Optics of the eye

I. Aims:

Students will familiarise themselves with the basic principles of geometric optics and the imaging properties of lenses. They will be required to determine the optical power of pairs of glasses.

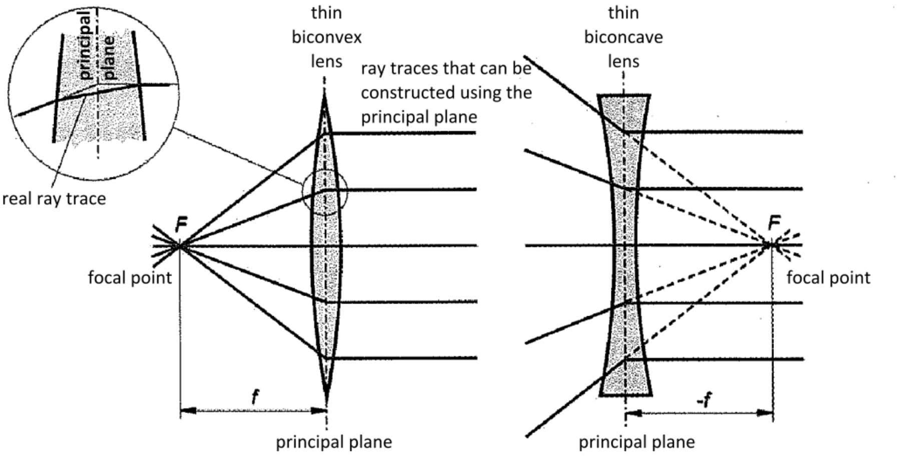
In medical practice, one encounters lenses in microscopic examinations and in correcting the refractive defects of the eye. In the second part of the practical, we shall study the optical properties of the eye.

II. Theoretical background

A. Optical lenses

In order to understand the optical properties of lenses, it is sufficient to use the ray model of light applied in geometrical optics. Here we assume that rays of light leave the object in all directions; these rays propagate in a straight line in a uniform medium, and refract at the boundaries between media. For so-called thin lenses, assuming a single refraction on the principal plane in the middle of the lens provides a good approximation of the real light trajectory, which makes ray tracing easier.

The two basic types of lenses are converging and diverging lenses. The names are based on the directions the parallel rays take after passing through the lens. Upon passing through a converging lens, rays travelling parallel to the optical axis will converge in a single point of the optical axis, which point is called the focal point of the lens (F). For symmetry reasons, a lens has two focal points on each side, at equal distances f (called the focal length) from the lens. Parallel rays refracting on a diverging lens will not meet but will diverge as if they had originated from a single point, which is called the focal point of the diverging lens. The distance of the focal point from the lens is called the focal length. By convention, *the focal length of a converging lens is positive*, whereas *the focal length of a diverging lens is taken with negative sign.*

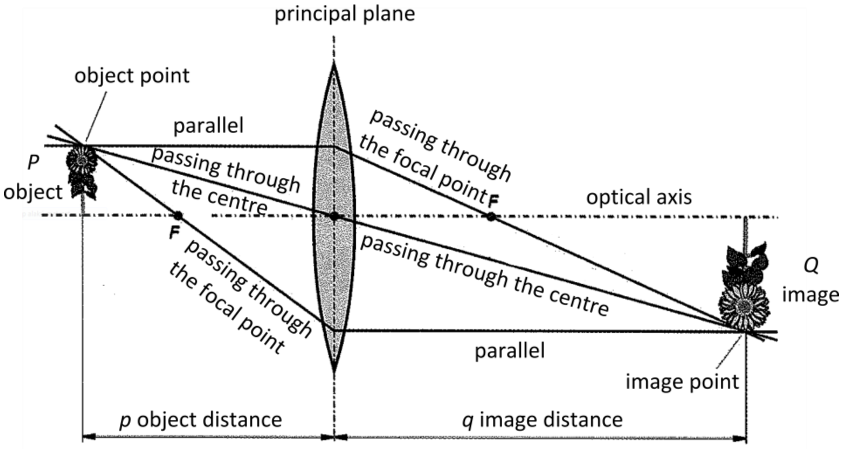


In the optics of glasses, lenses are usually characterised by the reciprocal of the focal length, called the optical power ($D = \frac{1}{f}$). The unit of optical power is the dioptre (1 dpt = 1 m^{-1}).

Optical power and focal length depend on the geometric parameters of the lens. The more convex the lens, the less the focal length and thus the greater the optical power. This explains why the eye is able to form sharp images of objects at different distances (accommodation): depending on the tension in the ciliary muscle, the curvature of the crystalline lens can change, thus adjusting its focal length.

B. Image formation

We are able to see an object point that is luminous or is illuminated if the light coming from it reaches our eyes. In optical image formation, the light scattered on the object passes through optical elements (like lenses) that change the direction in which it travels. The image point is the point in which the rays scattered from the object point meet again.



The focal length of the lens *(f)*, the object distance *(p)* and the image distance *(q)* are related by the thin lens equation:

$$D = \frac{1}{f} = \frac{1}{p} + \frac{1}{q}.$$

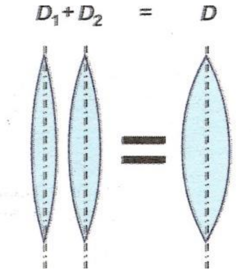
If the media on the two sides of the lens are different, with a refractive index n_p on the object side and n_q on the other side, the following formula is applicable:

$$D = \frac{1}{f} = \frac{n_\mathrm{p}}{p} + \frac{n_\mathrm{q}}{q}.$$

The linear magnification of the lens is defined as the ratio of the one-dimensional size of the image *(Q)* to the one-dimensional size of the object *(P)*. Using the thin lens equation, we can also express the linear magnification in the following forms:

$$N = \frac{Q}{P} = \frac{q}{p} = \frac{q-f}{f} = \frac{f}{p-f}.$$

Two thin lenses placed close to each other (as compared to their focal lenses) can be replaced by a single thin lens whose optical power is the sum of the optical powers of the individual lenses, taken with appropriate signs:



$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}, \qquad D = D_1 + D_2.$$

C. Accommodation of the eye

By changing the curvature of the crystalline lens, the resultant optical power of the eye can be controlled. This means that even for different object distances, sharp images can emerge on the retina, which is at a fixed distance from the crystalline lens. This process is called accommodation.

In resting state, the ring-shaped ciliary muscle is relaxed and the fibres of the zonule of Zinn contract, keeping the flexible crystalline lens flattened. When we direct our sight at a nearby object, the ciliary muscle contracts, forming a tighter ring. Then the he fibres of the zonule of Zinn relax, letting the crystalline lens round up by virtue of its own flexibility. Of course, the potential of increasing the curvature of the crystalline lens is limited. The point closest to the eye at which an object can be brought into focus through accommodation is called the near point (p_p). Here the optical power of the eye is the greatest. The point farthest away from the eye of which the totally relaxed (not accommodating) eye can still form a sharp image is called the far point (p_r). The *accommodation amplitude* is defined as the difference between the greatest and the smallest optical power:

$$\Delta D = D_\mathrm{p} - D_\mathrm{r} = \frac{1}{p_\mathrm{p}} + \frac{n}{q} - \left(\frac{1}{p_\mathrm{r}} + \frac{n}{q}\right) = \frac{1}{p_\mathrm{p}} - \frac{1}{p_\mathrm{r}}.$$

where *n* denotes the refractive index of the eye.

D. Determining visual acuity

In recognising objects, the most important role is that of *central shape perception*, which basically means the processing of the image formed in the fovea centralis. The angle made by the imaginary lines drawn from the extreme points of the object in sight through the optical nodal points of the eye is called the *visual angle.* Its value is approximated as

$$\text{visual angle} = \frac{\text{object size}}{\text{object distance}}\ [\text{rad}] = \frac{\text{object size}}{\text{object distance}} \cdot \frac{360 \cdot 60'}{2\pi}\ [\text{minute of arc}]$$

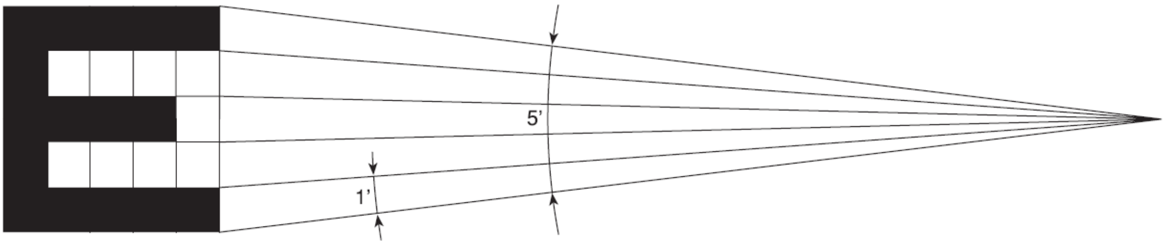
The smallest visual angle at which we are still able to distinguish between two distinct points A and B is called the *visual angle limit* (α). In the absence of visual disorders, the visual angle limit is 1 minute of arc (1′). The visual angle limit varies between individuals.

The optical resolution or visual acuity of the eye is the ratio of the normal 1′ visual angle limit to the actual visual angle limit α, expressed as a percentage:

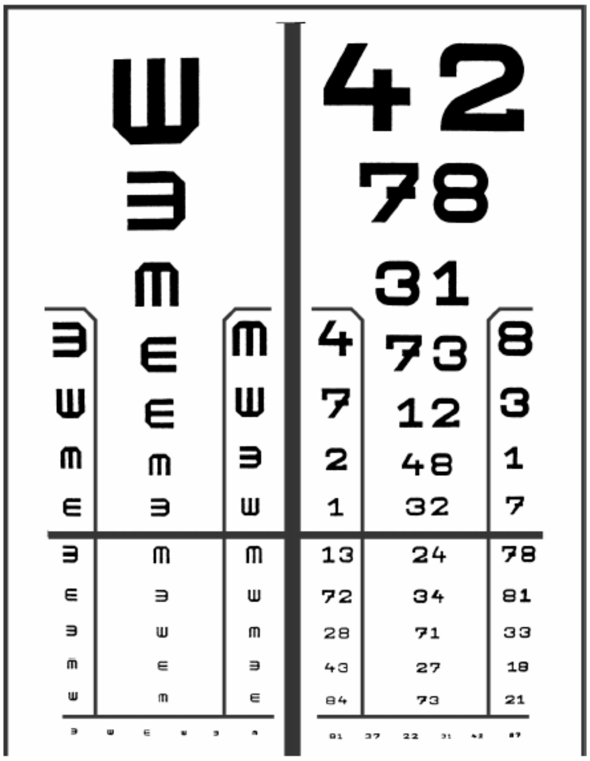
$$\text{visual acuity} = \frac{1'}{\alpha} \cdot 100\%.$$

This means that if the visual angle limit of someone is actually 1′, their visual acuity is 100%. At a visual angle limit of 2′, the visual acuity is 50%, whilst someone with a better than average visual angle limit of 0.8′ has a visual acuity of 125%. Visual acuity is greatest in the fovea centralis and decreases with the distance from it; on the blind spot, visual acuity is 0.

In practice, visual acuity is tested using *visual acuity tables.* Such tables show numbers, letters or signs that get smaller from top to bottom. The size of these signs is chosen so that it should correspond to certain visual angles when viewed from a determined distance. The signs are designed to fit a 5 × 5 grid. The whole sign corresponds to five times the smallest detail.

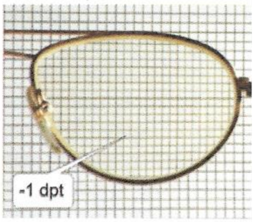


It is hard to design numbers and letters so that each detail in them corresponds to the same visual angle. For this reason, special signs, like the so-called Ammon sign, have been created. These signs have indeed the same level of perceptibility (they are isognostic) and can be made to subtend the same visual angle (they are isogonic). In Hungary, the patient is seated at a distance of 5 m from the visual acuity table. The Hungarian standard for visual acuity testing is the *Kettesy type decimal visual acuity table*. On the right of the table, numbers, on the left, Ammon signs are shown. The top number or sign corresponds to a visual acuity of 10% (10′ visual angle). The numbers or signs above the bottom line require a visual acuity of 100%. Recognising the numbers or signs below the bottom line is only required from people in special jobs (like test pilots).



E. Vision correction

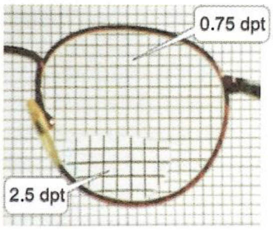
In normal vision (emmetropia), the accommodation of the eye can provide sharp vision between the near point (approximately 25 cm) and infinity. As compared to the normal case, image formation defects can be broken down into two basic types.



negative lens

Short-sightedness (myopia): In a patient suffering from myopia, the axial length (anteroposterior axis) of the eyeball is too large, thus the parallel rays originating at infinity are focused in front of the retina, and instead of a sharp point a blurred spot forms on the retina. The patient sees well in short range, that is, their far point is less than infinity. This defect can be corrected with a diverging (negative) lens.

Long-sightedness (hypermetropia): Some people have shorter than normal axial length of the eyeball, therefore the rays coming from nearby areas are focused behind the retina, and on the retina itself a blurred spot forms. Long-sightedness can be corrected with a converging (positive) lens.



positive bifocal lens

III. MEASUREMENT TASKS

A. Measuring the focal length of lenses

1. Study the lenses given. Determine if they are converging or diverging.

1. Use the converging lenses given to focus the projector's beam on the wall. Use the lens-image distance to determine the focal length and the optical power of the lenses. Determine the focal distance of the first lens, then that of the second lens. Afterwards place the two lenses

together, and determine the focal distance of the combination. Record the focal distances and the optical powers in the lab report.

NOTE: You cannot have a diverging lens form a real image (one which can be projected on a screen). In order to determine the focal length of a diverging lens, it should be combined with a converging lens of known focal length and use the appropriate equation to calculate the focal length of the diverging lens from the resultant focal length of the combination.

B. Image formation of the eye, determining the accommodation ability of individuals

1. Based on length measurements, determine the near (p_p) and far (p_r) points of your own eye. Substituting these data into the formula below, determine your accommodation amplitude.

$$\Delta D = D_\mathrm{p} - D_\mathrm{r} = \frac{1}{p_\mathrm{p}} - \frac{1}{p_\mathrm{r}}.$$

For the near point, a tape measure can be applied to determine distances, whereas for the far point, either use a tape measure or just estimate the distance. Students wearing glasses can perform the measurements with or without glasses.

2. The optical power of an average eye is approximately 60 dpt. What is the size of the image formed on the retina by an object of 1 m in size which is located at a distance of 10 m from the eye?

C. Studying the Kettesy type visual acuity table

1. When testing visual acuity, the patient sits at a distance of 5 m from the table, which contains Ammon signs of different sizes.

2. Stand at 5 m from the visual acuity table, determine which is the smallest sign your eyes can resolve. Measure the line width with a ruler, and calculate your visual acuity.