photo by Marco A. Donnini

CORRECTION of OPTICAL REFRACTIVE ERRORS in DIVERS USING OPTICAL MASKS

part one

INTRODUCTION

Good vision underwater is an important safety factor in diving. More than half of the world's population is affected by refractive errors that require the use of corrective lenses. However, divers often underestimate the problem, wrongly assuming that they can get by with poor vision underwater. Moreover, in our professional experience we have found that many divers do not realise that they don't see well underwater. Another problem is the lack of information about the methods available today that can correct or dramatically improve most errors even underwater.

In order to understand how visual errors can be corrected, we shall briefly describe the most common refractive errors. We shall then illustrate the main advantages and limitations of the use of underwater masks. In the second part of this article we shall describe the principal types of lenses used for correction as well as the various methods used to apply these lenses to the masks.

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ANATOMICAL AND PHYSIOLOGICAL REFRACTIVE COMPONENTs OF THE EYE. THE TOTAL OPTICAL POWER OF THE EYE

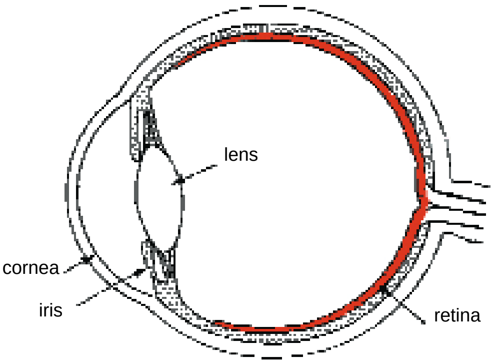


fig.1 Anatomy of the eye

The function of the transparent structure of the eye is to divert rays of light so that they are focused on the retina. The total optical power of the eye is made up of the combined refractive power of the cornea and the crystalline lens **(Fig. 1)**. The first is fixed and the second is variable as a result of a mechanism known as accommodation, which, in young people allows objects located at different distances from the eye to be brought into focus. In order to focus on close objects the power of the crystalline lens increases due to the contraction of a muscle called the ciliary muscle. The optical power of the eye, like that of lenses, is measured in dioptres.

OPTICAL POWER AND VISUAL ACUITY

Optical power is often confused with visual acuity, which is a measure of how much the eye sees (with or without lenses) and is expressed in terms of a fraction, e.g. 10/10 (in English speaking countries the corresponding value is 20/20). Thus, for example, a patient without visual defects would be able to see 10/10 without glasses. A near-sighted patient on the other hand would see 4/10 without glasses, but could attain 10/10 vision using a –1.00 dioptre lens.

THE CORNEA

The cornea is a clear structure in front of the iris that is permanently covered by a very thin, protective tear film. It is the curvature of the cornea that provides most of the eye's focusing power. However, the curvature of the cornea is not the only factor; the low refractive index of air in comparison to that of the corneal tissue also contributes to optical power. The greater the difference in the refractive index the greater the focussing power. When there is water instead of air, as happens when people swim without masks and with their eyes open, the refractive power of the cornea (and therefore that of the entire eye) becomes considerably reduced. This leads to increased temporary hyperopia underwater in a person who has normal vision.

fig.2 Example of how a person with myopia sees

THE IRIS

The iris is responsible for the so-called "colour of the eyes". It is a ring-shaped structure with a central aperture, called the pupil. The size of the pupil changes in response to the amount of surrounding light as a result of a very sensitive nervous mechanism. Its function can be compared to that of the diaphragm of a camera. When there is bright light the pupil contracts in order to avoid being dazzled and the retinal image acquires a higher depth of field. Conversely, in low light conditions the pupil dilates in order to allow more light to enter, but the depth of field of the retinal image is reduced. The constriction of the pupil in the presence of bright light can thus give good vision even for those with slight refractive errors both in water as well as out of the water.

THE CRYSTALLINE LENS

The crystalline lens is a natural biconvex lens situated behind the iris in the eye. Its curvature varies as a result of the contraction of the ciliary muscle. This allows the achievement of a mechanism that is comparable to the "auto focus" mechanism in cameras so that we can bring objects at different distances from the eye into focus. In order to focus on closer objects the brain sends impulses to the ciliary muscle which contracts. The power of the crystalline lens increases in this way, focusing light rays onto the retina.

THE RETINA

The retina is comparable to the film in a traditional camera, or to the CCD sensor in a digital camera. The aim of the entire natural optical system within the eye (cornea, crystalline lens and iris) is to make rays of light converge exactly on the retina. It is only in this way that a sharp image can be produced to send to the brain.

fig.4 Example of how a person with hyperopia sees

THE PRINCIPAL OPTICAL REFRACTIVE ERRORS

MYOPIA

Myopia is a condition in which the individual can see close objects well but is unable to see objects in the distance properly without using minus-power corrective lenses **(Fig. 2)**. The total optical power of the eye is excessive in comparison to the length of the eye. Rays of light coming from distant objects converge too far from the transparent structure of the eye and come to a focal point before they reach the retina. It can be caused by several factors: excessive length of the eyeball or excessive curvature of the cornea or crystalline lens. The eyeball is usually around 23.5mm long on average. The myopic eye is usually longer than normal: for every millimetre of extra length, myopia increases by 3 dioptres. Therefore, the images reach the retina out of focus and the resulting images of objects in the distance end up blurred. The defect is corrected by minus lenses (divergent).

HYPEROPIA

Hyperopia is a visual defect that prevents good vision both close up and far away in old people **(Fig.4)**. A young person with moderate hyperopia can, however, compensate for the error at least partially, using the mechanism of accommodation. In hyperopia the total optical power of the eye is insufficient with respect to the length of the eyeball. The rays of light coming from far away objects do not become sufficiently converged and would theoretically come into focus at a point behind the retina. The error can be corrected using spherical plus lenses (converging).

ASTIGMATISM

In the normal eye, the shape of the cornea resembles that of half a football. The spher-

fig.5 Example of how a person with astigmatism sees. Note that the horizontal markings on the gauge are out of focus while the vertical ones are sharp

ical shape of the cornea means that rays of light coming from a given point in space always reach a focal point at the same point, which, in the normal eye is exactly on the retina. With astigmatism, the cornea is oval and rays of light coming from an external point do not come to a focal point on a single point, but rather on to two lines perpendicular to each other. The retinal image becomes lengthened and more out of focus along one axis compared to the axis perpendicular to it. **(Fig. 5)**. Astigmatism can be myopic or hyperopic and can be corrected with cylindrical minus lenses in the case of the former and plus lenses in the case of the latter.

PRESBYOPIA

Presbyopia is a difficulty in focusing on near objects which usually occurs after the age of 45 years in most people **(Fig. 6)**. Presbyopia is caused by progressive hardening of the crystalline lens. As a result of the hardening the ciliary muscle, which is responsible for accommodation can no longer change the shape of the crystalline lens. In a person who does not have other visual defects, focussing remains fixed for distance vision.

For close vision an additional plus power lens will correct it.

For older divers the problems are associated with the ability to see instruments (diving computer, gauges etc.). Underwater photographers who have presbyopia in particular find it difficult to see the small liquid crystal screens of still cameras and digital video cameras.

The ability to see viewfinders in reflex cameras and Galilean system cameras is not however affected by presbyopia.

Some viewfinders have a control that allows potential hyperopic spherical refractive errors of the user to be corrected, but this is just for visual errors for distance vision and not for presbyopia.

In some cases, increasing the size of images is helpful for those who have presbyopia as well as for those who do not have presbyopia. For example, some underwater housings contain magnifying lenses (plus), which increase the size of the images in the frame counter and the display of the camera. “Magnifying” viewfinders increase the dimensions of the images seen through the viewfinder of the camera **(Fig. 7)**. Presbyopia can be corrected in a number of ways.

fig.6 Example of how a person with presbyopia sees

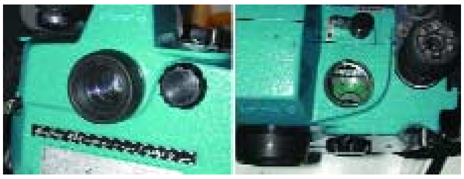


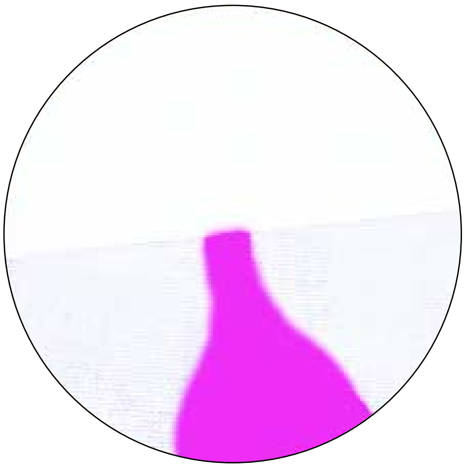
fig.7 Magnification lens and enlargement lenses in the frame counter of the camera

1. Monofocal Plus Lens (That is which only allows focusing of a single plane at a precise distance) for close-up that is chosen based on the average distance of the objects that are to be focused on. It works for people who don’t have visual errors for distance vision. They are mounted onto the lower part of the window in the mask, because we usually look downwards in order to see close up. The disadvantage is that the object has to be moved to a precise distance from the eye. Objects that are closer or further away from the pre-set focusing distance for the lens applied to the mask cannot be seen sharply.

2. Bifocal Lenses. When the person has a visual defect for distance vision and also has presbyopia, two lenses are used for each eye in the mask; one is mounted on the upper part of the mask window and one on the lower part (both on the internal surface of the glass). The upper lens corrects the defect for distance, the lower one for presbyopia. The lower lens only allows focussing at a precise pre-chosen distance.

3. Progressive focal lenses enable the user to focus on objects at different distances by looking at them through different parts of a lens that is constructed in a particular way. The more you look downward through the progression channel, the closer objects come into focus **(Fig. 8)**. In this way, presbyopic people can bring objects at different distances into focus, in contrast to monofocal and bifocal lenses.

fig.8 Progressive lens. The channel of progression is represented in red. The dioptre power of the lens increases in a vertical direction downwards along the progression zone. The distance vision zone is in white. The non-functioning area of the lens is in green.



They are used a lot in glasses, but are rarely used at present in diving masks for technical reasons and because they are costly to produce. They can only be used theoretically with special inserts for holding mask lenses in the mask, which, however, cause a lot of problems.

4. Monovision. This involves using a lens that allows one eye to see clearly for far away, and a lens that allows the other eye to see sharply close up. It is a solution of compromise. Not very many people can put up with this expedient, since only one eye at a time can be used in order to see sharply, while binocular vision is greatly changed for close up as well as for far away.

THE NORMAL EYE UNDERWATER

THE EYE IN DIRECT CONTACT WITH WATER

If you swim underwater with your eyes open without a mask, as mentioned above, the contact of the cornea with the water as well as the air greatly reduces the refractive power of the cornea. Underwater images end up out of focus because they don’t become focussed on the retina, but rather would come into focus at a point behind it. The eye is in a state of increased temporary hyperopia of around 40 Dioptres. Accommodation - which at its maximum reaches around 10-15 Dioptres and then only in children - is not capable of compensating for this error.

Apneists try to save as much air as possible during a dive in order to increase its duration. So as not to waste air in order to equalise the internal pressure of the mask, they use low internal volume masks. The ideal situation would be not to have a mask at all that has to be compensated for, but the mask cannot be eliminated completely because of the necessity for reasonable vision underwater. And so that is why apneists don’t dive without using eyewear. An alternative solution for apneists is to use scleral contact lenses.

THE EYE AND THE FLAT MASK

With the use of the flat glass mask the air/cornea interface is restored cancelling out the above-mentioned problems. But the problems associated with water/glass plane/air refraction are still present however. This results in an apparent increase in the size of images of around 33%. As regards the precision the increase in size varies depending on the distance of the object from the mask, but these variations are small, approximately 3-4 %. In addition, objects appear 25% closer than they are. There is also a reduction and peripheral distortion of the visual field. This is particularly important when looking downwards, because it can cause difficulty in reading and checking instruments and diving equipment. Optic masks have flat glass at the front and thus have all of the above-mentioned refractive problems. The same is true for corrective masks.

THE EYE AND THE DOME PORT MASK

This type of mask, only recently introduced, enables us to eliminate many of the problems associated with refraction that are caused by flat glass (enlargement, apparent closeness of images and reduction of the visual field) **(Fig. 9)**. However, as we shall discuss in more depth later on, they are not without some disadvantages.


fig.9 Mask with a Dome Port (courtesy of Hydro Optics)

THE DIVING MASK

1. The Mask as a Protective Device

Diving masks are considered protective devices and as such are subject to ANSI and EU safety standards. These strict standards ensure that they are resistant to impact. The mask glass is generally treated with a tempering process that increases its resistance. The tempering can be achieved using heat and this increases the resistance to impact by 2-3 times. Another process involves immersing the glass in particular chemical solutions. This provides a better optical result and increases the resistance to impact 5-10 times. However, when glass that is tempered using heat (non-chemically) breaks, it creates very small fragments that are not very sharp, and that are thus less dangerous than large, sharp shards, which are more likely to cut the skin. Tempered glass usually has the letter T printed on the edge.

2. Compensation of Pressure inside the Mask

One of the problems of diving masks is due to the need to equalize the internal pressure of the mask with the external pressure of water at whatever depth underwater. Without going into the details of how this happens, which are explained in training courses for divers, it suffices to say that failing to compensate for the pressure of the mask can lead to a suction-effect which can result in damage to the external surface of the eye such as the conjunctiva and subconjunctival haemorrhage. In rare cases, the internal structure of the eye can also be injured as a result of hyphema. In full-face masks equalization occurs automatically with breathing.

fig.10 10 Types of mask. One, two, three, four and six-window

3. Number of Windows in the Mask

The number of windows in diving masks that are currently available varies from 1 to 6 **(Fig. 10)**. Those with a single window have a single pane of glass, which is generally flat and have a field of vision that is slightly wider. Full-face masks are also of this type. Masks with two windows have two front windows separated by a pocket for the nose. The majority of masks that are suitable for optical corrective lenses are of this type. The two front windows should always be on the same plane, otherwise prism effects are caused that can cause disturbance of binocular vision and, in extreme cases, diplopia (double vision). Masks with three windows have a single front window and two side windows in order to increase the field of vision. Masks with four panes have two front panes and two side panes. Finally, there is a mask that has two front windows, two side windows and two lower windows. Lenses for presbyopia can be mounted on the two lower panes to aid in reading instruments.

4. Pantoscopic Tilt

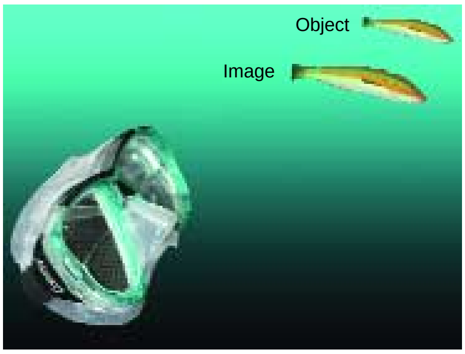
The pantoscopic tilt is the downward tilt of the plane of the front window of the mask **(Fig. 11)**. The greater the tilt, the greater the shift of the visual field downward; and the lower visual field is considered more useful. In fact, in most visual activities the individual normally looks slightly downwards rather than directly in front of him/herself. In addition, the plane of the glass should be perpendicular to the visual axis of the eye, which as we have said is generally straight down. Therefore, the glass of the mask should be always tilted downwards. This type of mask has only begun to appear recently on the market, in imitation of the position of the lenses in standard glasses.

fig.11 Pantoscopic Tilt

5. The Visual Field

A monocular visual field is all of the points in the space seen by an unmoving eye. The binocular field of vision is the combination of two monocular fields of vision, which overlap in a central zone, called binocular vision. The greater the visual field the greater the ability of the diver to immediately identify objects and potential sources of danger without moving his/her head. The field of vision of a diving mask is lower than that of the naked eyes in air in the first place because of the peripheral obstacle caused by the plastic of the mask (blinkered vision effect). The design of the mask can have a bearing on this aspect of the problem. The visual field of a flat glass mask in water is however always lower than that in air **(Fig.12)**. The reduction in the field of vision underwater is due to refraction. As a result of a physical phenomenon called *Total Internal Reflection*, the rays of light coming from the most external zone of the visual field do not penetrate inside the mask, but become completely reflected. The strong reflection that is often seen on the edge of a diving companion's mask is light that does not reach the person's eyes, but rather is totally reflected. This is an easy way of demonstrating the reduction in the peripheral visual field that occurs with flat glass masks. All masks with side windows have the advantage of better peripheral vision. However, each window is subject to the phenomenon of total internal reflection. The visual field is thus fragmented. When an object moves from the side window to the front window or vice versa, there is an optical "jump", which is caused by refraction and the internal visual obstacle created by the mask and which can be distracting. Others consider that the fragmentation of the visual field that occurs with masks with side windows is not very noticeable and is a small trade-off for the improved peripheral vision. Full-face masks have bigger windows, which give a greater visual field. The front flat part of the glass however has the same limitations as standard masks (total internal reflection, chromatic aberra-

fig.12 Underwater objects appear bigger and closer when seen underwater with a flat glass mask



tion etc.) The curved part at the edge, however, while not allowing precise focussing does allow objects at the edge of the visual field to be identified.

6. Enlargement of images and apparent closening of objects

As already stated, flat glass masks cause an apparent increase in the size of images of around 33% and cause objects to appear 25% closer **(Fig.13)**. Studies have however demonstrated that the brain adapts rapidly to the underwater environment so that initial errors in judging distances become significantly reduced during the course of a dive (Ross et al). Moreover, the estimation of distances and sizes improves with diving experience.

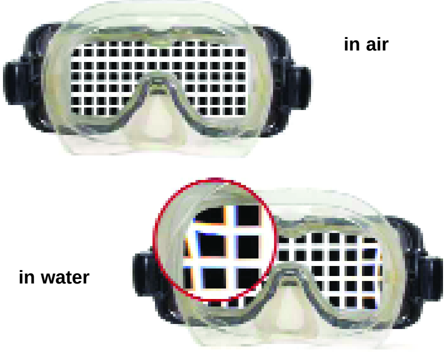


fig.13 Pincushion distortion and chromatic aberration with a flat glass mask (courtesy of Hydro Optix)

7. Peripheral Distortion of the Visual Field and Chromatic Aberration

With flat glass masks peripheral vision is thus reduced. However, in addition, the visual field as seen through the mask is subject to distortion at the edges as a result of refraction. The edges of the visual field as perceived through the mask undergo a distortion called “pincushion distortion”. In addition, light is dispersed as a result of the prism effect that causes light to split up into the colours of the visible spectrum **(Fig. 14)**. Generally, however, this distortion and aberration have little impact on the ability of the diver to see.

8. Accommodation underwater.

As mentioned above as a result of the refraction in water, everything appears to be closer and bigger. An object at 100 cm appears 33% larger and 25% closer. Depending on the distance of an object from the eye it is thus necessary to accommodate more underwater. It is as if the object were closer, and in presbyopic divers the closer the object the greater the power of the lens necessary to correct presbyopia and focus properly. The enlargement of images that occurs underwater with flat glass masks (33%) can assist in improving vision in cases of early presbyopia, but usually it is not enough to resolve the problem.

9. Impaired Vision due to Fogging

It is generally thought that mask fogging is caused by differences in temperature between the inside and the outside of the mask, but this only has a small bearing on the problem. The truth is that masks are dirty. The inside of the mask has a humidity rate of nearly 100% and the vapour condenses in tiny drips on every microscopic fragment of dirt, even on the uneven part of the glass. In this way mask fogging occurs. Anti-fogging solutions for masks contain a detergent that cleans the internal surface of the glass so that on condensing the vapour becomes stratified rather than coagulating in tiny microscopic drops. Saliva can also clean the glass, but this method, which used to work well with the old rubber masks, is less effective with silicone masks. During the manufacture of the mask, the silicone is coated with a chemical agent, which aids in removing it from the mould. This residual coating makes the glass dirty and causes it to fog even when saliva is used. Because of this, new masks should be thoroughly cleaned before use. Also, microscopic silicone particles can continually fall on the glass over the years and combine with other factors such as suncream, make-up and nasal secretions. This necessitates the use of cleaning and antifogging solutions in spray or gel form, which are specially formulated so as not to irritate the eyes.

fig.14 Spherical pre-ground lens

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