National university of Pharmacy
Department of Commodity science

Topic: OPHTHALMIC OPTICS. DEVICES and APPARATUS for DIAGNOSIS, CORRECTION and PROTECTION of VISION ORGANS

The objective: to familiarize with devices for diagnosis, correction and protection of vision. To learn how to determine kind, sign and strength of spectacle lenses.

Basic concepts and terms which should be acquired by students during their training and studying

Central vision, peripheric vision, accommodation, refraction, eye, emmetropic eye, myopia, hypermetropia, presbyopy, astigmatism, heterometropia.

Questions for self-training

1. Anomalies of eye refraction and their correction:
    - myopia;
    - hypermetropia;
    - astigmatism;
    - presbyopy (age hyperopia).
2. Devices and apparatus for examination of functions of vision organs.
3. Devices for gauging ophthalmotonus.
4. Classification of spectacle lenses (by manufacturing techniques, by quantity of optical zones, depending on a rated position of optical center, ability to correct vision defects).
5. Technical requirements for spectacle lenses.
6. Package and marking of spectacle lenses.
7. Classification of spectacle frames and requirements for them.
8. Kinds of protective and specialized glasses.
9. Contact lenses, their advantages and disadvantages.
10. Means for contact lenses care and their application.
11. Names and purpose of accessories for glasses and contact lenses.
12. Devices for control of means for vision correction (dioptrimeter, centriscope, keratometer).

Methodical maintenance of the lesson

1. Tests for control of knowledge of students in the lesson topic.
2. Assortment of spectacle lenses (afocal, bifocal, negative, positive, astigmatic, light-protective ones).
3. Spectacle frames.
4. Contact lenses.
5. Containers for contact lenses.
6. Multipurpose solution for contact lenses care.
7. Wetting drops for usage of contact lenses.

8. Skiascopic frames.
9. Desktop perimeter.
10. Ophthalmoscope mirror.
11. Maklakov’s tonometer.
12. A set of trial lenses.
13. The catalogue «Ophthalmologic equipment».
14. The catalogue «Ophthalmology and spectacle optics».
15. The normative documentation:

GOST 23265-78 Lenses spectacle. Specifications.
GOST of 18491-90 Frames of a corrective spectacles.
The general technical requirements and test methods.
GOST 3521-81 Materials optical. A method of bubble determination.
GOST 3521-81 Glass optical. A method for determination of glass hairline.
GOST 24052-80 Optics spectacle. Terms and definitions.
GOST 28956-91 Contact lenses. Terms and definitions.

Task N 1

Study assortment of devices and apparatus for correction of vision defects, using material - methodical maintenance, catalogues (see Annex 12).

Task N 2

In a warehouse of shop "Optics" spectacle lenses were delivered. Determine type, sign and power of spectacle lenses.

Write down results into the table 1 using sample below.

Working technique

To determine type and sign of spectacle lenses it is recommended to use «cross method», and to determine lens power – set of trial spectacle lenses.

1. Determination of lens type. Look on two perpendicular lines of cross image or on cross junction of a window frame through a lens placed before an eye on distance of 10-20 cm. Combine optical center of a lens with crossing point of cross lines, and then slowly turn a lens to the right and to the left in lens plane. If angle of crossing lines does not change, the examined lens is stigmatic. If angle of crossing lines changes («the scissors phenomenon»), the lens is astigmatic.

2. Determination of lens sign. Keeping a lens before cross image, move it slowly to the right, to the left, upwards and downwards: a) if cross image moves in the same direction as the lens, it is negative; b) if cross image moves in the direction opposite to those of the lens, it is positive; в) if cross image does not move, the lens is afocal.

3. Determination of lens power. To determine optical power of a lens put it tightly onto spectacle lense from a trial set of the same kind, but of the opposite sign, consistently increasing their power. Examine the summary optical effect of the investigated lens, combined with each lens taken from a set, on the cross image. Thus, it is possible to find a lens from a set which neutralizes optical action of researched lens.

Write down observations and results into the table using sample below.

Table 1

Results of determination of type, sign and power of spectacle lenses

Stages	Observations (example)
1) determination of lens type	The angle of cross lines does not change
2) determination of lens sign	The image of a cross moves together with a lens
3) determination of lens power	The lens +4,0 from a test set neutralizes optical effect of the tested lens
4) conclusion	Spectacle lens is stigmatic, negative, with optical power –4,0 D.

Task N 3

Into a shop "Optics" spectacle lenses were delivered. Carry out inspection analysis of the goods.

Write down results of the analysis into table 2 using sample below.

Working technique

Determine type and sign of spectacle lenses by “cross method”, and their power using set of trial lenses.

For filling table 2 use the normative documentation (GOST 23265-78 Spectacle lenses).

According to this GOST the symbols for spectacle lenses should contain:

- an inscription «Spectacle Lens»;
- designation of lens type (A – afocal, O – one-focal, B – bifocal T – trifocal; S – stigmatic, A – astigmatic, P – prismatic);
- designation of technological version – K (glued) or C (sintered); monolith lenses are not signed;
- designation of presence of lenticular edge – L (if present);
- value of diameter;
- designation of group (I or II);
- values of main parameters (refraction power, position of axes, etc.);
- designation of RD.

Example of symbol for one-focal (O) stigmatic (S) spectacle lenses of the 1st group 60 mm in diameter, with refraction power +3,0 D:

Spectacle lens OS ø60 I +3,0   GOST 23265-78

The given lens is intended for correction of hypermetropia.

Table 2

Inspection analysis of spectacle lenses

Name of parameter	**Characteristics**
The name of a product	One-focal stigmatic positive spectacle lenses
Symbolic designation	Lens spectacle OS ø60 I +3,0 GOST 23265-78
Purpose	It is intended for correction of hypermetropia
Technical requirements according to RD	– hairlines within the limits of useful diameter of a lens are not allowed; – within central zone of a lens (for group I) 30 mm in diameter there should not be bubbles, points and other foreign inclusions visible with naked eye. Two bubbles, points and other inclusions 0,05-0,2 mm in diameter are allowed if distance between them is more than 5 mm; – deviations (e.g., waves) in surface shape of lenses deforming image of examined object are not allowed; – it should not be more than 2 chips on lenses.
Package	Each lens should be wrapped into paper packing envelope or polyethylene film.
Marking	Onto each packing envelope of lens it should be specified: - trade mark of the enterprise - manufacturer - rating values of diameters - rating values of main parameters - inscription «Spectacle Lens» - designation of type and version of a lens - designation of this standard
Storage conditions	Lenses of high quality should keep their characteristics in temperature interval from –50 up to +50°C and relative humidity of 100 % at temperature 25°C in conditions of transportation
Presence of defects	Defects are absent

The conclusion: one-focal stigmatic spectacle lenses conform to requirements of RD.

Task N 4

Into a shop "Medical technique" ophthalmologic devices were delivered in assortment. Carry out inspection analysis of ophthalmologic devices, using catalogues.

Write down results into table 3 using sample below.

Working technique

For inspection an ophthalmologic Maklakov's tonometer is offered. It is necessary to carry out inspection analysis and to fill in the table.

Completeness of the device is evaluated using catalogues for ophthalmologic equipment.

Table 3

Inspection analysis of ophthalmologic tonometer

Name of the device	Purpose	Completeness
Tonometer ophthalmologic (Russia)	It is intended for gauging an ophthalmotonus by Maklakov's technique	- contact load 10 g (2 it.) - holder for a load (1 it.) - measuring ruler (1 it.) - case (1 it.) - passport (1 it.)

The conclusion: <u>ophthalmologic</u> <u>tonometer</u> <u>conforms to requirements of RD.</u>

Task N 5

Describe purpose and types of goods for contact lens care.

Fill in table 4 using sample below.

Working technique

For example, for analysis multipurpose solution RenuMultiPlus is offered. Multipurpose solution Renu MultiPlus is intended for cleaning of contact lenses, removing of protein sediments without stage of mechanical cleaning. The manufacturer of the given solution is Bausch and Lomb-IOM S.p.A., Italy.

Composition of the given solution includes: sterile isotonic solution containing boric acid, sodium edetate, sodium borate and sodium chloride; and active components: DYMED (polyaminopropyl biguanide), HYDRANATE (hydroxyalkyl-phosphonate), poloxamine.

Type of the goods can be found in catalogues and/or price-lists of manufacturers. Conditions of storage are specified onto package of the given solution.

Table 4

Purpose and type of the goods for contact lens care:

multipurpose RenuMultiPlus solution.
(name of the goods)

Name of parameter	**Characteristics**
Purpose	Keeps lenses clean and removes protein deposits without stage of mechanical cleaning

Continuation of table 4.

Name of parameter	**Characteristics**
Name of the manufacturer	Bausch and Lomb-IOM S.p.A., Italy
Composition	sterile isotonic solution containing boric acid, sodium edetate, sodium borate and sodium chloride; active components: DYMED (polyaminopropyl biguanide), HYDRANATE (hydroxyalkyl-phosphonate), poloxamine.
Types	- Solution universal BL 120 ml, Multiplus - Solution universal BL 355 ml, Multiplus - Solution universal "COMPLETE" by firm "ALLERGAN"- 60 ml - Solution universal "COMPLETE" by firm " ALLERGAN " - 360 ml - Solution universal “ Opti-Free Express ” by firm " Alcon " - 120 ml - Solution universal “ Opti-Free Express ” by firm " Alcon " - 360 ml. - Solution universal MULTISON – 375 ml - Wetting solution «SOLO CARE AQUA» 60 ml - Wetting solution «SOLO CARE AQUA» 360 ml
Conditions of storage	Store at room temperature (15-30°C) far from children. Do not use, if protective ring on a bottle is broken or absent

ANNEX 11

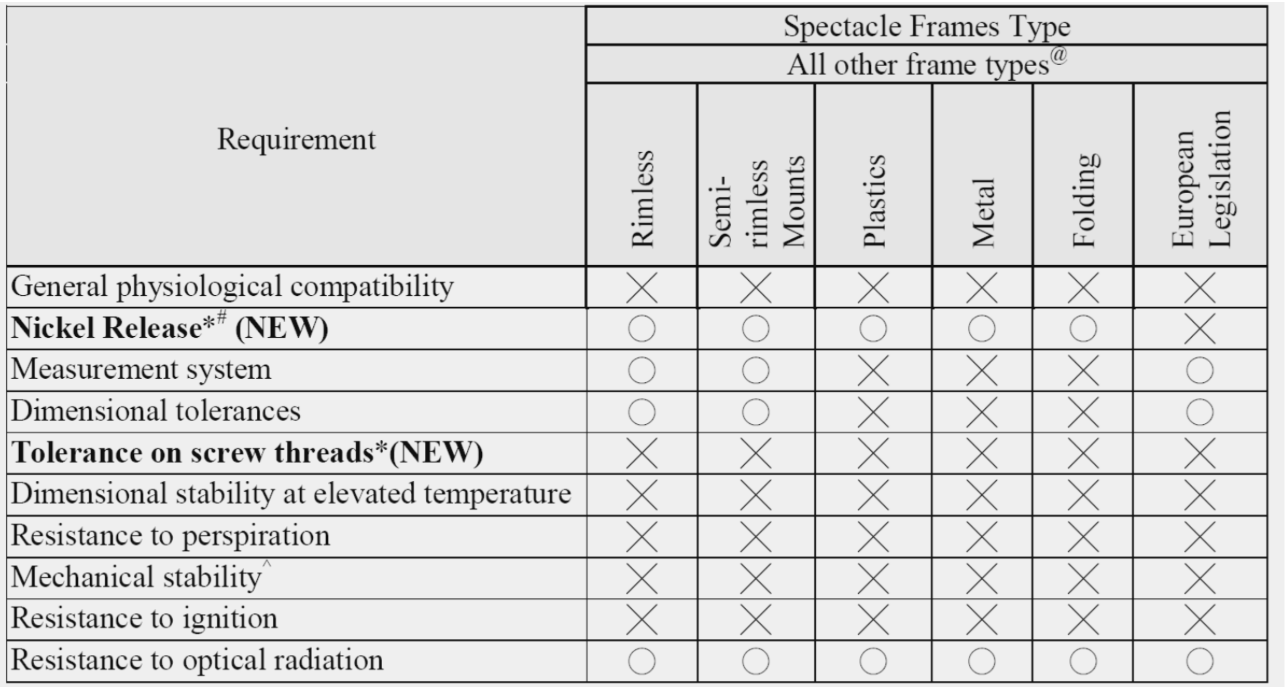
11.1. Normative documentation

ISO 12870:2004 Ophthalmic Optics – Spectacle Frames – Requirements and Test Methods

(abstract)

ISO 12870:2004 which was published on 1st August 2004 that cancels and replaces the first edition (ISO 12870:1997) and ISO 9456:1991. It specifies fundamental requirement for unglazed spectacle frames designed for used with all prescription lenses, and is applicable to frames at the point of sale to the consumers, by the manufacturer or supplier.

ISO 12870:2004 is applicable to all types of spectacle frame including those made from natural organic materials. However, this standard does NOT apply to complete custom-made spectacle frames or to products designed specifically to provide personal eye protection.



Requirement	Spectacle Frames Type					
	All other frame types@					
	Rimless	Semi-rimless Mounts	Plastics	Metal	Folding	European Legislation
General physiological compatibility	X	X	X	X	X	X
Nickel Release*# (NEW)	○	○	○	○	○	X
Measurement system	○	○	X	X	X	○
Dimensional tolerances	○	○	X	X	X	○
Tolerance on screw threads*(NEW)	X	X	X	X	X	X
Dimensional stability at elevated temperature	X	X	X	X	X	X
Resistance to perspiration	X	X	X	X	X	X
Mechanical stability^	X	X	X	X	X	X
Resistance to ignition	X	X	X	X	X	X
Resistance to optical radiation	○	○	○	○	○	○

*Nickel release and Tolerance on screw threads are the new requirements found in the ISO 12870:2004.

For metal and combination spectacle frames which come into direct and prolonged contact with the skin of swearer.

^ Including Bridge deformation, Lens retention characteristics and Endurance

@ “All other frame types” includes plastics and metal spectacle frames, including folding spectacle frames, having a rim completely surrounding the lens periphery.

X - General requirement that shall comply with in order to pass this International Standard;

○ - optional

ISO 18369-3:2006 Ophthalmic Optics - Contact lenses

(abstract)

It is important to establish that a specific lens manufacturing process can produce lenses to required parameters. This is important for both lathe cut lenses and also cast moulded lenses. A range of measurement methods can be used to determine various characteristics of the lens and these include radius of curvature and back vertex power. The contact lens properties are measured using the methods described in the following standard.

Measurement methods.

On completion of a sufficient amount of testing, the ability to produce finished lenses to an acceptable standard can be established by reference to ISO 18369-4:2006 Ophthalmic Optics - Contact lenses - Part 2: Tolerances.

The following table details the lens parameters and the methods used for their determination:

Parameter	**Method**	**Lens Type**
Radius of curvature	Optical microspherometry	Rigid
	Sagittal depth	Hydrogel
Back vertex power	Focimeter	Rigid & Hydrogel
Lens diameter	Projection method	Rigid & Hydrogel
Lens thickness	Dial gauge	Rigid & Hydrogel

Procedures:

Radius of Curvature - Optical Microspherometry

The microspherometer locates the surface vertex and aerial image (centre of curvature) with the Drysdale principle. The optical rnicrospherometer consists essentially of a microscope fitted with a vertical illuminator. Light from the target T is reflected down the microscope tube by a semi-silvered mirror and passes through the microscope objective to form an image of the target at T'. This is referred to as the surface image. The distance between the microscope and the lens surface is then increased, by either raising the microscope or lowering the lens on the microscope stage until another sharp image is observed. This is the aerial image. The distance through which the sample has been moved relative to the surface image is equal to the radius of curvature of the surface. The distance of travel is measured with an analogue distance gauge incorporated in the instrument.

Radius of Curvature - Sagittal Depth

Sagittal depth is the distance from the vertex of the contact lens surface to a chord drawn across the surface at a known diameter. For the determination of the sagittal depth of the back optic zone, the contact lens is rested concave side down against a circular contact lens support of fixed outside diameter. The spherometer projects the profiles of the contact lens, lens support and probe onto a screen. The projection system has a magnification of at least 10x and enables the lens, lens support and probe to be focused together. The operator ensures that the contact lens is centered on the support so that the probe approaches along the lens axis, and finally just touches the back vertex of the lens. This is the endpoint required to obtain a measurement value. The distance traveled by a solid mechanical probe from the plane of the lens support to the lens back surface vertex is the sagittal depth.

Back Vertex Power

The back vertex power of both soft and rigid contact lenses can be determined in air by the use of a focimeter. The focimeter is modified with a contact lens support so that the contact lens rests on a supporting ring. The lenses are equilibrated prior to measurement and the focimeter and support are kept at 20°C. The contact lens is placed with its posterior surface against the contact lens support to properly position the back vertex as the reference point for measurement. It is important that the back vertex be centered in the pupil of the lens stop and the lens surface be free of debris or solution. Therefore any surface liquid should be removed, particularly for hydrogel lenses immediately prior to measurement.

Lens Diameter

The diameter of both rigid and soft hydrogel contact lenses is measured using the projection comparator method. The projection system is capable of measuring to ±0.05 mm over a range of 0 mm to 17 mm. The scale of the screen represents a linear magnification of at least x15 and permits measurement accuracy of 0.05 mm for the contact lens diameter. The diameter of the lens is taken from a marked glass scale (similar to a microscope graticule) under the lens within the support, which is projected onto the screen. Hydrogel lenses are equilibrated at a temperature of 20°C ± 0.5°C and the projection comparator is also maintained at a temperature of 20°C. The contact lens is placed on the support which is then filled with saline which is also maintained at 20°C ± 0.5°C.

Lens Thickness

Thickness, measured through the section of a contact lens is made using a dial gauge for both rigid and soft contact lenses.

11.2. General information

The Principle of Compensation

By using those previously defined concepts, we can state the principle of compensation as follows: a lens placed in front of the eye compensates for its ammetropia when the image focal point of the lens coincides with the remote point of the eye.

This compensation principle applies only for the situation in which

a) the lens axis passes through the rotation center of the eye, and

b) the lens axis coincides with the eye visual axis.

The lens should be fitted in such a way that the first condition, which does not depend on the eye angular position, is satisfied. That way, astigmatism resulting from central oblique incidence will be avoided. The position in which a person aims at infinity, with visual axis parallel one to the other and to the floor, is defined as primary sight position.

At oblique sight directions from the primary position, the second condition is not satisfied, and a deeper (nonparaxial) study will be necessary to understand lens performance. The result of this analysis will determine the optimum lens design, which guaranties an oblique behavior as similar as possible as the paraxial one. In the rest of this section we will present the characteristics of the lens-eye coupling, which can be adequately described within the paraxial approximation.

Compensation of Spherical Ammetropia

Let us define the back vertex power of the lens as the inverse of the distance from the back surface vertex to the image focal point. In terms of surface refracting powers, F_1 and F_2, the back vertex power is given by

$$F_V = \frac{F_1 + F_2 - (t/n)F_1F_2}{1 - (t/n)F_1}$$

where t is the central thickness and η is the refraction index of the material. Let us assume that the distance from the back surface vertex of the lens to the object principal plane of the eye is d. According to the compensation principle, the back vertex power required to compensate a refractive error R is given by

$$F_V = \frac{R}{1 - dR}.$$

For refractive errors smaller than 4.5 D, the term dR becomes negligible and refractive error and back vertex power of the correcting lens are practically the same. For larger values of the refractive error, back vertex power differs from it by more than 0.25 D, and the difference must be taken into account.

Compensation of Astigmatism: The Dioptric Power Matrix

For an ophthalmic lens used to compensate astigmatism, the compensation principle should be applied in the two orthogonal planes where the maximum and minimum powers of the eye appear. Let us consider R_a and R_β the principal values of the refractive error, at meridians α and β = α + 90°. The principal powers of the astigmatic compensating lens will be $F_{Va} = R_\alpha /(l - dR_\alpha)$ and $F_{V\beta} = R_\beta/(1-dR_\beta)$. It is customary to name any of these back vertex powers as sphere (S), and the difference between them as the cylinder (C). For example, we can select $S = F_{Va}$, so that $C = F_{v\beta} - F_{Va}$. Of course, we can also set $S = F_{v\beta}$ and $C = F_{Va} - F_{v\beta}$. With these definitions, astigmatic lenses can be understood as the thin superposition of two elements — one purely spherical, with power S, and the other purely cylindrical, with power C — and whose axis is oriented along the meridian with power equal to the sphere. Complete description of astigmatic power requires three parameters. They could be the orientation of one of the principal meridians and their powers. Instead, it is more common to use the sphere, cylinder, and cylinder axis orientation. These three components are usually written as [S, C x α].

Although the use of sphere and cylinder is widely employed by ophthalmologists, optometrists, and practitioners, in a technical depiction of ophthalmic lenses, it is far more powerful to employ a matrix description of astigmatic power. Whereas sphere and cylinder still refer to power along principal meridians, power components referred to fixed coordinate axis can be grouped into a matrix form (tensor), so that any mathematical transformation or manipulation is easily written and performed. The dioptric power matrix, F, is defined as

$$\mathbf{F} = \begin{pmatrix} E + C\sin^2\alpha & -C\sin\alpha\cos\alpha \\ -C\sin\alpha\cos\alpha & E + C\cos^2\alpha \end{pmatrix}$$

and it accounts for all the thin lens properties of any astigmatic lens. The dioptric power matrix is just the 2 x 2 submatrix at the bottom left of the 4 x 4 ABCD matrix corresponding to the thin astigmatic lens.

For example, if we consider two lenses with power matrix F_1 and F_2, their superposition is corresponded with a matrix $F_1 + F_2$. The local thickness of the lens, t(x,y), is given by

$$t(x,y) = t_0 - \frac{(x \quad y)\mathbf{F}\begin{pmatrix} x \\ y \end{pmatrix}}{2(n-1)}$$

where t_0 is the central thickness and η is the refraction index of the lens material.

Lens Adaptation

We have already shown the relationship between lens power and refractive error. Now, we are going to describe the way a lens couples with the eye, modifying the way the eye perceives images. All the effects derived from this optical coupling are grouped under the concept of lens adaptation. The monocular effects are: prismatic effect, modification of the field of view, lens magnification, and ophthalmic lens aberrations. The first three effects can be analyzed in the paraxial regime.

Prismatic effect

From all the rays refracting in the lens and entering into the pupil of the eye, as shown in Fig. 2, only a narrow ray bundle contributes to the foveal vision. This bundle is mainly characterized by the chief ray, which passes through the rotation center of the eye, and the pupil of the eye, which determines the bundle diameter. The compensating lens does not only change the bundle vergence in order to bring it to a focus at the remote point. It also changes the direction of the chief ray, and henceforth, of the whole ray bundle. As a result of this change in direction, the eye has to rotate at an angle from the position in which it could observe the object without the compensating lens. The angle rotated by the eye (from the situation without the lens to the situation with the lens) is called the prismatic effect. Sight direction is characterized by two direction cosines. The prismatic effect will also have two components that will equal the differences between direction cosines before and after the compensating lens is introduced. The two components of the prismatic effect are arranged in a vector

$$p = \begin{pmatrix} p_x \\ p_y \end{pmatrix}$$

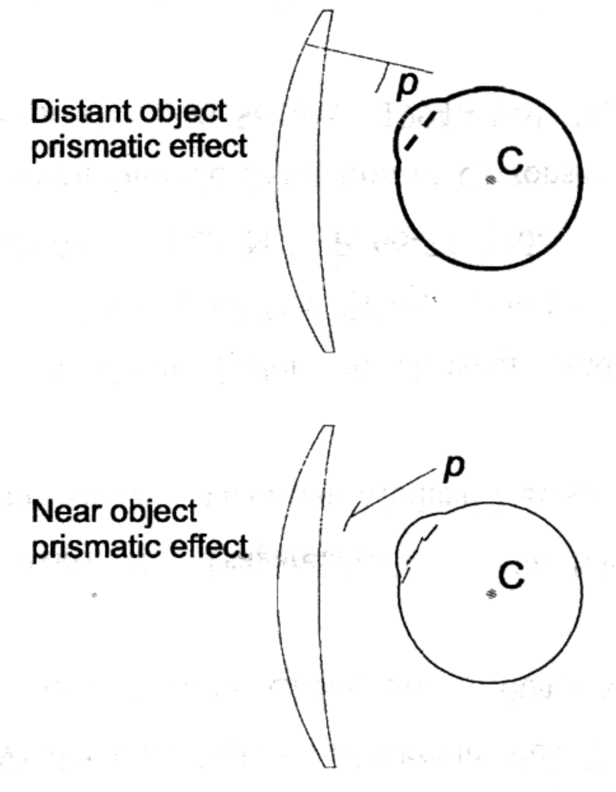


Fig. 2 Prismatic effect for a distant and near object.

The prismatic effect introduced by a lens with matrix power F at a point of coordinates r = (x,y) is given by

$\rho = -Fr$

which is called the matrix Prentice's law.

Prismatic effect at a point (x,y) becomes larger as the distance from the point to the optical center increases. Furthermore, prismatic effect is proportional to lens power. The prismatic effect introduced by a spherical lens has radial geometry.

The prismatic effect introduced by a purely cylindrical lens is perpendicular to the cylinder axis.

In some instances, prismatic effect is prescribed in order to compensate for a convergence or binocular visual problem. The required prismatic effect may sometimes be generated by lens decentring. The decentring $\delta r\cdot$, required to produce a determined prismatic effect *p*, is given by

$$\delta r = -F^{-1}p$$

Modification of the field of view

The dynamic field of view (the scope accessible to foveal vision via eye rotation) is modified by the presence of the frame and the ophthalmic lens (Fig. 3). The apparent field of view is defined in terms of the frame size, and is given by

$$\varphi_a = \arctan(hL_2)$$

where h is the distance from the frame border to the visual axis in primary position, and L_2 is the inverse of the distance from the back surface vertex to the rotation center of the eye, l_2. The real field of view takes into account the modification of the apparent field of view caused by the lens prismatic effect. The user experiences this visual field, and is given by

$$\varphi_\tau = \arctan[h(L_2 — F_V)]$$

Hyperopics experience a decrease of the field of view, whereas myopics experience an increase of the same.

Lens magnification.

Ophthalmic lens also modifies the size of the retinal image if compared with that of the uncorrected eye.

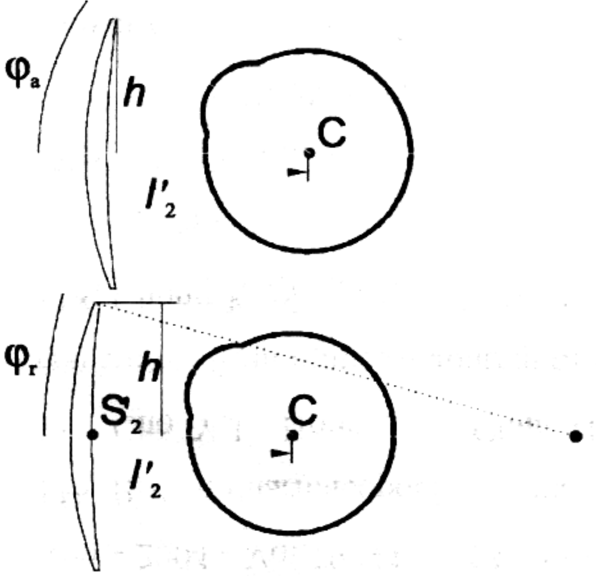


Fig. 3 Field of view through an ophthalmic lens.

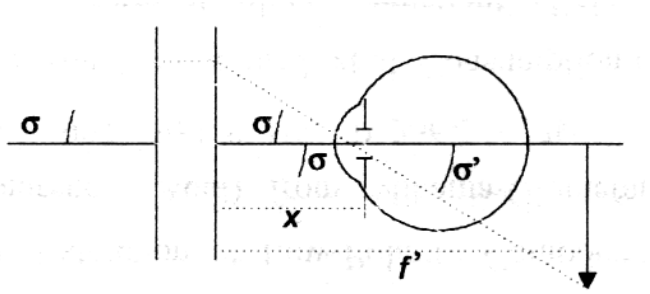


Fig. 4 Spectacle magnification.

Spectacle magnification (SM) is defined as the quotient between the size of the retinal image in the compensated eye and the size of the (blurred) retinal image in the uncompensated eye. SM is easily computed through the expression

$$\mathrm{SM} = \frac{1}{1 - xF},$$

where *x* is the distance from the image principal plane of the lens and the front pupil of the eye, and F is the lens power (Fig. 4). If we write this equation in terms of more handy parameters (back vertex power and distance from the back surface vertex to the corneal vertex, d) we obtain

$$\mathrm{SM} = \frac{1}{1 - (e/n)F_1} \frac{1}{1 - \mathrm{d}F_\mathrm{V}}$$

So, two terms contribute multiplicatively to spectacle magnification. The first term, called the shape factor, does not depend on lens power. The second term, called the power factor, neither depends on lens form factor nor on thickness. The shape factor may be used to equalize spectacle magnification in both eyes when aniseikonia (different image sizes in each eye) occurs. Lenses that use this principle are called iseikonic lenses.

Ophthalmic lens aberrations

We previously stated the conditions for which the paraxial description of the lens—eye system is adequate. At oblique sight directions, the lens optical axis does not coincide with the visual axis, and aberrations have to be taken into account. The typical situation is depicted in Fig. 5. The rays that impinge onto the fovea after refraction through the ophthalmic lens form a narrow pencil whose transversal extension is limited by the pupil of the eye. The ray passing through the center of the pupil and the rotation center of the eye is called the chief ray. It coincides with the axis of the ray bundle under consideration.

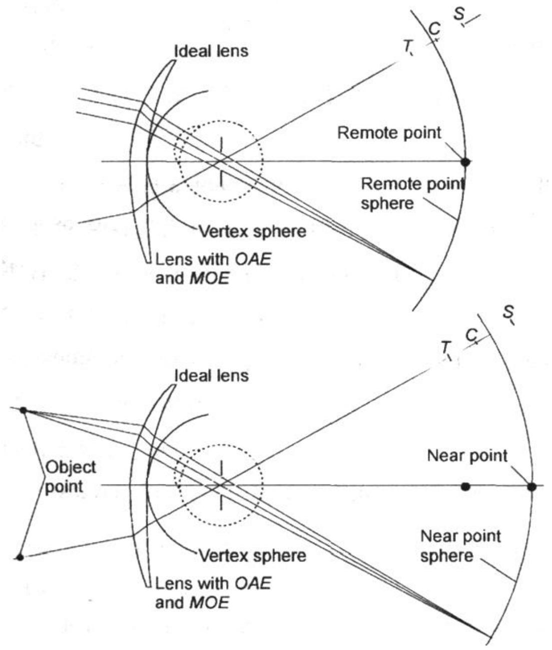


Fig. 5 Oblique astigmatism error (OAE) and mean oblique error (MOE) for a positive lens in the cases of distant and near objects.

At oblique sight directions, the principle of compensation must be slightly modified. In order to adequately compensate for the refractive error at an oblique sight direction, the ray bundle around the chief ray that refracts through the lens and goes through the eye pupil should focus onto the remote point sphere, exactly at the remote point of the eye for that oblique direction.

In this situation, only those aberrations relating to thin pencil of rays will be noticeable. Because of the small aperture of the ray bundle, spherical aberration and coma are not taken into account (they will be noticeable only for very high refractive errors). There will be distortion, although this aberration does not modify visual acuity but image position. Distortion is apparent when the whole field of view is taken into account. In any case, the brain adapts easily to distortion so the user ignores it after the first few days of wearing spectacles. Oblique astigmatism, which generates two focal lines, and field curvature, which generates the Petzval surface, affect visual acuity and are the aberrations to be corrected. Because of the particular characteristics of the lens-eye system, these two classical aberrations have to be redefined.

First, powers and focal lengths will be defined along the chief ray, and with reference to the vertex sphere. This is the sphere with center at the rotation center of the eye and tangential with the ophthalmic lens back surface. Let us take A as the point where the chief ray intersects the vertex sphere, and T and S as the tangential and sagittal focal lines of the refracted pencil, respectively. Finally, we take C as the point at which the disk of least confusion of the astigmatic pencil is located. The tangential, sagittal and mean oblique powers, F_T, F_S, and F_C are defined respectively as

$$F_T = \frac{1}{AT}, \quad F_S = \frac{1}{AS}, \quad F_C = \frac{1}{AC}$$

and it can be demonstrated that $F_c = (F_T + F_s)/2$.

The oblique astigmatic error (OAE) is defined as the difference between the oblique tangential and sagittal powers. The mean oblique error (MOE) is defined as the difference between the back surface power and the mean oblique power. As can be observed, the ophthalmic lens should present the field curvature so that the compensation principle at oblique sight directions is satisfied. The MOE then stands for the difference between the actual field curvature and the rate required for the refractive error that the lens compensates for. An ideal ophthalmic lens should have negligible values of oblique errors for all values of the obliquity angle, u[2]

Chromatic aberration will always be present in ophthalmic lenses. Transverse chromatic aberration (TCA), in particular, has the largest impact on visual acuity at oblique sight directions. Unfortunately, there is no way to control it except for the selection of materials with the highest Abbe number.

Ophthalmic lens design.

This section will show the relationship between the shape of an ophthalmic lens and the oblique errors of the same, and how they can be minimized. The parameters that completely describe a thick lens with spherical surfaces include the two radius of curvature of the surfaces, the index of refraction, the thickness, and the transversal diameter. The election of the refraction index is limited to the use of a few selected and widely available plastic and glass materials. The central thickness is also limited by constructive constraints. For negative powers, the central thickness needs to be large enough to guarantee security. For a positive lens, the central thickness is determined by the transverse diameter and the expected value of the edge thickness. In any case, the variation range is within a few millimeters. Lenses are available in standardized diameters (typically 50-80 mm), which allow the users to fit the lenses in a large variety of frames properly. We conclude that these parameters cannot be left free in order to reduce aberration. The relation between the required back vertex power and the lens parameters establishes a constraint between the two surface radii so that only one free parameter is left—which can be any of the surface radii or, more commonly, any of the two surface powers of the lens. Without losing generality, let us assume that the back surface power is left free in order to optimize lens performance. The objective of the lens designer will be to find the value of the back surface power that best fit the designer's criteria for oblique errors correction (see next section for an explanation of these criteria).

In order to compute for the oblique powers, it is necessary to determine the angles and points of incidence of the chief rays on the two lens surfaces first. To do that, a backward exact ray tracing of the chief ray is carried out. Once the trajectory of the chief ray is completely known, Coddington equations can be applied to each surface so that the position of the tangential and sagittal focal lines are determined. Finally, some geometrical computation to find the intersection of the chief ray with the vertex sphere leads directly to the oblique powers and henceforth to the oblique errors. Full analysis can be programmed in a few lines of code so that extensive computation of oblique errors as a function of the back (or front) surface power can be easily carried out.

Best Form Lenses. Point-Focal and Percival Solutions

It should be recalled that although oblique astigmatism is zero for the primary position, it increases with the angle of incidence. For a given sight direction, there will be a determined amount of astigmatism which will depend on the lens shape factor. If absolute value of the lens power is not too large, a shape factor can be found for which the astigmatism generated at the first surface is cancelled out exactly by the astigmatism at the second refraction. A lens with this property is called point-focal (with punctual focus). This condition can only be met for a determined sight direction. Fortunately, astigmatism remains negligible for smaller angles, so it can be assumed that in a point-focal lens the tangential and sagittal shells merge onto the unique Petzval surface, which is generated by the field curvature. Usually, the radius of curvature of the Petzval surface of a point-focal lens does not coincide with the radius of the far point sphere. Henceforth, the focus will not fall onto the far point sphere for an oblique sight direction, and the lens will suffer from power error. This error is negative for myopic people and positive for hyperopic people, leading in all cases to under-correction at oblique incidence. Hyperopic persons will be able to cancel this error via a small amount of accommodation (usually less than half a diopter).

Instead of looking for lenses with punctual focus, one could try to eliminate the power error—that is, to bring the disk of least confusion onto the far point sphere, at least for one oblique sight direction. This was proposed by English ophthalmologist A. Percival (1914), who noticed that the blur patch on the retina was smaller when a lens was made to satisfy his criterion than when it was made to be point-focal. For example, consider a +5.00 D lens, made with crown glass ($n = 1.523$), and assume that it will be made with a central thickness of 3.5 mm, and that it will be worn so that $1'_2 = 27$ mm. Exact ray tracing for a 35° rotation of the eye shows that with a back refracting power of — 6.50 D, the lens will be point-focal, whereas a back refracting power of — 4.00 D will enable the lens to satisfy the Percival criterion. If the diameter of the pupil is assumed to be 4 mm, the size of the blur patch for the point-focal design will be 0.0255 mm (13 foveal cones). For the Percival design, the blur patch coincides with the disk of least confusion, which for this lens has a diameter of 0.0135 mm (seven foveal cones). This result led Dr. Percival to propose the power error free lens form (or bending, as it is usually named in ophthalmic optics) as the optimum design. Indeed, the Percival form is not as advantageous as could be derived from the previous result. First, the disk of least confusion is not an evenly illuminated blur patch (as it is in the case with point-focal lenses), and the distribution of light on it is more complicated.

Second, hyperopic may bring to focus the blur patch of a point-focal lens via a small amount of accommodation. Third, the Percival condition is more critical than the point-focal condition to variations of the design parameters (fitting distance and object vergence). Finally, variations in accommodation cause the blur patch to lose its rotational symmetry in Percival lenses, whereas circularity of the blur patch is preserved in point-focal lenses. For all these reasons, point-focal forms were mainly chosen for the manufacture of ophthalmic lenses for most of the 20th century.

A design compromise that is widely used nowadays consists of making lenses free from tangential error— that is, lenses for which die tangential shell coincides with the far point sphere. The astigmatism of such a lens is quite small (about half of the astigmatism of a Percival form) and the design is stable relative to die variation in fitting distance and object vergence. In relation to die fitting distance, it is assumed mat variations of up to ±6 mm, from the mean value of 27 mm, may arise. When the fitting distance increases, the lens tends to become point-focal, and when the fitting distance decreases, die lens tends to take a Percival form. In relation to object distance, a tangential error-free form designed for distance vision behaves quite well for near vision. In changing from distance to near vision, power error remains remarkably similar, and astigmatism simply changes its sign.

In all these cases, aberration elimination (regardless if it is OAE, mean oblique power error, or oblique tangential error) is accomplished via meniscus-shaped lenses. For these lenses, any of these aberrations at each surface presents opposite sign, so the proper lens bending may bring the aberration absolute values to be equal on each surface and are henceforth compensated. Nevertheless, compensation of aberrations with spherical surfaces presents some limitations. On the one hand, this compensation effect only works in a determined range of lens power, which depends on the aberration to be compensated, the fitting distance, and the refraction index of the lens material (central thickness has very little effect on aberration). The powers for which aberration can be compensated usually range from high-powered negative lenses (about — 25 D) to medium-powered positive lenses (about 7 D). It therefore follows that it is not be possible to have high-powered spherical lenses free from oblique errors—like, for example, the lenses for correcting aphaquia. On the other hand, given a determined power, spherical surfaces yield two different bendings for which any of die oblique errors may be compensated. The steeper bending is called the Wollaston form, and it uses very high refractive powers (typically with back surface powers of about - 20 to - 35 D). Wollaston lenses are so curved mat they are difficult to manufacture, and difficult to cut in order to fit them to a frame. Indeed, they are also quite unsightly, hi his experiments, Wollaston discovered that these lens forms were free from astigmatic error, and he called them periscopic. The shallower bending is called the Ostwalt form. They have more distortion than those with Wollaston bending, but they behave similarly with respect to oblique errors. Although modern spherical lenses are made with bending as close as possible to the Ostwalt form, the prevalent aesthetic criteria nowadays demands for even flatter lens designs.

The third-order approach to the calculation and cancellation of the oblique astigmatism, or the power error has provided analytical solutions for the point-focal and Percival formats in the past. For a thin lens, when these two aberrations are expressed in terms of the total power of the lens, F', and one of the surface powers of the lens, the loci of the formats having zero oblique astigmatism (or zero error power) are on two ellipses called Tscherning ellipses. Once the surface power of one of me surfaces is known, the other is easily found by using the thin lens assumption.

The location and form of the Tscherning ellipses depend on the index of refraction, and the distance from the back vertex of the lens to me center of rotation. These ellipses have been plotted in Fig. 6, where tile map of the aberrations is analyzed. An initial view of this graphic shows that, for a given value of total power (i.e., for a given refractive compensation), mere are two possible formats that cancel the aberration under analysis. One of the formats has lower absolute value of the surface powers than the other format. This means that the surfaces will be flatter in one of the formats. This flatter solution is the Ostwald format, and the other is the Wollaston solution. Both of them should be equivalent within this third order and thin lens conditions.

An exact calculation based on real ray-tracing can be used to know the formats having a given value of aberration. These formats depend now on the actual parameters of me lens: index of refraction, central thickness, transversal diameter, and radii of curvature of the surfaces. They also depend on the consideration of far vision or near vision. In Fig. 6, we show a contour plot of me oblique astigmatism aberrations for far vision. The contour lines correspond with values of 0.125, 0.25, and 0.5 D of aberration.

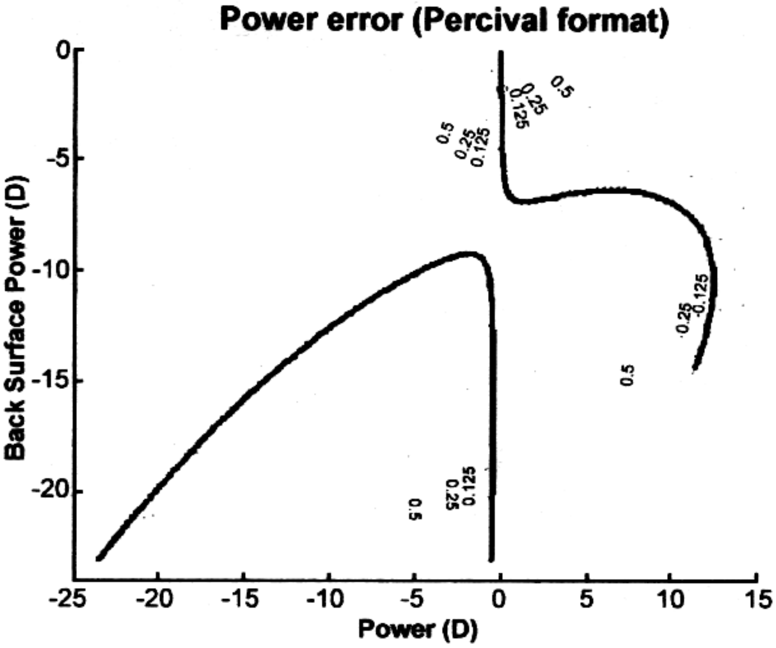


Fig. 6. Map of the mean oblique error in terms of the total power of the lens and the back surface power. The bold solid line represents the formats having null aberration. The thin solid line corresponds with the academic solution provided by the Tscherning ellipse.

The two facts related with spherical surfaces — limited range of power for which oblique errors can be corrected, and pronounced bending, even with the Ostwalt form— have led to the onset of aspheric surfaces in the ophthalmic industry.

Lenses with Aspheric Surfaces

Aspheric surfaces were introduced in the ophthalmic industry to overcome the limitations of spherical surfaces. The most widely used family of aspheric surfaces are the conicoids. They are surfaces with revolution symmetry obtained by turning around a symmetry axis of any of the classical conic curves: ellipse, parabola, and hyperbola — giving rise to the concept of ellipsoid, paraboloid, and hyperboloid, respectively.

The main geometrical characteristic of the conicoids is that tangential curvature radius of paraboloids, hyperboloids, and oblate ellipsoids (prolate ellipsoids) become larger (smaller) than the main curvature radius at the vertex, as the observer moves farther away from it in the radial direction. The increase of the tangential curvature radius produces a reduction of the tangential power so that OAE can be compensated for with flatter lens forms when the front surface is substituted by a paraboloid, hyperboloid, or oblate ellipsoid. The oblate ellipsoid can be used to compensate for astigmatic error in high-powered lenses if the designed will grind it on the back surface, where the increased back tangential power will compensate for the front tangential power of the front spherical surface (this was the design for the Katral lens by Zeiss, the first aspheric introduced for aphaquia and high hypermetropia). The first aspheric designs used in ophthalmic optics were all intended to compensate for oblique errors in high-powered positive lenses. In 1950, W. Merte introduced a kind of plano-aspheric lenses known as Merle's conicoidal lenses. For each back vertex power, asphericity parameter of the back surface can be exactly calculated in order to eliminate the OAE for a determined sight angle.

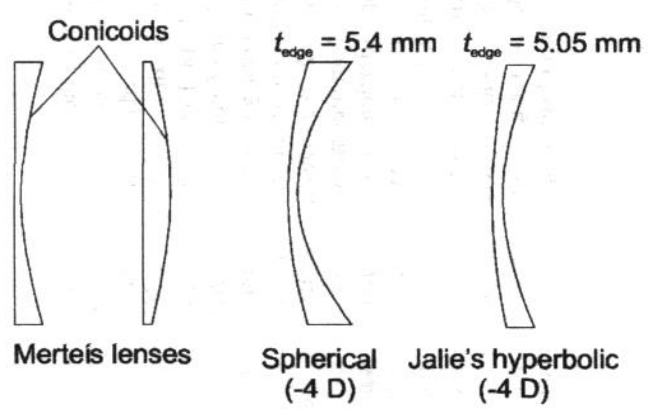


Fig. 7 Aspheric formats for ophthalmic lenses.

In 1981, M. Jalie patented the Jalie's hyperbolic lenses for which the surface of greater curvature (front surface in positive and back surface in negative lenses) is substituted by a hyperbolic surface. Jalie's design allows for flatter and thinner lenses for each available power, while keeping optimum oblique performance (Fig.7).

Nowadays, aspheric lenses are available for medium-and even low-powered lenses, both positive and negative. New aspheric surfaces beyond conicoids have been introduced in the ophthalmic industry—for example, the polynomial surfaces or those described via splines. Typical applications of these surface descriptions are blended lenticulars, for which there is an aspheric, smooth transition from the curvature radius of the optical zone to the outer rim of the lens.

As a general rule, aspheric designs of any power allows for flatter, thinner, and lighter lenses in any range power, while keeping oblique errors and distortion equal or smaller than those in spherical lenses.

Merit Functions

Ophthalmic lenses for compensating spherical ametropies, although simple optical systems, are very well adapted to the performance of the eye. However, in the dispensing and fitting of these lenses, there are some other aspects that need to be included in the design aside, from optical performance. These aspects can be aesthetic (curvature of the front surface, presence of power rings in negative lenses, etc.), ergonomic (thickness, weight, distance of wearing), manufacturing-related (maximum diameter, thickness of the rim, etc.), related with the intended use of the lens (for far vision, or near vision), or directed to compensate some other anomalies of the vision that an optometrist may indicate. All these design elements, along with the optical performance of the lens, are included in a merit function that is minimized within the design process. These merit functions share a similar structure with those employed for precision optics, but are properly adapted for ophthalmic use. For example, the difference between the actual oblique power error and the target do not enter squared into the merit function, as the practice goes with other aberrations. This is because the sign of power error is important. Positive power error can be compensated by a small accommodation by hyperopic persons, while myopic persons can compensate for negative power errors. Finally, the output of the merit function optimization must be discretized into corrected curve lens series, as previously explained.

This is the actual process practiced in the ophthalmic lens design nowadays. Different designs are presented to the user, in terms of their relative performance, to comply with the expectations of the wearer of the lens. This information should be available to the optometrist and the dispensing professional to assist the patient and the user in choosing the optimum ophthalmic lens.

Lenses for presbiopia

There are many different ways to compensate presbyopic patients. These options include near-vision monofocal lenses (which must be alternated with distance vision lenses when the presbyopic also happens to be ammetropic), bifocal lenses, trifocal lenses, progressive addition lenses, and monofocal lenses with increased depth of focus, which only became available in the last five years. Each type of lens is calibrated to suit specific presbyopia conditions, age, and patient activities. Monofocal lenses have the advantage of a wide field of view (limited by the frame) and good optical quality, as the lens belongs to an excellent lens series. However, ammetropic persons will have to alternate between two spectacles when passing from distance vision to near vision. Patients with a very short accommodation range will even need a further spectacle for intermediate vision.

Bifocals and Trifocals

Bifocals have two regions with different powers; one region, usually at the upper portion of the lens, for distance vision, and another region at the bottom for near vision, which is called the segment. Usually, the near region is made by a local modification of curvature or refraction index in the lens for distance vision, which is called the main lens. Since the invention of bifocals in 1785 by B. Franklin, there have been many different designs, usually depending on the availability of adequate manufacturing technology. Nowadays, there are two main technologies:

One-piece solid bifocals. The near region is generated by a change of curvature of the front surface. Solid bifocals may be further subdivided into invisible (without steps in the line which separate the two regions), blended (with smooth transitions between regions), and executive styles (with straight edge).

Fused bifocals. The near region is generated by a piece of glass with higher refraction index inserted in the main lens.

Bifocals allow the presbyopic patient immediate change from distance to near vision, but they have some limitations.

Prismatic effect is difficult to control hi the near region. When the shape and size of the near zone is fixed, very little degree of freedom is left to properly locate the optical center of the near portion.

Some types of bifocals (mainly those with round segment) present image jump, which is a sudden change in the prismatic effect caused by the addition lens. Image jump produces scotoma, and makes adaptation to bifocal lenses difficult.

The separation line between distance and near vision may produce an unsightly lens. Also, stepped separation lines may produce light dispersion and/or parasite reflections that may lead to user annoyance.

Aberrations in the near portion become larger than those in monofocal lenses. Usually, the lens form is selected for optimizing distance vision. In solid bifocals the curvature of the front surface in the near portion grows, so best form condition is lost. In fused bifocal, a different material and a third surface are introduced in the near portion, so best form condition is also lost.

In general, there is a trade-off between image jump and the amount of prismatic effect in the near portion, both being determined by the position of the optical center of the addition. Round segments produce prismatic effects in the near region similar to those in monofocals, whereas they present the largest values of image jump. In contrast, segments with straight edge present the larger prismatic effects and smaller or negligible image jumps.

When the amplitude of accommodation decreases to less than 1 D, clear vision at intermediate distances is compromised with bifocals. To help the patient manage this situation, trifocal lenses were invented by J.I. Hawkins in 1826. They have two segments: one for intermediate vision with half the addition, and a second one for near vision with full addition. Trifocals are made with the technology for fused bifocals. Previous equations are easily generalized to compute image jumps and prismatic effect in trifocal lenses. The main drawbacks of trifocal lenses are decreased fields of view, annoying separation lines, and unsightly aspect.

Progressive Power Lenses

Progressive power lenses were designed and introduced in an attempt to improve the performance of previous multifocal (trifocal and bifocal lenses) variants. The objectives were clear vision at all distances, elimination of separation lines, and a more aesthetic lens. The first progressive lens with commercial success was the Varilux 1, which was designed by B. Maitenaz, with Essilor, in 1958. Increase of power from the upper portion to the bottom of the lens is achieved by progressively increasing the curvature radius of the front surface. In Varilux 1, the half upper part of the surface was spherical. Some millimeters below the point for distance vision, the curvature of the horizontal sections begin to increase smoothly. The region in which the curvature increases is called the progression zone. At the bottom of this region, power stabilizes in an area named reading or near portion. It can be demonstrated that progressive variation of the surface curvature must introduce surface cylinder, which will turn into astigmatic aberration. To avoid it, Varilux 1 was designed so that all the points along the vertical central meridian were umbilical (locally spherical).

Since the launch of Varilux 1, there has been five generations of progressive lenses from Essilor. When patents of Varilux 2 (launched in 1972) expired, many other manufacturers have entered the market with competitive designs. In Varilux 2, aspherization of surface horizontal meridians was introduced. This gave designers more degrees of freedom to reduce lateral astigmatism beyond the imposition of Minkwitz rule. Lens asymmetry was also introduced to take into account the convergence of the visual points when going from distance to near vision. This was implemented by introducing a continuous displacement (inset) of the umbilical line to the nasal side along the progression zone. Newer designs came out successively to address various problems: variation of the inset as a function of age and/or ammetropia, improvements of the binocular behavior of the pair of progressive lenses, reduction of lateral astigmatism, reduction of gradients of sphere and astigmatism, improvement of the lens ergonomics, and quite recently, reduction of the swimming effects as a consequence of differential distortion of the extrafoveal field of view. The search for better progressive lenses has stimulated active research on ophthalmic optics and vision in the last 15 years. Many works have been published concerning the measurement of these lenses, as well as the physiological consequences derived from their use.

11.3. Techniques used by opticians

The specialist often determinates type, sign and optic power (refraction) of ocular lenses in shops “Optics” and in pharmacies where the vision correction products are produced and sold. A dioptrometer is optic equipment providing quickest and the most precise method of measurement. Also one can determinate type and refraction of lenses by “cross method” with the test ocular lens set.

Determination of lens type. One should look through a lens, placed 10-20 cm far from eye, at two perpendicular lines – cross image or crisscrossing of window frame. One need to match optic center of a lens with the cross point and then to turn it slowly to the right and to the left in plane of a lens.

Lens is considered *stigmatic* if the angle of crossing lines doesn’t change.

Lens is considered *astigmatic* if the angle of crossing lines changes while turning the lens (“scissors phenomenon”).

Determination of lens sign. One moves a lens to the right, to the left, up and down looking on a cross:

a) *negative* – the cross image moves in the same direction as the lens.
b) *positive* – the cross moves in the direction opposite to lens moving.
c) *afocal* – the cross doesn't move.

Determination of lens power. In order to determine lens power the analyzed lens is put onto the lenses of the same type but of the opposite sign, taken from the test ocular lens set. Consecutively increasing optic power, every lens from the set combined with analyzed one is tested for the total optic effect on the cross. Thus it's possible to find the lens that neutralizes optic power of analyzed lens. So the analyzed lens optic power is equal to those of the lens that neutralized it, but has the opposite sign.

Prescription of glasses. There are the following indications in prescriptions for proper work of an optometrist:

- glasses purpose – for regular wear; for work or for far sight.
- type and optic power of lens for every eye;
- position of lens axis – if astigmatic lens is prescribed;
- distance between optic centers of ocular lenses that is equal to distance between centers of pupils;
- position of astigmatic lens axis, indicated by the standard Tabo table: for every eye it is counted out in degrees on upper semicircle counterclockwise; zero is near the right end of the horizontal meridian.

There are Latin indications used in prescriptions of glasses:

O. D. – oculus dexter –right eye
O.S. – oculus sinister –left eye
O.U. – oculi utriusquae – both eyes
Convex – positive
Concave – negative
Sphaera – spherical, stigmatic
Cylinder – cylindrical, astigmatic
Axis - axis (of astigmatic glass)
Planum – plane afocal lens
D.P. - distantia pupillarum –distance between centers of pupils.