more suitable for obtaining multilayer vision and stronger near vision additions compared to their refractive counterparts. A wide range of solutions is feasible given the various parameters at play in designing diffractive implants. Diffractive implants are less sensitive to the spherical aberration of patients and can be pupil independent (if not apodized).

Conversely, they are generally more prone to halos although the latter can be reduced by working with continuous range of vision multifocals. Furthermore, it is also important to note that refractive technologies can also cause dysphotopsia (glare) in some cases.

Mathematical tools are clearly needed to compare the optical qualities obtained with different implants.

- **THE PHASE AND CONTRAST CONCEPTS FOR MULTIFOCAL & EDOF IMPLANTS**

Modulation Transfer Function (MTF) curves are currently used to compare multifocal and EDOF intraocular implants. These curves highlight the contrast (0% = white letter against white background, 100% = black letter against white background) obtained with an implant depending on viewing distance or implant addition and for a given spatial frequency (i.e. letter size). The higher the curve, the better the contrast (0 to 100%).

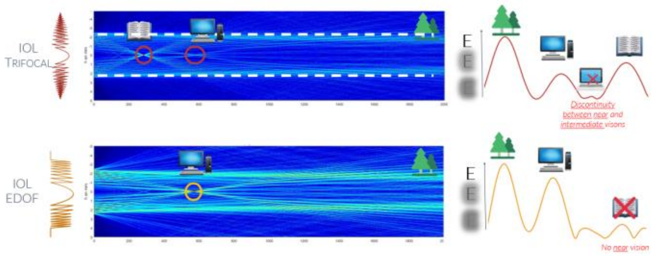

Figure 10 – Optical ray propagation (left) and corresponding MTFs depending on the addition (right) of a diffractive trifocal implant and an EDOF implant.

Two-dimensional MTF curves are generally plotted for a spatial frequency of 50 c/mm. However, it is interesting to note that these curves can be presented in 3-dimensional slices with optotype size as an additional variable. [3] This allows optical implant performance to be compared, e.g. up to 100 c/mm (corresponding to a visual acuity of 10/10).

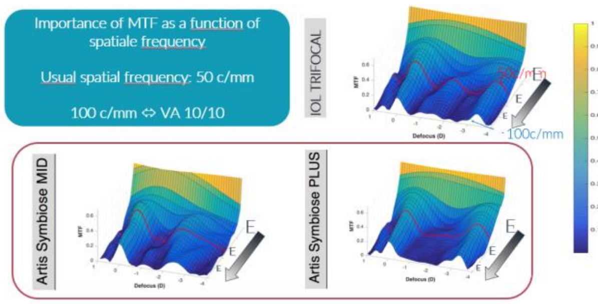

Figure 11 – MTF slices depending on addition and spatial frequency (c/mm) for various diffractive multifocal implants [3]

This MTF concept is therefore very important but still not sufficient. Indeed, as a contrast is always positive by definition (ranging from 0 to 100%), the MTF concept alone is not enough to determine whether the black and white colours of the "E" optotype have been inverted for the patient at a certain distance.

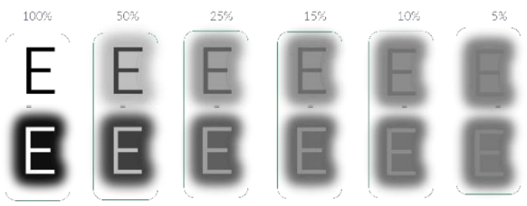

Figure 12 – Optotypes with decreasing contrast (top line) and inverted colours (bottom line)

As shown below in the radial test pattern, this "colour inversion" is the physical phenomenon that occurs when vision becomes blurred. This is phase inversion.

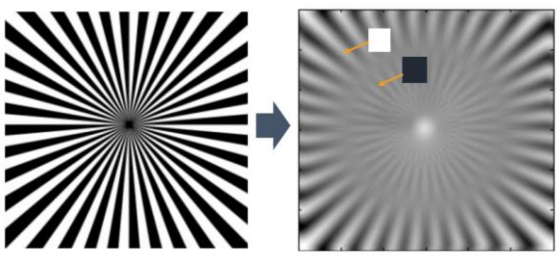

Figure 13 – Image of a perfect radial pattern (left) seen through an implant (right). The image on the right shows successive phase inversions.

Thus, as MTF is used to compare the contrast of the intraocular implants, it is interesting to analyse the phase transfer function (PTF) according to vision distance.

To understand how PTF is obtained, it is necessary to revert to the basics for calculating optical implant quality - see the trifocal example in Figure 14:
To qualify an optic, engineers use PSF (Point Spread Function), which represents the image of a point (e.g. a star) seen through the implant.
The PSF is converted by Fourier Transformation to obtain the Optical Transfer Function (OTF). The OTF contains all of the information pertaining to implant quality and can take both positive and values negative (in yellow).
The MTF (always positive and ranging from 0 to 100%) is obtained from this curve by taking the absolute value (in green). Information is therefore lost, namely the point at which letter "E" undergoes colour inversion. This missing information is found in the PTF, which corresponds mathematically to what is known as the OTF "argument" (in red).

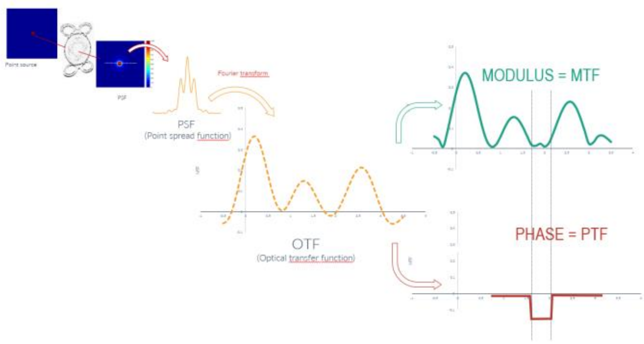

Figure 14 – MTF and PTF calculations as a function of vision distance from a light point seen through a trifocal implant.

Thus when the PTF is constant (therefore continuous), the image remains sharp. Conversely, when resolution is lost, the phase changes. This is known as phase inversion. The image is not sharp at that distance. This is typically what happens with a trifocal implant between near vision at 40 cm and intermediate vision at 80 cm.

The phase concept therefore complements the contrast concept and provides information on the sharpness of the image. It is important to have both adequate contrast (MTF) and a continuous phase (PTF) to ensure comfortable vision over an extended depth of focus.

The following example shows an implant with an asymmetrical contrast of 90 to 40 cm, decreasing gradually but remaining readable because of the continuous phase.

Contrastingly, the trifocal implant example shows typical discontinuity around 60 cm, which can be seen with phase inversion. Texts are therefore more difficult to read.

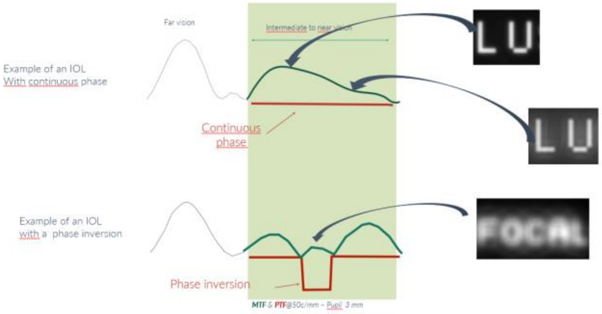

Figure 15 – Examples of MTF and PTF of two diffractive multifocal implants. Top: a diffractive continuous phase implant. Bottom: a trifocal implant.

CONCLUSION

Numerous adjustment variables are used in the design of multifocal and extended depth of focus intraocular implants. Various combinations of these variables allow multiple configurations to be considered. An understanding of the benefits and limitations of the various optical principles is helpful in selecting the appropriate optics for a given patient.

The concepts of MTF and PTF are important tools in analysing and comparing the optical performance of various refractive or diffractive multifocal and EDOF implants. Whilst the concept of MTF (contrast) is more familiar, the phase (PTF) concept, which represents the sharpness of an image, is less well-known. The PTF is important for the design of continuous phase implants to provide comfort of continuous sharp vision in the correction of presbyopia.

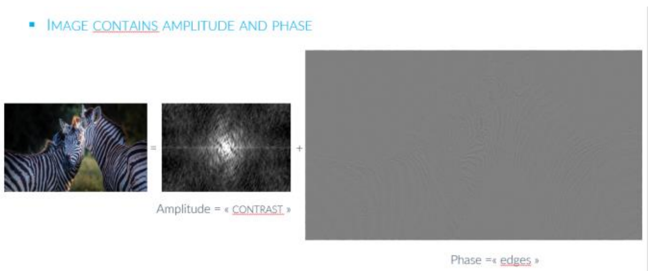

Figure 16 – Illustrations of image amplitude and phase.

References:

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