Cornea–Contact Lens Interaction in the Aquatic Environment

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Purpose: A large population of ametropic scuba divers wear contact lenses. We discuss optics and corneal physiology, as well as the types of contact lenses that are appropriate for underwater activities.

Methods: We reviewed an extensive body of literature to formulate guidelines to aid the contact lens fitter in satisfying individual sport diver's needs.

Results: Optical factors such as image displacement and light wavelength shifts require that contact lenses for underwater use be suitably modified. Underwater images appear nearer and larger (requiring greater accommodation) and are made up almost exclusively of the short wavelength end of the spectrum. Correction of presbyopia, in particular, is influenced by these factors. For example, presbyopic contact lens-corrected myopes require greater near adds underwater than when viewing the same objects in air. In general, presbyopes should consider monovision correction to facilitate underwater visual tasks. Although divers wearing rigid gas permeable contact lenses run the risk of more corneal problems than soft lens wearers if conservative ascents are not adhered to, there are no compelling reasons to change lens types in patients who are already fully adapted. Soft contacts, while very stable on the eye during diving, present a greater risk of lens contamination by sea or fresh water exposure. However, the latter problems are easily overcome by using disposable soft lenses.

Conclusion: In this paper, we present several suggestions for lens material, modifications required for underwater ametropia correction, and wearing modalities for the sport divers. An understanding of the dramatic changes that impact the properties of light, corneal physiology, and visual perception which accompany the diver below the surface will enable the contact lens fitter to design a lens appropriate to the needs of the individual patient.

Introduction

The underwater scene observed by the scuba diver under optimal conditions may be breathtaking, but it can also be visually unsettling. Consider, for example, that objects underwater are illuminated primarily with blue-green light and undergo a 25% displacement toward the eye. Furthermore, light scatter reduces the visibility of even large objects. Such constraints of vision are compounded even further for divers requiring ametropic or presbyopic corrections. The latter group probably amounts to one-third of the more than 3 million certified divers in the United States, since 20% are over age 40, and about 25% of most populations are 6 D or more myopic.[1]

The wearing of contact lenses by a growing portion of the sportdiving population has long been accepted as the most convenient and optically appropriate solution.[2–6] But the attendant problems associated with lens wear while diving can be quite complex and not entirely free of danger to the eyes.[7–9] Indeed, a huge international literature exists detailing many aspects of lens wear while engaged in underwater activity.[10] It is the specific purpose of this study to describe the relevant parameters before attempting to fit the ametropic sport diver who (as opposed to commercial divers) typically limit the depth and duration of a dive.

Before considering the factors involved in contact lens dispensing to divers, it is important to recognize first how image formation in an aqueous medium impacts on lens design decisions.

The modifying properties of water on light

There are three major factors which affect image formation underwater: (A) scatter, (B) wavelength shifts, and (C) image displacement.

Scatter: Scatter occurs when photons encounter suspended particles of organic and inorganic matter. It varies widely with geographical location; but regardless of the dive locale, the degree of turbidity greatly affects the amount of light available for vision, particularly along the diver's line of sight. In the best circumstances, it has been calculated that only 20% of surface light reaches to a depth of 33 feet.[11] The consequent light loss, by itself, obviously reduces the perception of small high contrast objects, but more importantly, scatter also attenuates the contrast (defined by the luminance ratios of object to its background) which affects the visibility of objects of *all* sizes.[12] Furthermore, light striking small particles also produces back scatter, making objects beyond the point of regard even less visible.

Scatter is not the only phenomenon that reduces light quantity below the water. As the obliquity of light incident on the surface changes with time of day, the amount of light steadily diminishes as the critical angle in water (48.6 degrees) is approached. Beyond this angle, the quantity of light actually entering the water is markedly reduced.

Wavelength Shift: Long wavelengths are quickly absorbed entering water, thus producing a *blue shift* even at modest depths.[13,14] Under these circumstances, the human eye becomes myopic[15] because of its chromatic aberration (Figure 1). Restricting incident light to the short wavelengths also reduces visual acuity. This derives from the fact that contrast sensitivity and spatial resolution diminish when stimuli are composed of bluish light.[16,17] Therefore, while it may at first appear that the myopia induced by the prevalence of short wavelengths may aid accommodation (due to simple object-image displacement considerations) in near point situations, there is still an overall degradative acuity effect[15]. In fact, we will show that any accommodative advantage produced by a blue shift is overwhelmed by the focusing demand imposed by underwater image displacement.

Vision problems induced by the shift to short wavelengths may be lessened by using a tinted mask (Figure 1). Some manufacturers of diving masks (such as Sea Vision, St. Petersburg, FL) have attempted to color compensate for the shift by using yellow or pink faceplate tints, though the extent to which overall light transmission is reduced by this maneuver is unknown. It should also be recalled that if the diver is old enough (i.e., 50 years and over) to have significant ocular lens yellowing, a natural blue absorbing filter is produced. In fact, by the time we reach age 60 only one-third of short wavelengths incident on the eye reach the retina; by 70 years of age another one-third is lost.[18]

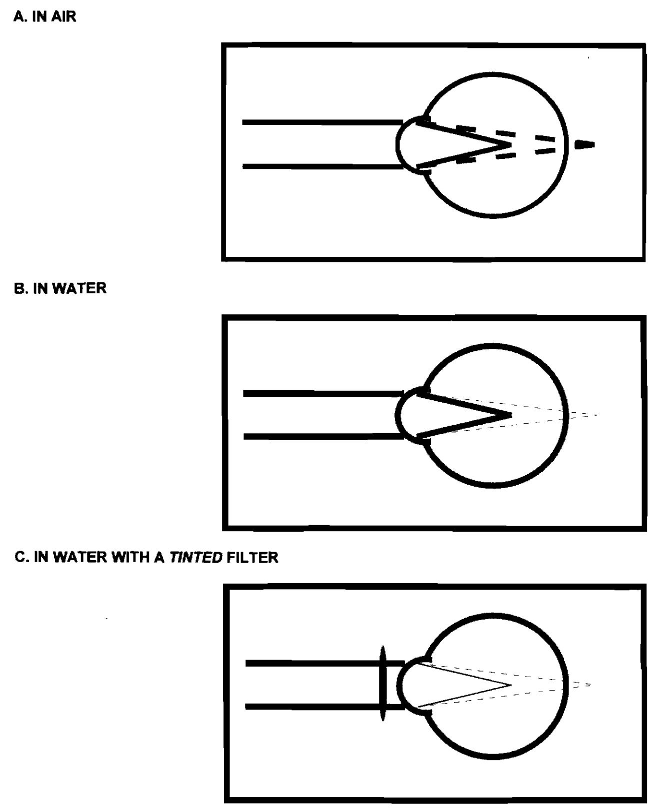

Figure 1 *A. Light incident on the eye is dispersed to form a chromatic interval. Short wavelengths (solid line) are focused about 1 D in front of the retina and long wavelengths (dashed line) about 0.50 D behind the retina.* ***B.*** *In water, the long wavelengths are selectively absorbed producing a chromatic interval composed almost entirely of short wavelengths; thinner lines indicate absorption has taken place. C. By placing a tinted filter of appropriate color (yellow or pink), balance is restored between the short and long wavelengths.*

Image Displacement: A forward displacement of an object under water (toward the face mask) is affected by the difference in index of refraction between air and water ($n_{water} - n_{air} / n_{water}$).[19] Therefore, underwater objects appear approximately 25% closer to the faceplate than their true distance.[17] While this foreshortening produces a 1.25× magnification, the displacement also requires an increased accommodative effort to maintain object-image conjugacy on the retina. Combined with the shift to the blue wavelengths, image displacement places an onerous accommodative burden on the scuba-diving myopic presbyope. Figure 2 shows the additional amount of accommodation required to maintain a focused image at different distances. Note that even at the 70 cm, 0.5 D more accommodation is required.

Vision underwater

With and Without a Mask: The primary purpose of a face mask is clearly not to *protect the eyes*, but to provide a chamber of air within which the optics of the eyes are preserved. Without a mask, the water-eye interface reduces the refractive power of

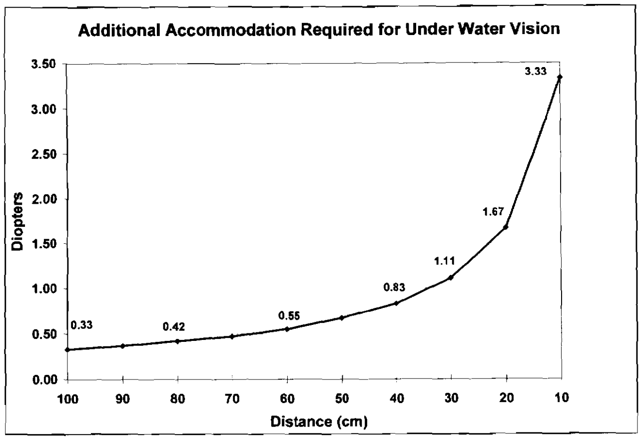

Figure 2 *Because objects underwater appear 25% closer to the eye, more accommodation is required to retain object-image conjugacy at the retina. The graph shows that at typical scuba diving viewing distances, 0.75 to 1.00 D of additional accommodation are needed.*

the eye by two-thirds.[20] While very high myopes may suffer less under such circumstances, no diver wishes to have vision further compromised in an environment which degradates retinal imagery.[21]

We will not discuss the many disadvantages of a spectacle correction mounted in the mask except to point out the obvious fact that vision is lost both during the dive if the mask is removed in an emergency, and upon reemergence when the mask is normally removed. Compared to the material expenses of diving equipment and travel, any required ametropic correction with contact lenses is a trivial expense, since scuba enthusiasts having finally arrived at their favorite undersea grotto, certainly wish to view the scene with the utmost clarity.

Contact lens wearing considerations

Effect of Pressure: The increased atmospheric pressure encountered as the scuba diver descends has been studied intensely by physiologists and physicians for over 50 years. Interestingly, one of the first effects noted very early on, long before underwater activity became commonplace, was the formation of gas bubbles in the vitreous and retinal circulation of various animals subjected to conditions of inadequate decompression.[22] However, the vast majority of recreational divers do not engage in diving requiring decompression and ophthalmic manifestations of decompression sickness are uncommon.[23] Nevertheless, minor ocular problems are known to be associated with diving.[24,25] Here we shall consider only the specific problems of cornea–contact lens interaction that may be experienced by the sport (and not by the commercial) diver.

First, it should be stated that there is no effect of increased atmospheric pressure on the corneal curvature underwater since the globe is filled with an incompressible fluid. Indeed, keratometry performed in a hyperbaric chamber has demonstrated that there is no change in K-readings even at a simulated depth of 165 feet.[26] But increased pressures do affect the partial pressure of the gases within the mask. At sea level, the atmospheric pressure equals 1 bar or 14.75 pounds per square inch and doubles every 33 feet of descent. At a depth of 33 feet, therefore, the partial pressure of inhaled oxygen is twice that of the surface and the partial pressure of oxygen within the mask is concomitantly increased. The increased pressure also causes more dissolved gases to enter tissues as compared with surface conditions. When pressure is reduced (during the ascent), these dissolved gases are expelled. The release rate is dependent on the ascent rate.

There are a number of variables governing gas release (*off-gassing*), such as depth and duration of the dive. In addition, tissues that have a high rate of blood flow and high circulation are considered *fast compartments* and off-gas more quickly than tissues with minimal blood flow. The cornea and tear film are exceptions to this rule. Although there is no blood flow, the gas-dissolving properties of these tissues (and their purging) is very rapid. Such a fast exchange may also produce bubble formation beneath a contact lens, an event which may decrease acuity. The mechanics of this phenomenon for rigid gas permeable (RGP) lenses (rarely observed under soft lenses) is described below.

Bubble Formation Beneath a RGP Contact Lens: Bubble formation under RGP lenses fabricated from a great variety of materials have been reported by many investigators.[9,27–30] The actual formation of bubbles is simple and based on a combination of two factors: tear dynamics and Boyle's Law. There is general agreement that as the diver ascends, outgassing (probably of nitrogen, although this is controversial) from the cornea and from the tear film produces the bubbles trapped under the contact lens.[27,30–32] As the diver approaches the surface, the size of the bubbles increases in diameter. Poor tear exchange resulting from a tight lens or faulty blink behavior then traps the bubbles behind the lens.[27,33] If the bubble diameter exceeds that of the tear film depth, spherical impressions (dimpling) will be impressed on the cornea producing blurry vision.[25,34] Typically, blink mechanics *are not* normal during ascent because divers tend to stare through the mask while looking upward in an attempt to orient the body using vision.

In one study, the bubbles disappeared within 15 to 20 minutes after the diver returned to surface atmospheric pressure.[3] In another study, it should be noted that when divers wore PMMA lenses, bubbles were noted even at modest depth and duration, the effect being easily resolved by lens fenestration.[27] For recreational diving, it has been found that appropriately controlled ascent greatly reduces bubble formation.

Oxygen Supply to the Cornea within the Mask: Normal oxygen metabolic requirements of both the cornea and conjunctiva are dependent on the intrinsic oxygen uptake of these tissues as well as their surface area. The rate of oxygen uptake is 7 $\mu L/cm^2$/hour by the cornea and 1.5 $\mu L/cm^2$/hour by the conjunctiva. Taking into account the relevant surface areas, one can calculate that the oxygen requirement for both eyes is about 30 μL O_2 μL/hour. Despite the fact that sport divers breathe compressed air (and not compressed oxygen), it is readily apparent that there is ample oxygen available to the corneas considering that: 1) to avoid *mask squeeze* the diver exhales through his nose into the mask, and 2) the volume of air in a mask is about 200 mL. Consider also that the concentration at the beginning of the dive is 20.8% oxygen and at the end of the dive might be equivalent to expired oxygen (16%). We can calculate that the total volume of oxygen is 3,200 μL, more than 100 times the requirements of the conjunctiva and the cornea. Corneal hypoxia is no more likely to occur while diving than on the surface.

Lens Loss: Surprisingly, lens loss is not a problem in scuba diving.[35–37] Soft lenses are unlikely to become dislodged and RGP lens wearers report little difficulty in maintaining a lens on the cornea even when a mask is flooded. Some dive enthusiasts have submerged their heads into water without a mask to demonstrate that by half closing the eyes a RGP lens will not displace.[2,35] Clearly, the same partial lid closure maneuver would work equally well with soft contacts, though because of the lens size and fitting characteristics, displacement (and, ultimately, loss) is rarely a problem. However, these observations must be tempered by the fact that most of the studies and anecdotal evidence is provided by *experienced lens wearers.*

Lens Type Recommendations: Adapted RGP lens wearers, regardless of lens type, should not be encouraged to change lens types. The literature is replete with contradictory data on RGP lens loss during mask filling, induced corneal edema, and the like.[27,30,38] A careful reading of these reports clearly demonstrates, however, that the RGP lens wearer is innovative, daring, and extremely adaptable! Only a negative patient experience should entice the examiner to change lens type. After all, a well fit RGP lens allows more oxygen to the cornea than most soft lenses, does not allow irritating substances to be absorbed by the lens material even after prolonged exposure, is durable, and requires minimal care.

But the majority of ametropic scuba divers (like the general population) wear soft contact lenses and many of the same considerations we ask of surface lens wear apply to underwater use. For example, does a soft lens prevent the cornea from receiving sufficient oxygen in the confines of a mask? In point of fact, the cornea probably gets *more* oxygen through the lens underwater than on the surface. As a diver descends, the partial pressure of oxygen increases so that even a soft lens of modest Dk will transport more oxygen as compared with surface conditions. In addition, it is generally reported (and confirmed by the authors' own experience) that the very humid mask interior makes soft lenses extremely comfortable for underwater wear.

Lens wear precautions

What then are the contraindications for soft lenses during dive activity? As compared to RGP lenses, hydrophilic lenses absorb and retain any surrounding fluid. If a mask becomes filled with sea water and not purged quickly enough, the soft lens wearer's eyes may become very irritated. For unlike lakes or swimming pools, sea water may be 25 times more hypertonic than tears. However, the degree of irritation is no more than that experienced by a swimmer wearing no lenses. It should also be noted that soft lenses soaked in hypertonic solutions tend to fit looser.[33,39] But the accidental accumulation of sea water in a lens

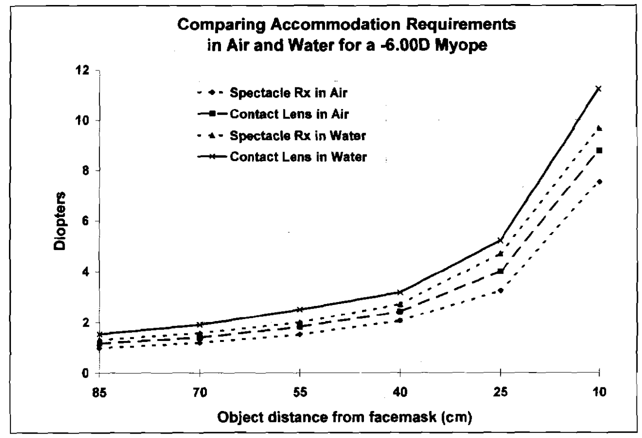

Figure 3 *Underwater activity imposes a double accommodative burden on the contact lens corrected myope brought about by both the contact lens optics and the forward image displacement. For example, the contact lens corrected myope viewing an object at 40 cm must accommodate 1.50 D more than when viewing the same object through spectacles in air.*

during scuba or snorkeling activities is a rare occurrence, and no special lens fitting considerations are required.

However, the absorption of water (particularly fresh water) by soft lenses clearly increases the possibility of serious infection.[40,41] Lenses, RGP or soft, should be thoroughly purged in a rinse solution containing disinfectant after surfacing, even after small exposures to water during the very limited dive times incurred by the recreational diver. We suggest the use of disposable lenses (such as the Vistakon Acuvue Daily Wear), since removing and disposing of a lens immediately after a dive, and rinsing out the eye with artificial tears containing disinfecting preservative before inserting a new lens, will greatly reduce the risk of corneal or conjunctival infection.

One often overlooked problem is that defogging chemicals are often applied to the inside of masks; divers wearing soft lenses should minimize the use of such agents, since the lenses may absorb them and be a source of irritation.

Ametropic correction using contact lenses

The Young Myope: For myopes under age 40, with at least 4 D of accommodation, the main concern is simply correcting the additional myopia incurred by the blue shift. The actual amount of additional minus required can be ascertained by using the duochrome test during the contact lens fitting exam. For example, the examiner may wish to overcorrect with enough minus so that the patient reports that letters on the green side of the red-green chart appear darker. The additional amount of minus power (probably between –0.50 and –1.00 D) should suffice. If the patient has color compensation filters built into the face mask, the duochrome test should be performed with the mask over the contacts.

Theoretically, a low myope of about –0.50 D may not require any correction while underwater because of the 1.25% magnification. But such a patient may still be myopic because of the blue shift. Even the emmetrope may require some minus underwater because of the color shift. In the latter case, however,

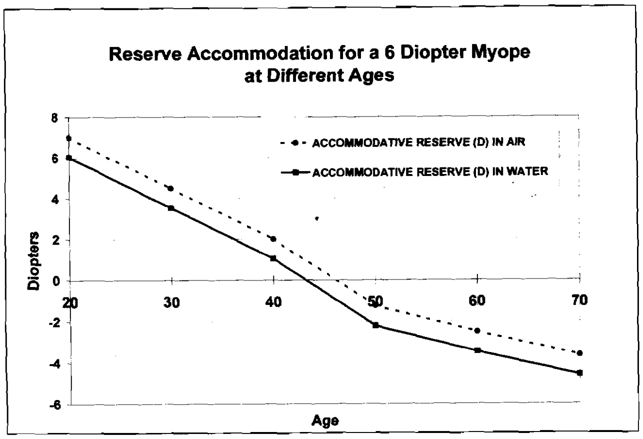

Figure 4 *At age 40, the contact lens corrected 6 D myope can focus on an underwater object placed 25 cm away and still have about 1 D accommodation in reserve. However, 10 years later, no reserve is left and 2 D of add are required in the same viewing situation. The actual amount of addition over the distance Rx is indicated by the negative numbers.*

a compensatory tint in the face mask should prove adequate.

The Myopic Diver with Presbyopia: The demographics of scuba diving indicate that the fastest growing segment are persons over age 40. Because of limitations imposed on vision (due to scatter and turbidity), the visual attention of the sport diver is usually restricted to objects ranging in distance from about 3 m to 15 cm. In addition to age-related accommodative loss, more accommodation is required when myopes switch from spectacles to contact lenses.[42] Figure 3 compares the accommodative demand made when a –6 D (spectacle corrected) myope with the Rx on the face mask wears contact lenses while viewing objects at a variety of distances in air and water. At 40 cm, about 1.5 D more focusing is required when wearing a contact lens under water than when viewing the same object in air using the equivalent spectacle correction. If a closer viewing distance is required, say while checking a depth gauge or wrist watch, the extra accommodation may exceed 2 D. A cautionary note is worth mentioning. In addition to the extra focusing effort by the lens wearer (Figure 3), there may also exist a further accommodative burden if the contact lens Rx was over-minused in order to compensate for the blue shift. Of course, if a diver has only a low degree of myopia (less than –3 D), then the additional accommodation required is significantly less.

It is obvious from the above that careful consideration must be given to the degree of presbyopia in an individual patient. Since accommodative reserve is age-related, we have graphed in Figure 4 the extant reserve for the 6.00 diopter contact lens corrected myope viewing an object 25 cm away for different ages. Again, the comparison made is between air and underwater viewing; minus numbers indicate how much plus must be *added* to the Rx in order to focus on the object. Note that a 50 year old diver requires almost twice the add power when viewing the object underwater as in air.

Hyperopia and Pseudophakia: Because the blue shift underwater aids hyperopic correction, less overall plus may be required. Additionally, when the hyperope switches from spectacles to contacts, *less* accommodation is required to focus on near objects. However, image displacement underwater still requires that additional plus (similar to the presbyope) be added to the contact lens Rx.

It is not known how many divers still pursue the sport after receiving implants following cataract surgery. But it may be assumed that their numbers will increase as the general population of divers increases. Again, whatever add is required in air must be increased to account for the forward image displacement that occurs under water. Since the blue shift and chromatic aberration of the eye would impact pseudophakics more than the general population, it is highly recommended that a face mask with a compensating tint be used.

Monovision: If a patient already wears one contact lens adjusted for near vision, then it only remains for the power to be increased (Figure 4). Thus, a 50 year old 6 D myope requiring a +1.25 D monovision add in air would need about +2.00 D when he dives. *Any* degree of myopia increases the accommodative burden, though the actual amount of additional add is more related to object displacement than refractive error. Interviews with presbyopic divers reveal excellent results while wearing a monovision contact lens correction. Presbyopic divers wishing to try monovision, should be tested in the office with the usual fitting techniques, keeping in mind that additional strength may be required in the near vision eye.

Are there disadvantages in wearing a monovision Rx while diving? For example, do we lose 3-D clues? Since there are gross spatial distortions underwater and distance estimation and stereoacuity are so poor to begin with, professional divers require special courses to relearn hand-eye coordination skills.[11,12,42–45] But for sport divers, whose main enjoyment is passively viewing the underwater scene, we need not be overly concerned that monovision will pose a problem. In any case, depth cues using non-stereo vision are usually gained by experience. However, in special instances, such as underwater photography in which distance estimation is critical (the camera must be set according to the subject's distance), monovision may prove troublesome.

Finally, there may be a small number of patients who are already adapted to some type of bifocal contact lens. In such cases, one need only inquire whether the current bifocal lens add is sufficient for the near tasks encountered by the patient during diving activities. However, since bifocal lenses are costly, monovision or a combination of a bifocal and distance lens should be suggested as an alternative visual correction.

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