Published in final edited form as:
Optom Vis Sci. 2011 September ; 88(9): 1119–1126. doi:10.1097/OPX.0b013e318222365e.

Determining spherical lens correction for astronaut training underwater

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Abstract

Purpose—To develop a model that will accurately predict the distance spherical lens correction needed to be worn by National Aeronautics and Space Administration (NASA) astronauts while training underwater. The replica space suit's helmet contains curved visors that induce refractive power when submersed in water.

Methods—Anterior surface powers and thicknesses were measured for the helmet's protective and inside visors. The impact of each visor on the helmet's refractive power in water was analyzed using thick lens calculations and Zemax optical design software. Using geometrical optics approximations, a model was developed to determine the optimal distance spherical power needed to be worn underwater based on the helmet's total induced spherical power underwater and the astronaut's manifest spectacle plane correction in air. The validity of the model was tested using data from both eyes of 10 astronauts who trained underwater.

Results—The helmet visors induced a total power of −2.737 D when placed underwater. The required underwater spherical correction (F_W) was linearly related to the spectacle plane spherical correction in air (F_{Air}): $F_W = F_{Air} + 2.356$ D. The mean magnitude of the difference between the actual correction worn underwater and the calculated underwater correction was 0.20 ± 0.11 D. The actual and calculated values were highly correlated (R = 0.971) with 70% of eyes having a difference in magnitude of < 0.25 D between values.

Conclusions—We devised a model to calculate the spherical spectacle lens correction needed to be worn underwater by National Aeronautics and Space Administration astronauts. The model accurately predicts the actual values worn underwater and can be applied (more generally) to determine a suitable spectacle lens correction to be worn behind other types of masks when submerged underwater.

Keywords

Refraction; Geometrical Optics; Optical Design; Presbyopia; Astronaut

INTRODUCTION

The refractive power of the anterior corneal surface (refractive index ~ 1.376) is largely neutralized when placed in direct contact with water due to water's similar refractive index (~1.333).[1] This anterior corneal surface power can be restored to its native condition by

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reinserting a layer of air in front of the cornea, as when wearing swimming masks or goggles with planar surfaces. However, the use of swimming masks or goggles with non-planar surfaces introduces additional optical power due to their curvature and the differing refractive indices of water (outside the goggle's surface) and air (inside the goggle's surface).[2]

One group of individuals who commonly use masks with non-planar surfaces are National Aeronautics and Space Administration (NASA) astronauts. Preflight training for simulating weightless-conditions and practicing extravehicular activities (EVAs) (or work done outside of the spacecraft) is conducted underwater in the NASA Neutral Buoyancy Laboratory (NBL) as shown in Fig. 1. Astronauts typically perform 1 to 3 EVAs per mission and spend about 30 hours training underwater in the NBL for each EVA conducted in space. While performing their training in replica space suits, astronauts must look through their helmet's curved visors, which introduce refractive power when submerged in water. Consequently, astronauts (many of whom are presbyopic) need to wear an altered spectacle correction for distance to compensate for this additional refractive shift when underwater. Depending on the level of presbyopia and particular training demands, a spherical power of +2.00 D to +2.50 D is traditionally added to an astronaut's manifest distance correction when training underwater. Based on feedback from the astronaut, the power of the underwater correction is iteratively refined after each session until a final correction is subjectively reached. Although this method has successively corrected astronauts for underwater training, it is empirical and subject to trial and error. The goal of this work was to better define an initial underwater correction by objectively calculating the optimal spherical correction to be worn underwater by an astronaut based on their native distance correction (in air) and the properties of the helmet's visors. These methods can be applied to any type of swimming or diving mask when worn underwater.

METHODS

Helmet Visor Properties

The helmet in the astronaut's NBL-modified space suit consists of two visors (Fig. 2a). The outermost visor of the helmet will be referred to as the "protective visor" and the innermost visor will be referred to as the "inside visor." The protective visor is made of acrylic, having a refractive index of 1.49 (at 589 nm) and an Abbe number of 55.3. The inside visor is made of polycarbonate, having a refractive index of 1.586 (at 589 nm) and an Abbe number of 29.9.

The optical power of the front surface of each visor was measured using a lens clock at the center and outer edges of the visor. These power measurements were converted into curvature measurements by incorporating the fact that the lens clock was calibrated for a refractive index of 1.53. Fig. 2b and c show the radii of curvature calculated at each measured position for the protective and inside visors. Neither visor is completely spherical throughout its entire profile. However, curvature is fairly uniform over the central and lower portions of each visor through which the astronaut looks. Therefore, the central-most values of 147.2 mm and 124.7 mm were used as the front surface radii of curvature for the protective and inside visors, respectively, in subsequent calculations. Based on measurements of the protective visor's bottom edge, both visors were assumed to have a uniform 2-mm thickness (as it was not possible to measure the thickness of the inside visor). Because of this 2-mm thickness, the back surface radii of the protective and inside visors were taken to be 145.2 mm and 122.7 mm, respectively. The visors were separated by a thickness of approximately 2 mm.

Modeling the Visor-Induced Power Underwater

When training in the NBL, the space suit helmet is completely submersed underwater, as illustrated in the vertical cross-section in Fig. 3. The small gap between the protective and inside visors becomes completely filled with water when submerged in the tank, rendering the protective visor's equivalent power, $F_{eq\text{-}PV}$, to be approximately zero. The protective visor's front and back surface powers ($F_{1\text{-}PV}$ and $F_{2\text{-}PV}$, respectively) were calculated using the following equations:

$$F_{1-PV}=\frac{n_{PV}-n_{water}}{r_{1-PV}} \qquad F_{2-PV}=\frac{n_{water}-n_{PV}}{r_{2-PV}} \quad (1)$$

where

n_{PV} = refractive index of protective visor = 1.49

n_{water} = refractive index of water = 4/3

$r_{1\text{-}PV}$ = front surface radius of curvature of protective visor = 147.2 mm

$r_{2\text{-}PV}$ = back surface radius of curvature of protective visor = 145.2 mm

Substituting these values into Eq. 1 yielded front and back surface powers of +1.064 D and −1.079 D, respectively. The equivalent power ($F_{eq\text{-}PV}$) of the protective visor/water system could then be calculated using the following equation:

$$F_{eq-PV}=F_{1-PV}+F_{2-PV}-\frac{d_{PV}}{n_{PV}}F_{1-PV}F_{2-PV} \quad (2)$$

where

d_{PV} = thickness of protective visor = 2 mm

When surrounded by water, the protective visor had an equivalent power of −0.013 D and acted as an extremely mild diverging thick lens.

To illustrate the mild diverging effect of the water/protective visor/water interfaces on the propagation of an input beam of parallel light, ray tracing was performed (Fig. 4) using Zemax optical design software (Zemax Development Corporation, Bellevue, WA). (It is important to note that while Zemax ray tracing was used to illustrate the model, it was not required to find the solution.) For an arbitrarily selected input beam diameter of 200 mm, the beam diameter at the back surface of the visor was 199.53 mm. As shown in Fig. 4, the output beam diameter measured at the spectacle plane (taken to be a typical value of 60 mm behind the inside visor's back surface) was 199.64 mm, verifying that the beam very slowly diverged as the image plane moved further from the visor. Because of the very small equivalent power of the protective visor/water system and the negligible change in beam diameter with increasing distance, we ignored the impact of the protective visor on the overall change in power in subsequent calculations. Therefore, the water/protective visor/ water layers were effectively treated as a single layer of water, requiring us to examine only the impact of the water/inside visor/air interfaces on the incident light.

Figure 5 shows the propagation of a parallel input beam of light through the water/inside visor/air interfaces to the spectacle plane (located 60 mm behind the back surface of the inside visor). When immersed underwater, the inside visor caused the emerging light to diverge, mainly due to the visor's curvature and the refractive index difference between the polycarbonate visor and air. For an arbitrarily selected input beam diameter of 180 mm (chosen for illustration purposes), the output beam diverged to a diameter of 204.84 mm at the spectacle plan. This observation was confirmed by calculating the equivalent power of the water/inside visor/air system, $F_{eq\text{-}IV}$, given as:

$$F_{eq-IV}=F_{1-IV}+F_{2-IV}-\frac{d_{IV}}{n_{IV}}F_{1-IV}F_{2-IV} \quad (3)$$

where

$$F_{1-IV}=\frac{n_{IV}-n_{water}}{r_{1-IV}}=\text{front surface visor power (at water/visor interface)}$$

$$F_{2-IV}=\frac{n_{air}-n_{IV}}{r_{2-IV}}=\text{back surface visor power (at visor/air interface)}$$

n_{water} = refractive index of water = 4/3

n_{IV} = refractive index of inside visor = 1.586

n_{air} = refractive index of air = 1.00

$r_{1\text{-}IV}$ = front surface radius of curvature of inside visor = 124.7 mm

$r_{2\text{-}IV}$ = back surface radius of curvature of inside visor = 122.7 mm

d_{IV} = center thickness of inside visor = 2 mm

Substituting these values into Eq. 3 yielded front and back surface powers of +2.026 D and −4.776 D, respectively, and an equivalent power of −2.737 D for the water/inside visor/air system. (It is worth noting that simplifying the water/inside visor/air system to a water/air system separated by a single refracting interface with a radius of curvature, $r_{1\text{-}IV}$, would yield a power of −2.673 D, similar to the equivalent power just calculated for the water/inside visor/air system.) Therefore, because the water/protective visor/water system could be modeled as a single layer of water, the equivalent power of the water/inside visor/air system (−2.737 D) represents the total optical power created by the helmet's visors when submerged underwater.

Determination of Underwater Spherical Correction

Based on the previously presented models and calculations, astronauts will need to wear an altered spectacle correction to compensate for the negative power induced by the helmet's visors when underwater. To determine the spherical refraction that should be worn inside the helmet, we can treat the helmet's visors as a single diverging thin lens that has a power of −2.737 D (F_{Helmet}) and is placed at the secondary principal plane of the water/inside visor/air system (located 0.93 mm to the right of the inside visor's back surface). Thin lens approximations may be used sufficiently to determine the spherical correction needed to be worn underwater, F_W, at a distance of 60 mm from the inside visor's back surface. This scenario is illustrated in Fig. 6, which depicts two thin lenses separated by a distance, d, of 59.07 mm (representing the distance from the secondary principal plane of the water/inside visor/air system to the spectacle lens plane, or 60 mm – 0.93 mm). The first thin lens represents the water/helmet visors system and has a power of F_{Helmet} = −2.737 D. The second thin lens represents the desired underwater spectacle correction (F_W) that is to be determined based on F_{Helmet} and the astronaut's spherical spectacle correction in air, F_{Air}.

As illustrated in Fig. 6a, parallel light that is incident on the first thin lens from a distant object will exit the lens divergent. The virtual image formed at the secondary focal point of the first lens, F'_{Helmet}, becomes a real object for the second thin lens with power F_W (Fig. 6b). Because our goal is to calculate the power of the second thin lens (power, F_W) based on the astronaut's spherical correction in air (F_{Air}), we can effectively split the second thin lens (F_W) into a combination of two thin lenses (F_1 and F_{Air}) that are in contact. (These lenses are drawn with separation in Fig. 6b for illustration purposes.)

$$F_W = F_1 + F_{Air} \quad (4)$$

To produce the vergence at the corneal plane required for proper distance correction, parallel light must be incident on the second new thin lens (or the astronaut's distance spherical correction in air, F_{Air}). Therefore, the purpose of the first new thin lens (F_1) is to yield parallel light after refracting light from the intermediate object located at F'_{Helmet}. This goal can be achieved by placing the primary focal point of the first new thin lens (F_1) at the intermediate object location. As shown in Fig. 6b, the primary focal length of the first new thin lens (f_1) is the sum of the secondary focal length of the water/visors thin lens (f'_{Helmet}) and the distance, d, between the thin lenses representing the water/visors system and the required underwater correction:

$$f_1 = f'_{Helmet} - d \quad (5)$$

The power of the first new thin lens is then

$$F_1 = -\frac{1}{f_1} = -\frac{1}{(f'_{Helmet} - d)} \quad (6)$$

Substituting Eq. 6 into Eq. 4 yields:

$$\begin{aligned} F_W &= F_1 + F_{Air} = F_{Air} - \frac{1}{(f'_{Helmet} - d)} \\ F_W &= F_{Air} - \frac{1}{\left(\frac{1}{F_{Helmet}} - d\right)} \end{aligned} \quad (7)$$

or

$$F_W = F_{Air} - \frac{F_{Helmet}}{(1 - dF_{Helmet})} \quad (8)$$

As seen above, the process of generating Eq. 8 is analogous to performing a vertex distance vergence correction in which the power of the thin lens representing the water/visors system (F_{Helmet}) is translated a distance, d, to the spectacle lens plane. Substituting our known values for d and F_{Helmet} yields a desired underwater spherical refraction of

$$F_W = F_{Air} + 2.356D \quad (9)$$

Equation 9 can now be used to calculate the required underwater spherical lens correction, F_W, knowing the astronaut's distance spherical correction in air, F_{Air}.

The validity of this model and its calculations was examined by comparing the underwater spherical lens correction calculated using Eq. 9 with the actual spherical lens correction worn by 10 astronauts when training underwater. (All research on human subjects followed the tenets of the Declaration of Helsinki and was approved by NASA's Division of Space Medicine and the University of Houston's Committee for the Protection of Human

Subjects.) Actual spherical lens corrections were determined as follows: A subjective manifest refraction was first performed in air to obtain F_{Air}. As dictated by Eq. 9 and depending on the astronaut's age (i.e., their level of presbyopia) and specific training demands, a spherical power of +2.00 D to +2.50 D was added to the manifest spherical power to obtain the actual spherical correction worn underwater. Based on feedback from the astronaut after the training session, the spherical power could be refined to yield a final underwater spherical correction. This actual value was compared with the calculated underwater spherical correction (F_W) predicted by Eq. 9.

RESULTS

As shown in Table 1, there was close agreement between the calculated and actual values, validating these model calculations. The mean magnitude of the difference between the actual and calculated underwater spherical refractions was 0.20 ± 0.11 D with a correlation coefficient of R = 0.971. In 70% of eyes, the magnitude of the difference between the actual and calculated values was less than 0.15 D [a value that is less than the step size and accuracy with which one can prescribe a spherical correction (0.25 D)]. The largest differences between the actual and calculated underwater spherical corrections were observed in astronauts 5, 6, and 7 (mean difference = −0.36 D), with the actual values worn being less than the calculated values. The differences in these three astronauts were likely due to the fact that they were prepresbyopic with some remaining accommodative amplitude (presbyopic eyes are in bold in Table 1). It is common practice to intentionally undercorrect the younger, prepresbyopic astronauts so that the actual distance spherical correction worn underwater is slightly less than the full calculated value. The younger, prepresbyopic astronauts have sufficient accommodative amplitude to cope with the slight undercorrection when submersed in the NBL. Additionally, the slight undercorrection can create less blur for these eyes while they are on the pool deck (in air). In contrast, the full calculated underwater spherical correction is usually pushed on the presbyopic astronauts due to an absence (or near absence) of their accommodative response. Therefore, presbyopic astronauts typically have less of a difference between the actual and calculated correction values. These concepts were evidenced by the data presented in Table 1, as the mean magnitudes of the difference between the actual and calculated underwater spherical refractions were 0.26± 0.13 D and 0.14 ± 0.02 D in the pre-presbyopic and presbyopic astronauts, respectively.

Finally, astronauts should visually experience some minification when wearing their underwater spectacle correction and looking through the helmet visors underwater. The two thin lens system of F_{Helmet} and F_1, illustrated in Fig. 6b, effectively acts as a reversed Galilean telescope that the patient looks through with their best spectacle correction in air (F_{Air}). This telescope consists of a −2.737 D powered objective (F_{Helmet}) and a +2.356 D powered eyepiece (F_1). The magnification provided by the telescope in its afocal configuration for distance viewing is +0.86x, indicating that an image has the same orientation as the object but is smaller in size. Therefore, the size of an object viewed underwater when the astronaut wears their underwater spherical lens correction (F_W) will be slightly smaller than when viewing the same object in air through the astronaut's best spectacle correction (F_{Air}).

CONCLUSIONS

We have presented a simple model to calculate the distance spherical correction that must be worn to compensate for the optical power induced when wearing a space suit helmet with curved visors underwater. The model depends linearly on the native distance spherical correction (in air) and can accurately predict the underwater correction as exemplified in a set of astronauts. Moreover, these same methods can be used more generally to calculate the refractive correction that must be worn behind any mask or goggle (such as traditional scuba masks, etc.) when submerged underwater.

Acknowledgments

We thank Dr. Ray Applegate and Dr. Heidi Hofer for providing comments on the manuscript. Work performed by Drs. Gibson and Strauss was conducted at the National Aeronautics and Space Administration (NASA)'s Johnson Space Center under the Wyle Integrated Science and Engineering Group's Occupational Medicine/Occupational Health Contract, NNJ06HB47C. The views expressed in this article are those of the authors and do not reflect the official policy or position of NASA or the United States Government.

References

1. Steele AL. Vision Underwater. Phys Educ. 1997; 32:387–392.
2. Chou B, Legerton JA, Schwiegerling J. Improving underwater vision: Contact lenses and other options can help patients safely maximize their vision underwater. Contact Lens Spectrum. 2007; 139:41–44.

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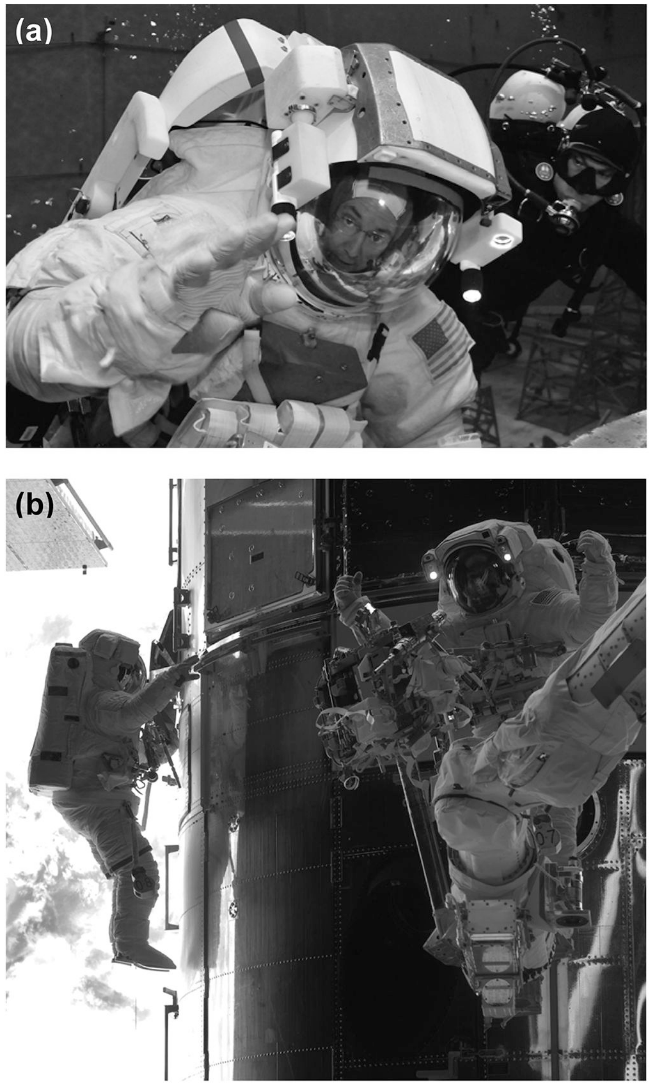

Fig. 1.
(a) A NASA astronaut practicing extra-vehicular maneuvers underwater in the NBL in preparation for performing tasks in space, such as repairing the Hubble Space Telescope as shown in (b). The non-planar visors of the space suit's helmet introduce refractive power in the underwater environment due to their curvature.

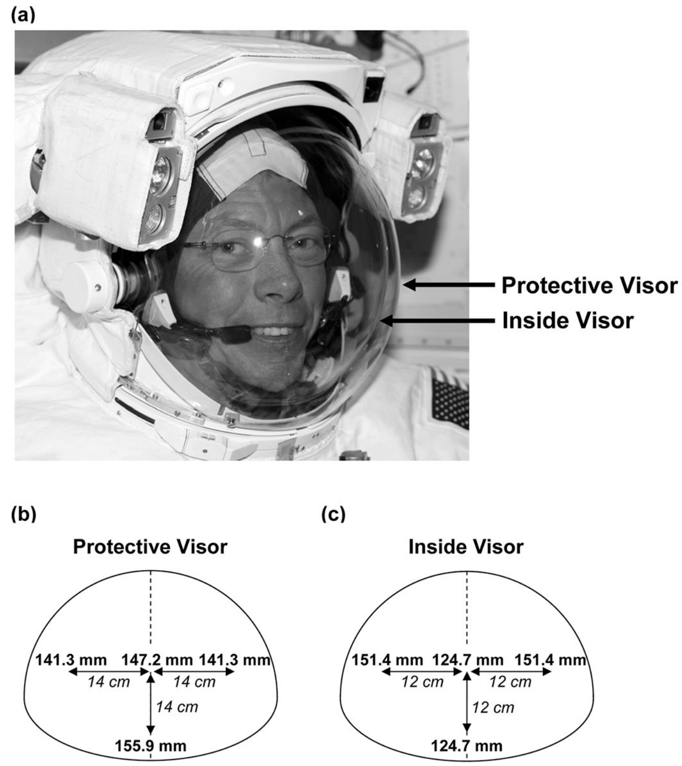

Fig. 2.

(a) Image of a NASA astronaut wearing the space suit helmet. The helmet's protective and inside visors can clearly be observed. (b, c) Calculated radii of curvature (in mm) for different locations on the front surface of the (b) protective and (c) inside visors of the space suit helmet (when looking head-on at the helmet). Approximate distances from the center of the visor to each measured location are indicated in italicized font. The inside visor was smaller than the protective visor. Dashed lines indicate location of vertical slices used in subsequent cross-sectional figures, Zemax modeling and calculations.

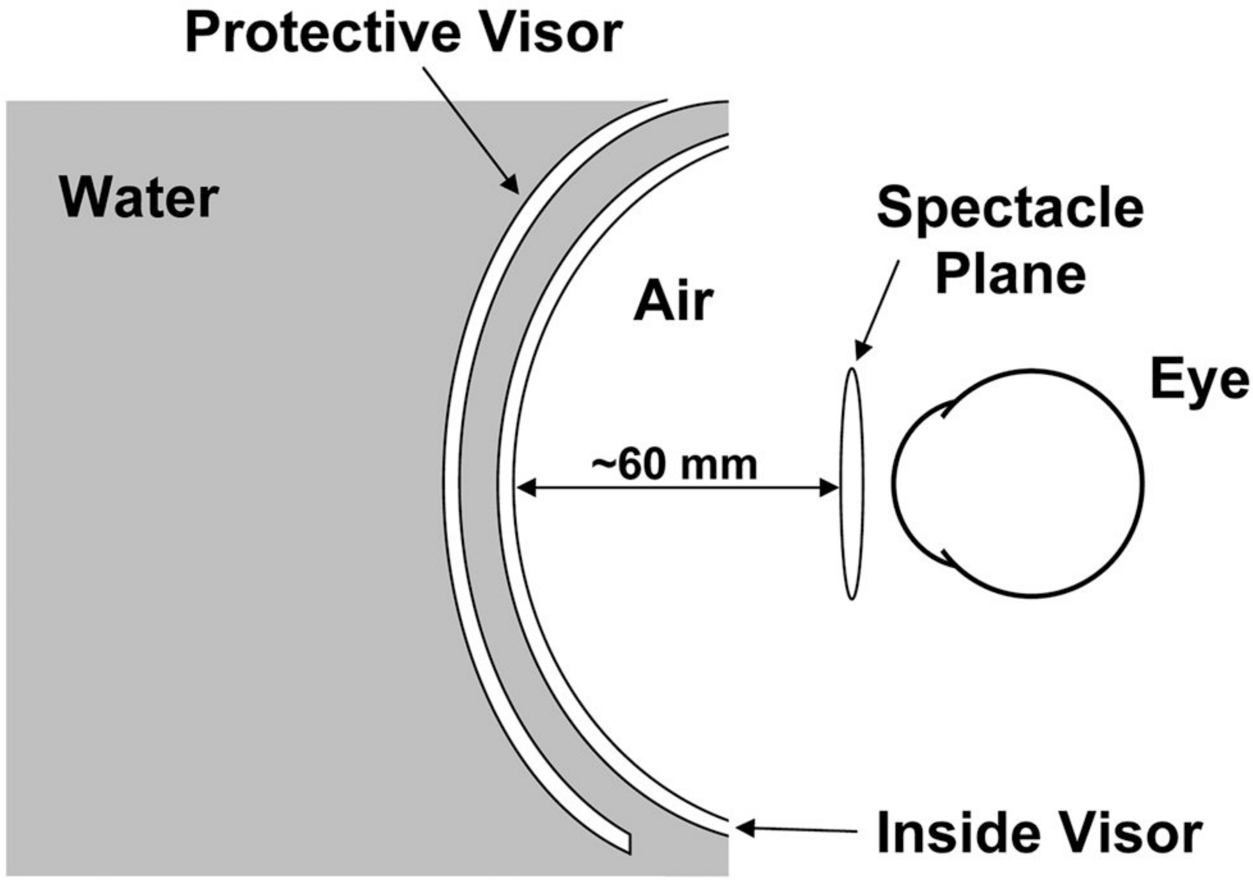

Fig. 3.
Cross-sectional view of a space suit helmet worn underwater. Water fills in the gap between the protective and inside visors, effectively negating any optical effects from the protective visor. The majority of refraction occurs at the inside visor because this is the location of greatest change in refractive index (i.e., visor to air transition). Since many astronauts wear refractive correction inside their helmet, the spectacle plane was taken to be a typical value of 60 mm behind the inside visor.

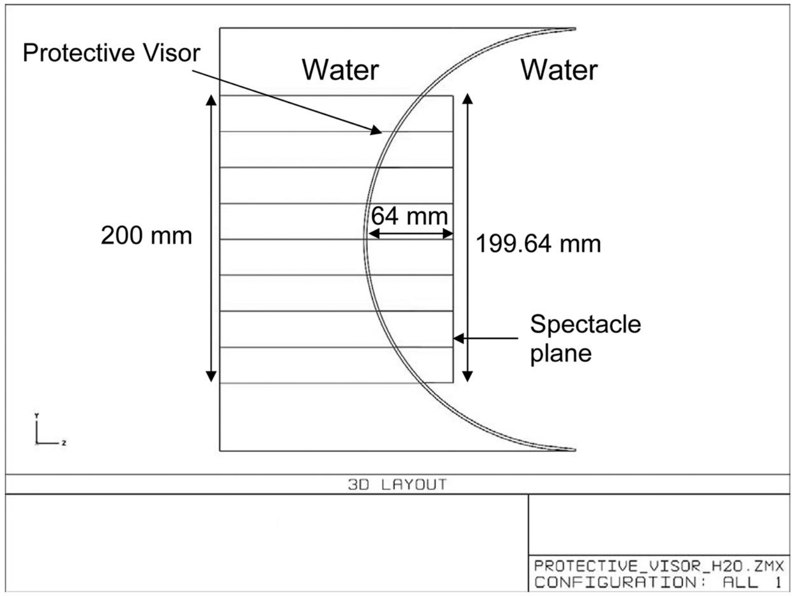

Fig. 4.
Zemax ray tracing model of the water/protective visor/water interfaces (wavelength = 550 nm). Visor thickness was 2 mm and front and back surface radii of curvature were 147.2 mm and 145.2 mm, respectively. Input beam diameter was 200 mm. After experiencing very slight refractions at the water/protective visor and protective visor/water interfaces, the output beam diameter at the spectacle plane (60 mm from the inside visor's back surface, or 64 mm from the protective visor's back surface) was 199.64 mm. Therefore, there was a negligible change in beam diameter due to the protective visor's curved profile when surrounded by water.

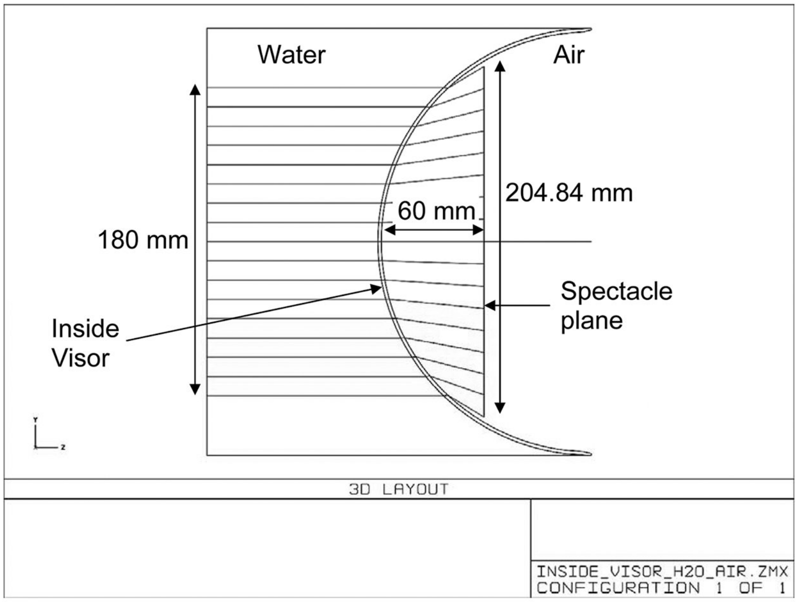

Fig. 5.
Zemax model of the water/inside visor/air interfaces (wavelength = 550 nm). The parallel input beam (diameter = 180 mm) diverged after refraction at the interface between the visor's back surface and air. The output beam diameter at the spectacle plane (60 mm from the inside visor's back surface) was 204.84 mm.

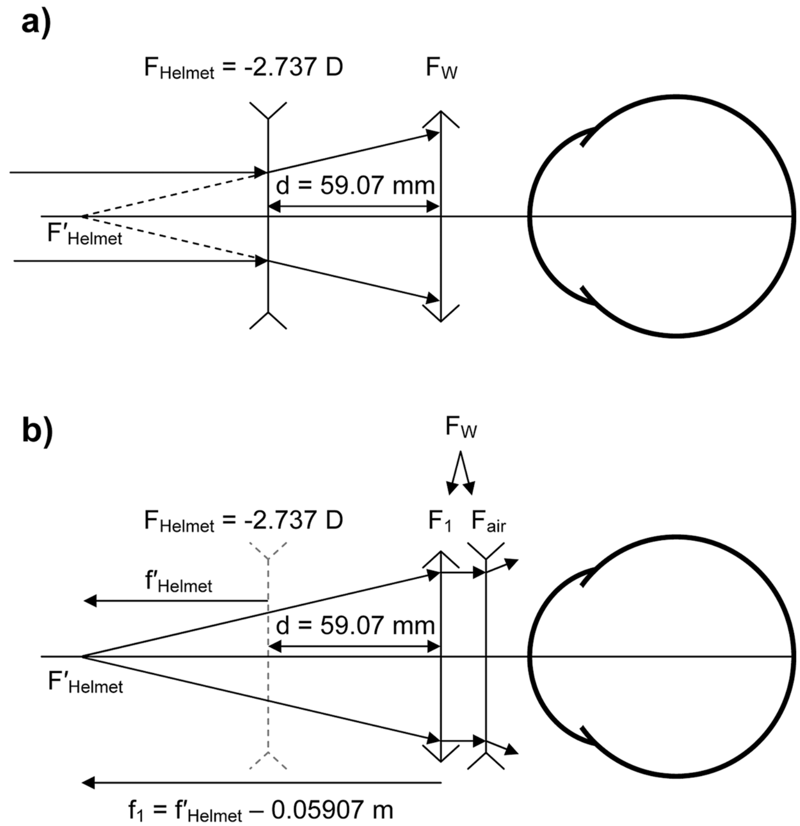

Fig. 6.

Thin lens system used to determine the required spherical correction to be worn inside the space suit's helmet when underwater, F_W. The power of the water/helmet visors system is represented by the first diverging thin lens with power, $F_{Helmet} = -2.737$ D. The second thin lens is the required underwater spherical correction, F_W, which is separated from the thin lens representing the water/helmet visors system by a distance, d, of 59.07 mm (i.e., the distance from the secondary principal plane of the water/inside visor/air system to the spectacle plane). (a) Parallel light from a distant object diverges after refraction by the first (water/visor) thin lens and forms a virtual image at its secondary focal point, F'_{Helmet} (dashed lines). (b) The virtual image produced by the first thin lens becomes a real object for the second thin lens representing the required underwater correction (power, F_W). This second thin lens can be decomposed into the sum of two new thin lenses in contact: the first new thin lens (power, F_1) yields parallel light which is required for the second new thin lens, the native distance spherical correction in air (power, F_{air}). (The lenses have been separated in the figure for illustration purposes only.) The primary focal length of the first new thin lens, f_1, is the sum of the secondary focal length of the water/visors thin lens (f'_{Helmet}) and the separation (d) between the water/visors thin lens and the required underwater correction thin lens.

TABLE 1

Comparison of the Native Distance Spherical Correction in Air (D), the Calculated and Actual Distance Spherical Corrections Underwater (D) and the difference between the Actual and Calculated Distance Spherical Corrections Underwater (D) in the right and left eyes of 10 astronauts.

Astronaut Number		Native Distance Spherical Correction in Air, F_{Air} (D)	Calculated Distance Spherical Correction Underwater, F_W (D)	Actual Distance Spherical Correction Underwater (D)	Actual – Calculated Distance Spherical Correction Underwater (D)
1	**OD**	**−0.50**	**+1.86**	**+2.00**	**+0.14**
	OS	**−0.50**	**+1.86**	**+2.00**	**+0.14**
2	**OD**	**+1.00**	**+3.36**	**+3.25**	**−0.11**
	OS	**+1.00**	**+3.36**	**+3.25**	**−0.11**
3	OD	−0.50	+1.86	+1.75	−0.11
	OS	−0.50	+1.86	+1.75	−0.11
4	**OD**	**+0.50**	**+2.86**	**+3.00**	**+0.14**
	OS	**+0.50**	**+2.86**	**+3.00**	**+0.14**
5	OD	−0.50	+1.86	+1.50	−0.36
	OS	0.00	+2.36	+2.00	−0.36
6	OD	+0.50	+2.86	+2.50	−0.36
	OS	+1.00	+3.36	+3.00	−0.36
7	OD	0.00	+2.36	+2.00	−0.36
	OS	0.00	+2.36	+2.00	−0.36
8	OD	0.00	+2.36	+2.25	−0.11
	OS	0.00	+2.36	+2.25	−0.11
9	**OD**	**+0.50**	**+2.86**	**+3.00**	**+0.14**
	OS	**+0.50**	**+2.86**	**+3.00**	**+0.14**
10	**OD**	**−1.50**	**+0.86**	**+1.00**	**+0.14**
	OS	**−2.75**	**−0.39**	**−0.25**	**+0.14**

Eyes that were presbyopic are in bold type. All other eyes were pre-presbyopic.