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# The Issue of Visual Correction Compatibility with Helmet-Mounted Displays

by Clarence E. Rash, Melvyn E. Kalich, Corina van de Pol, and Barbara S. Reynolds

Aircrew Health and Performance Division

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This paper examines the compatibility issues of helmet-mounted display (HMD) designs, the requirement for providing compatible vision correction, and the methods available in order to achieve this requirement. First, the problem of limited HMD eye clearance is defined in the context of protective devices and visual correction methods. Next, past efforts to mitigate this problem via the use of specially modified spectacles and contact lenses are reviewed. Finally, current and future potential solutions to this problem are explored.

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## Introduction

For tactical purposes, U.S. Army aviation emphasizes a low-light level operational capability, i.e., night and foul-weather operation. To achieve this goal, image intensification ($I^2$) and forward looking infrared (FLIR) night imaging sensor technologies have been incorporated into military aircraft. Examples of systems implemented to achieve this goal include the Aviator's Night Vision Imaging System (ANVIS) (Figure 1), used in most Army aircraft, and the Pilot's Night Vision System (PNVS) used in the AH-64 Apache helicopter. The ANVIS is a combination sensor and display system. The AH-64 PNVS is a nose-mounted sensor and inputs its imagery to a helmet-mounted display (HMD) known as the Integrated Helmet and Display Sighting System (IHADSS) (Figure 2).

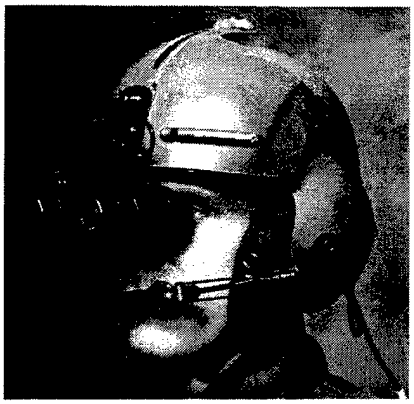

Figure 1. The Aviator's Night Vision Imaging System (ANVIS).

Figure 2. The Integrated Helmet and Display Sighting System (IHADSS).

Both ANVIS and IHADSS are mounted on the aviator's helmet, and their optical components are located almost directly in front of the aviator's eye(s). This close proximity results in a very small distance between the optics and eye(s). This has proved to be an important equipment compatibility issue. The operational requirements of Army aviation have necessitated that aviators be provided with protection against directed energy (e.g, lasers, microwave radiation, etc.) and chemical warfare environments. Protection has been generally in the form of protective spectacles, goggles, and/or masks. Most of these protective add-on devices must be located between the HMD optics and the eyes. Oxygen masks are an additional requirement for moderate above-sea-level altitudes. Current HMD designs provide little space for incorporation of these additional devices and systems.

In addition, as aviators age, they undergo changes in their visual capability. Aviators experience the same sort of refractive error progression as the general population; individuals who are nearsighted or farsighted tend to become more nearsighted or farsighted with age, resulting in increased dependence on glasses or contact lenses. One of the most pronounced effects is the ability to accommodate, i.e., change focus. Human range in accommodation generally decreases with age from a robust 11 diopters at age 20 to a limiting 2 diopters by age 50 (Records, 1979). As a result, to retain the experience of older aviators, there is a requirement to provide visual correction, and this correction must be useable while flying with HMDs.

This paper examines the compatibility issues of HMD designs, the requirement for providing compatible vision correction, and the methods available in order to achieve this requirement. First, the problem of limited HMD eye clearance is defined in the context of protective devices and visual correction methods. Next, past efforts to mitigate this problem via the use of specially modified spectacles and contact lenses are reviewed. Finally, current and future potential solutions to this problem are explored.

## Concepts of optical and physical eye relief

HMDs are examples of optical systems. Simply stated, an optical system consists of one or more optical elements. These optical elements include lenses, mirrors, prisms, filters, etc. One of the simplest optical systems is a magnifying glass, which consists of a single lens encased in a ring that may have a handle attached. Beyond the simple magnifier, practically all optical systems contain multiple optical elements. HMD optical systems are generally quite complex and can consist of a dozen or more optical elements.

Most optical systems have their elements fixed in place within a housing. Furthermore, these systems are designed to be viewed by the human eye. Figure 3 shows the optical design of a simple pupil-forming compound microscope and the path of light rays through the system. For ease of discussion, the optical elements are presented only. Light rays passing through the system form an image at the exit pupil. Simply defined, the exit pupil is where the eye must be placed in order to optimally view the image. The exit pupil can be thought of as the area through which all of the image-forming rays pass. [Note: Technically, the exit pupil is a volume in space.] If the eye is placed behind or in front of the exit pupil, the eye will not capture some of the rays. This results in a reduced field of view (FOV).

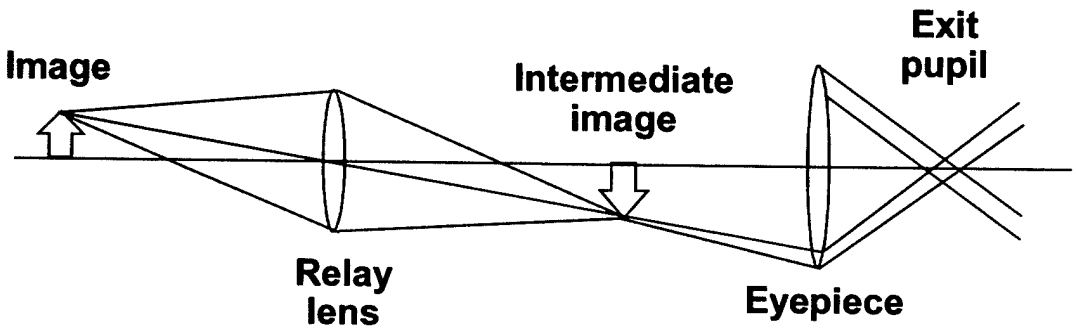


Figure 3. The path of light rays through a pupil-forming optical system.

An important characteristic of the system in Figure 3 is the distance along the optical axis between the last optical element and the exit pupil (where the eye would be positioned). This distance is known as the "optical eye relief." Figure 4 expands the final element of the system and presents this distance. In addition, it further refines the definition of the optical relief as the distance along the optical axis from the last optical surface to the cornea of the eye. [Note: Often, the entrance pupil of the eye, which is approximately 3 mm behind the surface of the

cornea, is used as the reference point in the definition of optical eye relief.] When an optical system is defined, the optical eye relief distance is often cited as an important parameter.

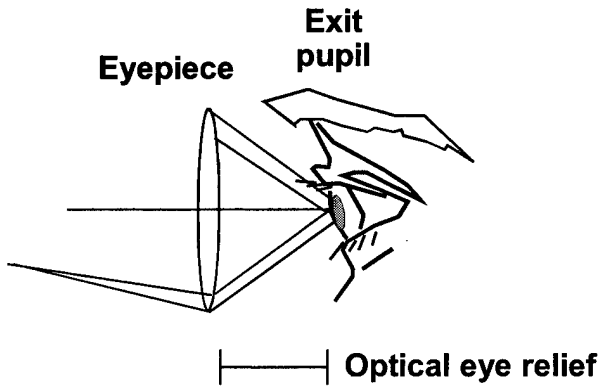


Figure 4. Defining the optical eye relief distance as the distance along the optical axis from the last optical surface to the cornea of the eye.

In Figures 3 and 4, the optical system was depicted as exposed optical elements. But, in practice, one cannot ignore the system housing. Figure 5 shows a side cut-away view of the example optical system showing the last optical element as enclosed in the housing. The most noticeable difference when the housing is considered is the extension of the housing beyond the final surface of the last optical element. This difference impacts the available (or usable to the viewer) optical eye relief distance. A new distance requires definition, that of the distance from the plane through the outer edge of the housing to the cornea of the eye. This new distance is often referred to as "physical eye relief." Physical eye relief is, at best, equal to optical eye relief. In practice, physical eye relief almost always is less than optical eye relief.

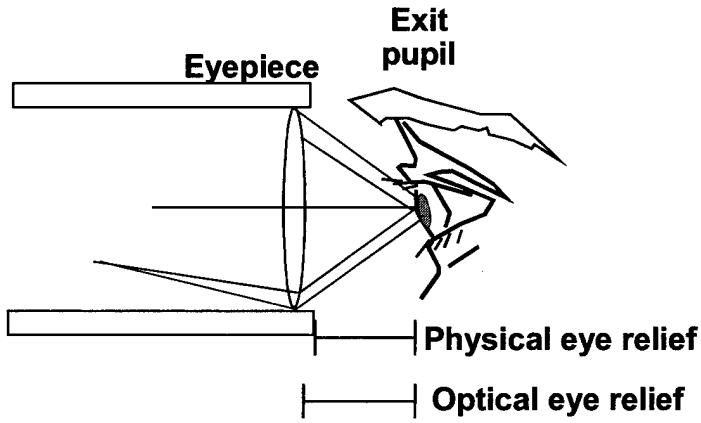


Figure 5. A side cut-away view of the example optical system showing the last optical element as enclosed in the housing.

As was mentioned previously, HMD optical systems can be quite complex in design. In Figure 6, two HMD designs are illustrated. On the left is the Monolithic Afocal Relay Combiner (MONARC) design, which is an off-axis, rotationally symmetrical lens system with modest FOV

potential, but is an excellent see-through approach. This design is an example of a folded catadioptic design. On the right is an example of a modest off-axis catadioptric design with a plano combiner (Droessler and Rotier, 1989). This design achieves a 50° x 60° FOV with a 10-mm exit pupil and a 30-mm optical eye relief (measured from plano combiner intercept to apex of eye along primary line of sight).

Both of the examples in Figure 6 are pupil-forming systems. For pupil-forming systems, the eyepieces collimate virtual images that are formed using relay optics. The primary purpose of the relay optics is to magnify the real image, with the eyepiece providing additional magnification. The pupil-forming system forms a real exit pupil, i.e., the rays actually pass through the exit pupil position. In nonpupil-forming systems, a simple eyepiece is used to collimate or focus a real image source. ANVIS (also referred to as night vision goggles) are an example of a nonpupil-forming system.

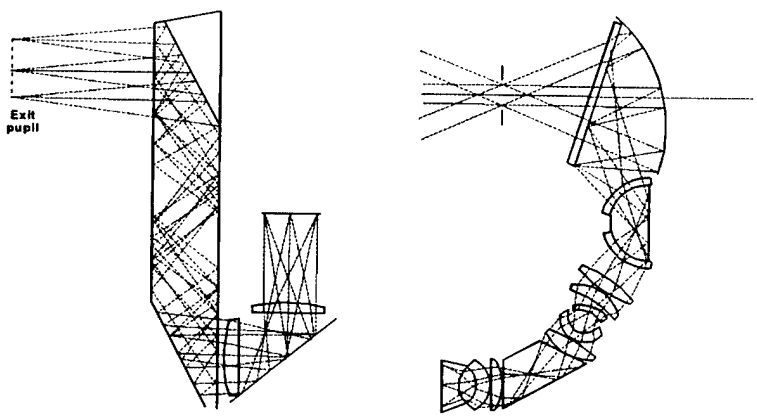


Figure 6. Examples of HMD optical designs: Monolithic Afocal Relay Combiner (MONARC) system (right) and an off-axis catadioptric design with plano combiner (left) (Droessler and Rotier, 1989).

Table 1 provides a partial listing of a number of past and present rotary-wing HMD programs. Values for selected system design parameters are given for comparison. The IHADSS is the HMD system that has been fielded on the AH-64 Apache since the early 1980s. The Helmet Integrated Display and Sight System (HIDSS) is the HMD system currently in design for use in the RAH-66 Comanche. Where the IHADSS is a monocular HMD, based on a miniature cathode-ray-tube (CRT) as an image source, the HIDSS is a biocular HMD that incorporates dual miniature active matrix liquid crystal display (AMLCD) sources. A recent configuration of the HIDSS is presented in Figure 7.

The third rotorcraft HMD presented in Table 1 is currently in the research and development stage and is a novel scanning laser HMD design being developed by Program Manager, Aviation Electronics Systems (PM-AES), referred to as the Microvision, Inc., version of the Aircrew Integrated Helmet System (AIHS-MV) HMD (Figure 8).

Table 1.
Summary of rotary-wing HMD programs.

| Parameter | ANVIS | IHADSS | HIDSS | AIHS-MV |
|---|---|---|---|---|
| Vehicle | All rotorcraft | AH-64 Apache | RAH-66 Comanche | Unidentified |
| Program type | Production | Production | R&D | R&D |
| Display | Image Intensifiers (2) | Miniature CRT (1) | AMLCDs (2) | Laser diodes (2) |
| Presentation mode | Binocular | Monocular | Biocular | Biocular |
| Percent overlap | 100% | N/A | 30% | Not available |
| Exit pupil | N/A | 10 mm | 15 mm | 15 mm |
| Optical eye relief | N/A | 10 mm | 25 mm | 40 mm |
| Physical eye relief | 15-30 mm | 0 to few mm | 25 mm | Unidentified |
| FOV | 40° circular | 40° x 30° | 52° x 30° | 52° x 30° |

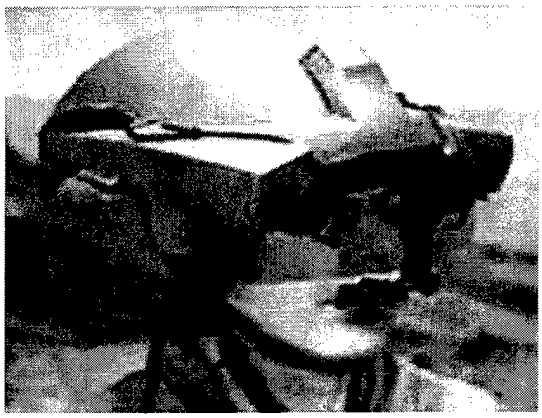

Figure 7. The Helmet Integrated Display and Sight System (HIDSS).

Figure 8. Scanning laser HMD (AIHS-MV) (2000 design).

In summary, optical eye relief distance is an optical system design parameter. However, it is a misleading parameter when the optical design is intended for use in systems such as HMDs where intervening devices must be placed between the optical system and the users eye, e.g., corrective spectacles, oxygen masks, nuclear, biological and chemical (NBC) protective mask, etc. A more useful parameter is physical eye relief. Physical eye relief distance, usually less than optical eye relief distance, takes into consideration the physical features of the structure and housing of the optical system's elements and these features' impact on reducing the "real" distance available between the optical system "HMD" and the viewer's eye.

While the emphasis on the concept of physical eye relief is a step forward in reducing the confusion about, and the problems associated with, the HMD compatibility issue, it still addresses only one side of this issue. In the fielding of the AH-64 IHADSS HMD (Rash et al., 1987), a valuable lesson was learned about the impact of head and facial anthropometry on HMD fit and the associated compatibility issue (see following section, "Compatibility issues with the IHADSS"). During this initial fielding experience, it was discovered that several facial dimensions and the variation in the range of the values of these dimensions had a huge impact on the ability to fit the IHADSS HMD optics, which are at the heart of the compatibility issue. The specific facial dimensions that were found to be most critical were: menton-sellion length (the distance between the top of the nose and the bottom of the chin, necessary for oxygen and protective mask nose cups); eye inset (the distance between the supraorbital notch (eyebrow) and the cornea of the eye, as well as the distance from the most forward point of the zygomatic process (cheekbone) to the cornea; the disparity between eye inset for the two eyes; and the disparity between the vertical positions of the two eyes (Rash, ed, 1999).

One impact of the variation in these facial dimensions is that the concept of physical eye relief, while compensating for the structure of the optical system housing, is shown to require further refinement to compensate for variation in facial features. It is suggested that a third distance concept be introduced that incorporates the influence of facial anthropometry. A suggested name for this third distance is "eye clearance distance."

Since head and facial anthropometrics will vary across individuals, the true available distance within which additional devices or systems can be interjected, the eye clearance distance, is an individual measure. So, while this concept may be used in and its value measured during an HMD fitting session, HMD systems specifications must still rely on the physical eye relief metric. However, HMD system program managers must be aware that even an "adequate" physical eye relief distance will not guarantee a 100 percent population fit.

Before leaving the description of eye relief, it may be worth addressing the question of why the HMD design cannot simply provide a greater eye relief distance. For any HMD design, the two starting parameters that must be decided upon are exit pupil size and eye relief. However, these two parameters have considerable impact on the size of the last optical element in the HMD's eyepiece and the focal length of the system. All of these factors combined have additional impact on packaging size and total head supported weight, very important parameters for HMD use in the rotary-wing environment. In conclusion, the designer simply cannot make the eye relief distance as large as may be desired.

## Compatibility issues with the IHADSS

The IHADSS was the first integrated "helmet, head tracker and display" HMD system developed by the U.S. Army. It is used on the AH-64 Apache attack helicopter, which was fielded during the early 1980s. Developed by Honeywell, Inc., Minneapolis, Minnesota, the IHADSS has demonstrated that HMDs can be used successfully in the military rotary-wing aviation environment.

The IHADSS is a monocular design. Imagery obtained from a nose-mounted FLIR sensor is reproduced on a miniature, 1-inch diameter, CRT mounted on the right side of the helmet. The image on the face of the CRT is optically relayed to the pilot's right eye. The relay optics and CRT are referred to as the Helmet Display Unit (HDU) (Figures 9 and 10). Two optical elements of the HDU should be noted. The first is the objective lens that is positioned almost perpendicular to the pilot's face. This lens is approximately 1-3/4 inches in diameter and is mounted as the last element in the HDU housing barrel. The second is the beam splitter mounted on the side of the HDU barrel farthest from the face. The beam splitter, also referred to as the combiner, reflects the IHADSS imagery into the pilot's eye.

Figure 10 demonstrates the difference in the concepts of optical and physical eye relief for the IHADSS HMD. The IHADSS design optical eye relief is 10mm. By definition, this distance is the distance along the optical axis from the last optical element (center of the combiner) and the exit pupil. Figure 10 clearly shows why the optical relief distance is not a functional (practical) parameter. The center of the combiner is located well back behind the lip of the HDU barrel housing. The HDU barrel and the interaction between the barrel and the wearer's cheekbone limit how close the combiner can be placed in front of the eye. This situation severely reduces the available distance between the pilot's eye and the plane that passes through the closest physical HDU structural element, and it is this distance that defines the physical eye relief.

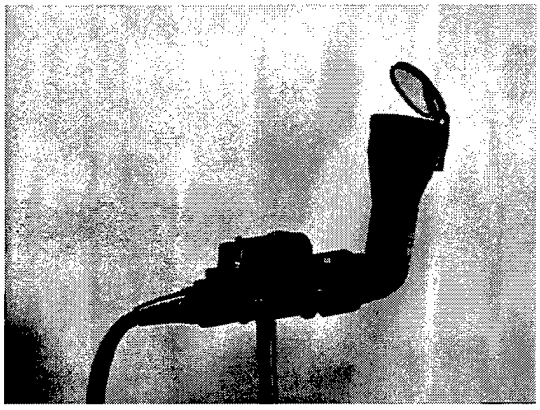

Figure 9. Helmet display unit (HDU photo).

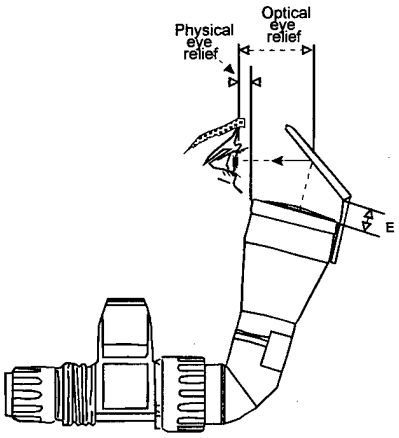


Figure 10. Helmet display unit (HDU drawing).

The interrelationship between eye relief and the IHADSS design first manifested itself during initial flight tests of the AH-64 Apache. In order to meet Range Safety Officer's requirements to provide laser protection on firing ranges, the U.S. Army Aeromedical Research Laboratory (USAARL) was requested to design a prototype spectacle which could be outfitted with Shott

KG-3 glass capable of providing the proper level of protection against reflected energy from the Apache's Neodynium; Yttrium, aluminum, garnet (YAG) laser range finder. The approach taken was to start with the standard aviator spectacles and modify the shape and orientation of the right lens frame to allow wearing behind the IHADSS HDU. While this design, referred to as the "modified" aviator's spectacles (Figure 11), was intended only to meet the requirements for this initial flight test, these modified spectacles became standard issue not only for laser protection but also for vision correction.

Because of the adoption of the modified spectacle as standard issue, and because of anecdotal complaints from aviators that the spectacles were obstructing their HDU use, USAARL conducted a study (McLean and Rash, 1984) to investigate the effect of the modified spectacle on the IHADSS FOV. In this study, 11 subjects (7 of whom were AH-64 instructor pilots) had their 30 x 40 degree IHADSS FOV measured both with and without the modified spectacles. Even after optimum fit of the IHADSS and spectacles, 2 of the 11 subjects were found to have a measurable reduction in FOV while wearing the modified spectacles. The general conclusion of the study was that when sufficient care was taken in the fit and alignment of the helmet, HDU and modified spectacles, there was no significant field of view loss when wearing modified spectacles. However, the authors expressed concern over the ability to achieve optimal fitting in the field environment.

In order to provide NBC protection for the AH-64 aircrew, a series of gas masks have been developed. The first version of this series was the XM-43 (Figure 12). The faceplate of the XM-43 was a full-face bromobutyl/natural rubber blend molded face blank. Two molded polycarbonate lenses were mounted into the faceplate. The lenses were in very close proximity to the eyes and were spherically shaped. The mask design allowed for under-the-helmet use. In 1987, USAARL evaluated the visual performance of this mask to include the effect of the mask on IHADSS FOV (Walsh, Rash and Behar, 1987). Four candidate AH-64 instructor pilots, who previously had been fitted with their IHADSS helmets, had their FOV measured both with and without the XM-43 mask. The resulting data showed an average FOV loss of 11 percent in all meridians except in the vertical direction, where an average loss of approximately 6 percent was experienced.

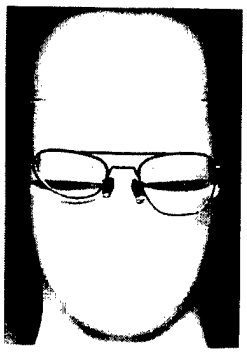

Figure 11. The modified aviator's spectacle.

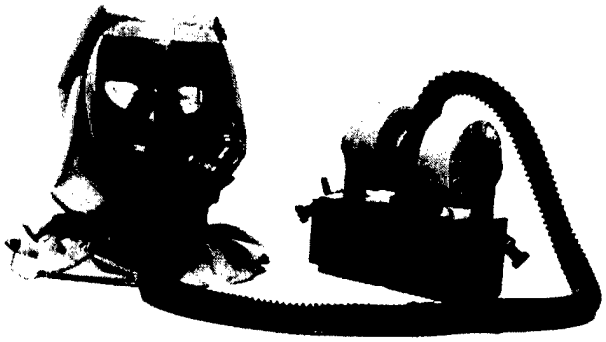

Figure 12. XM-43 nuclear, biological and chemical mask.

Later in that same year, a second study looking at the effects of an improved M-43 (previously XM-43) mask on IHADSS FOV was conducted (Rash and Martin, 1987a). In this study, 22 AH-64 instructor pilots were evaluated for FOV loss for the combination of the HDU and the M-43 mask. Each subject experienced a loss in FOV through the HDU when wearing the M-43 mask. The average FOV loss was 12.4 percent. The implication of these results was that the pilot typically would encounter loss of some portion of symbology information when wearing the M-43 mask. It is reasonable to expect that such loss would result in degraded performance by the aviator.

Attempts to incorporate visual correction into the M-43 mask have not been completely successful. Specifically, because of the close fit design of the mask, optical inserts do not fit into the mask. Further, the presence of the HDU prohibits the option of an optical outsert. "Glue-on" corrective lenses for the M-43 were shown to produce unwanted magnification and distortion (Crosley, Rash and Levine, 1991).

Over the fielding period of the AH-64, three user evaluations of the IHADSS have been conducted. The first evaluation, in 1987 (Rash and Martin, 1987b), presented two questions that addressed the compatibility issue. The first question asked aviators about any discomfort experienced while using the HDU. Of the 133 respondents, 58 (44 percent) answered in the positive, several citing interference while using the modified laser spectacles. The second question directly addressed the use of the modified laser spectacles. Sample comments included: "...I cannot see the left half of the image in the HDU," "...they cause distortion and decrease (my) FOV," "...they hurt, and restrict my vision...," and "...you can only put so many things over my eye."

In 1990, a study titled "Visual Issue Survey of Apache Aviators (VISAA)" (Behar et al., 1990) was conducted specifically to address the visual medical concerns associated with the Apache IHADSS. Several questions addressed aviator wearing of the modified spectacles. Of the 16 subjects, 11 (69 percent) indicated that they use the modified spectacles with the IHADSS. Of these 11 subjects, 10 (91 percent) reported interference in the ability to see the IHADSS symbology while wearing the modified spectacles. The major complaints were lack of wearing comfort and incompatibility between the spectacles and the combiner lens.

In 2000, an expanded version of the above 1990 study was conducted (Rash et al., 2000). While the primary focus again was visual issues, the study also addressed helmet fit and noise protection. A total of 216 Apache aviators participated in this study with an age range of 23-53 years, total flight experience range of 220-9500 flight hours, and AH-64 experience ranging from 20-5000 flight hours. These demographics represented the full scope of the Apache aviator community. Of the 216 respondents, approximately two-thirds were somewhat or completely satisfied with their helmet fit. However, numerous comments provided by the aviators mentioned spectacle interference and frustration with not being able to see either the corners or sides of their display in the HDU. Selected aviator comments include: "(modified) glasses obscure symbology, especially torque," "If I use my glasses at night, I lose the top left portion of the display," and "...several other aviators have simply removed the right lens from their glasses..."

In summary, the extremely limited physical eye relief distance provided by the IHADSS has resulted in a major incompatibility issue with respect to the NBC mask and laser protective/vision corrective spectacles. While there have been no alternative solutions to providing NBC and laser protection, contact lenses (CLs) have been used as an interim solution to the vision correction issue, while overcoming the physical eye relief compatibility issue.

## Historical solutions for visual correction

Approximately one-third of U.S. Army aviators require vision correction. Historically, spectacles have been the method employed. However, when HMDs are required for flight, CLs can afford the pilot vision correction, without the physical limitations imposed by HMD use.

### Traditional refractive error correction

#### Spectacle use by Army aviators

Prior to 1998, U.S. Army Commissioned Officer and Warrant Officer pilot applicants were held to a different vision standard. Warrant Officer candidates were required to have 20/20 vision without correction while commissioned officers could be 20/50 without correction, correctable to 20/20. This has subsequently changed (Surgeon General Memorandum, 12 August 1999, HQ ATSQ-CG). Now both Commissioned and Warrant Officer Flight School Applicants have the same vision standard, given in AR 40-501, 4-12 (Table 2). Snellen visual acuity defines the minimum angle of resolution that an eye can see (Figure 13). The presence of any error in the focus of the eye reduces acuity. Figure 14 ius a simulation of the effects of degrading visual acuity (or defocus) on instrument legibility. Defocus is also known as refractive error and can include myopia (near-sightedness), hyperopia (far-sightedness) and astigmatism. Astigmatism is usually when focus of an image along its vertical axis is different from that along its horizontal axis, producing blur along one of the axes; less frequently, axes other than vertical or horizontal may be involved. Figure 17 shows one impact of astigmatism defocus on acuity. Most pilot applicants therefore start their flight career with low or no refractive error.

Over time, vision can change, as with late-onset myopia, requiring a stronger prescription and/or correction for presbyopia, a noticeable reduction in the eye's ability to change focus. Presbyopia is a consequence of the gradual hardening of the crystalline lens inside the eye that begins in early childhood and continues until the individual completely loses ability to change focus (accommodate), sometime after 50. This inability becomes noticeable somewhere in the late 30s or 40s. For a far-sighted person, this manifests itself as an inability to see near objects clearly, even though distant objects may be very clear. Presbyopia requires a different correction for near and distance vision, usually a kind of bifocal or trifocal.

The number of rated aviators requiring some kind of correction for refractive error is substantial. A statistical study of Apache aviators showed 20 out of 58 individuals answering a questionnaire wore spectacles (eyeglasses). This is particularly important when you consider that Apache pilots fly using a monocular helmet-mounted display, IHADSS (Behar et al., 1990). Schrimsher and Lattimore (1990, 1991), reviewing the U.S. Army Epidemiology Data Register

(AEDR) for years 1986-89, found that 21 percent to 23 percent of active U.S. Army aviators wore spectacles (contact lenses were prohibited at that time); 25 percent to 28 percent of Reserve aviators and 28 percent to 35 percent of National Guard aviators wore spectacles. Of Active Duty, Reserve and National Guard aviators wearing spectacles in 1989, 8 percent, 15 percent and 20 percent, respectively, were presbyopic. Shannon and Mason (1994) and Stone (1993) showed that there was a marked increase from 1986 to 1992 in percentage of Army aviators over 40. A 1989 U.S. Air Force study (Miller et al., 1989) showed that 27 percent of Air Force pilots

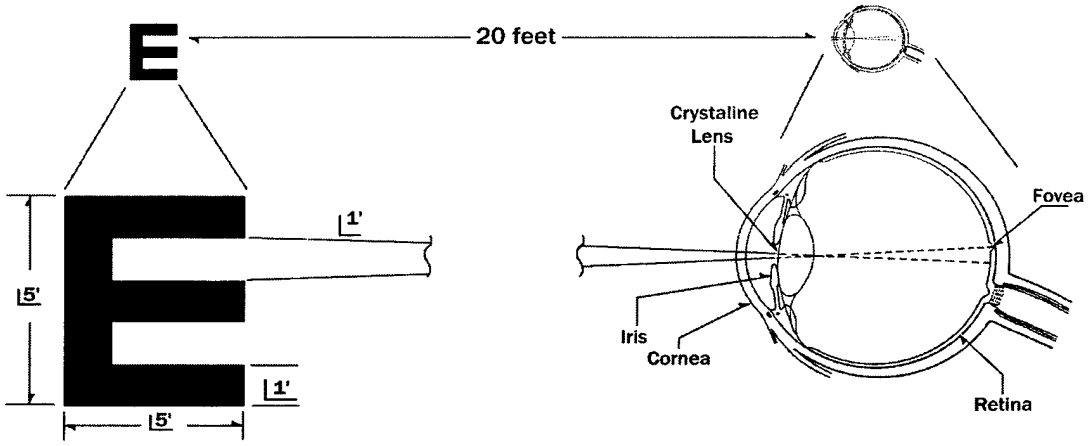


Figure 13. A high contrast 20/20 Snellen letter viewed at 20 feet has a height of 5 minutes of arc and critical detail of 1 minute arc.

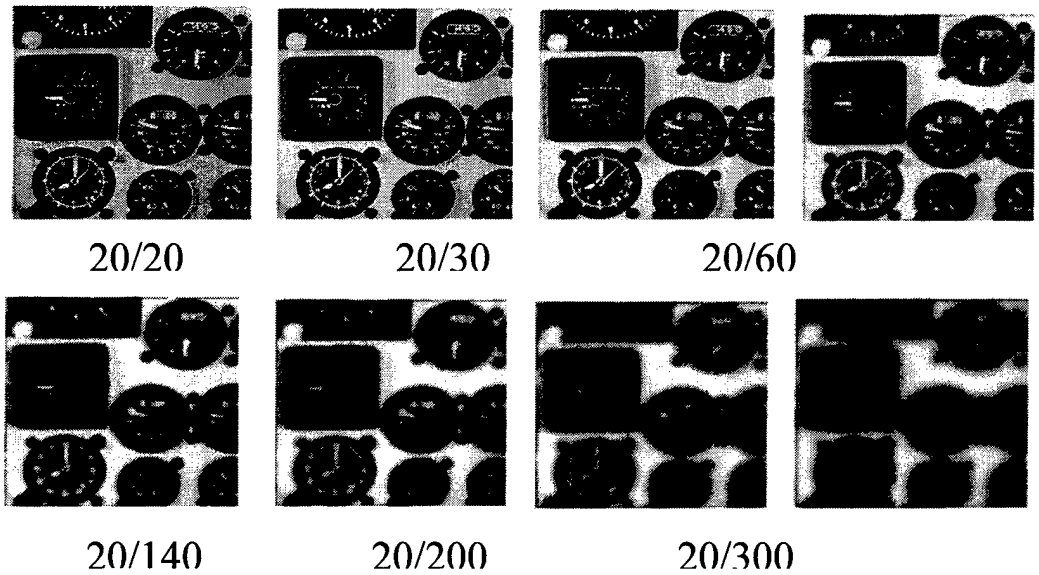


Figure 14. Instrument appearance with different visual acuities. Cockpit instruments are usually designed so they can be read by pilots with 20/70 vision.

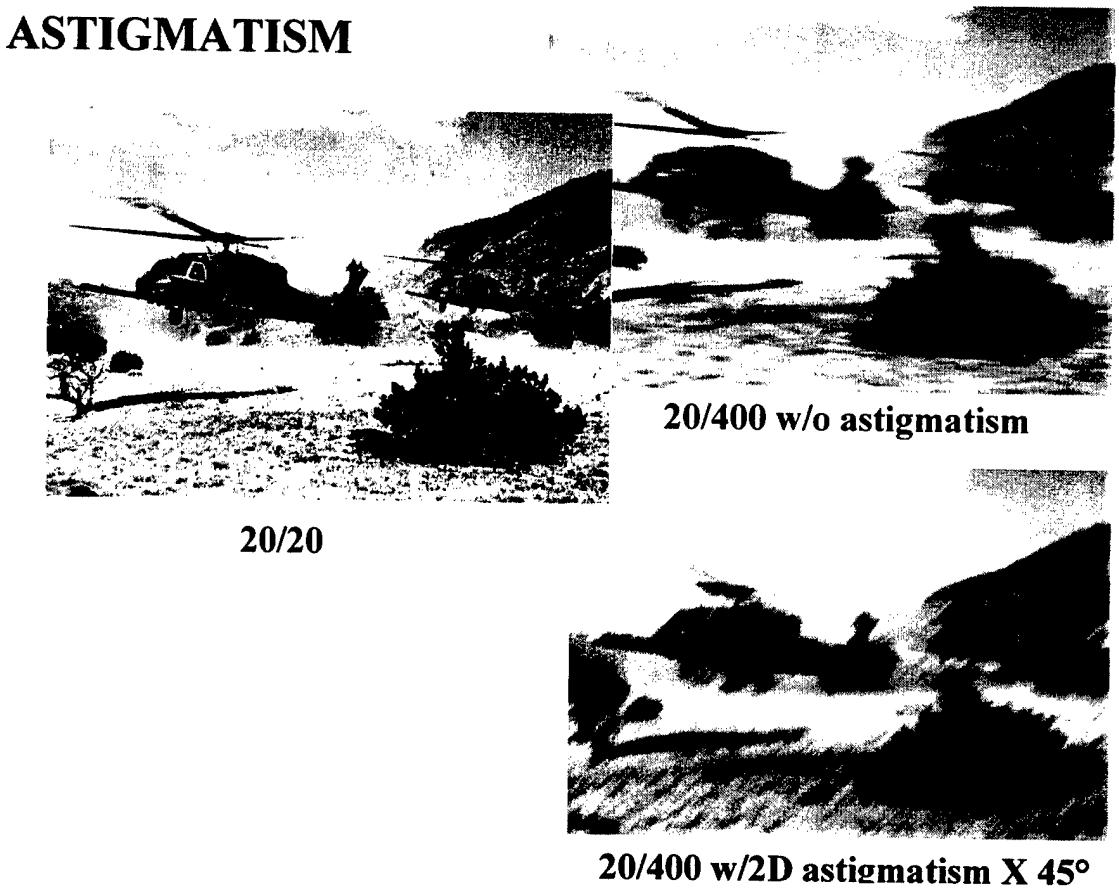


Figure 15. The affect of astigmatism.

Table 2.
Cycloplegic refraction error maximum

**CYCLOPLEGIC REFRACTION ERROR MAXIMUM**
**U.S. ARMY FLIGHT SCHOOL APPLICANT**
**AR 40-501, CLASS 1A**

Uncorrected Distance and Near Snellen Visual Acuity for each eye not worse than 20/50.
Corrected Distance and Near Snellen Visual Acuity for each eye not worse than $20/20^{-1}$.
Astigmatism 1.00 Diopters Cylinder.
Hyperopia not in excess of + 3.00 Diopters Sphere.
Myopia not in excess of – 1.50 Diopters Sphere.

**MANIFEST REFRACTIVE ERROR MAXIMUM**
**U.S. ARMY RATED AVIATOR**
**AR-40-501 CLASS 2**

Uncorrected Distance and Near Snellen Acuity for any eye not worse than 20/400 and/or not correctable to 20/20.
Manifest Refractive Error not of such magnitude that the individual cannot be fitted with aviation spectacles.

and 51 percent of navigators wore spectacles. Their normalized, age-related data showed that a fairly constant percentage of 21- 40-year-old Air Force pilots wore eyeglasses, but that almost 50 percent in the age bracket 41- 45 did. About 90 percent of pilots overage 45 wore eyeglasses. It's worth noting that rated U.S. Army aviators go by a different and lower standards than flight school applicants, allowing fit, older, experienced pilots to be retained well into their 40s and 50s (Table 2, U.S. Army Regulation 40-501, 4-12, Class 2).

The refractive problems described above have traditionally been corrected using spectacle lenses. Younger pilots, able to accommodate effectively, can use a single-correction spectacle lens, sufficient to see clearly in the distance and to allow focus on cockpit instruments. Presbyopic pilots need a bifocal spectacle lens, one portion of the lens correcting vision for infinity (appropriate for viewing through an aircraft windscreen), the other correcting for the average distance to cockpit instruments (van de Pol et al., 2000a; Miller, Kent and Green, 1989). The near correction for instrument viewing is set just low enough on the spectacle lens so that it does not interfere when the pilot is looking over the glare screen and out of the cockpit. In some cases, an upper segment may be placed above the central portion of the spectacle lens, correcting for the average distance to the elevated instruments (Figure 16).

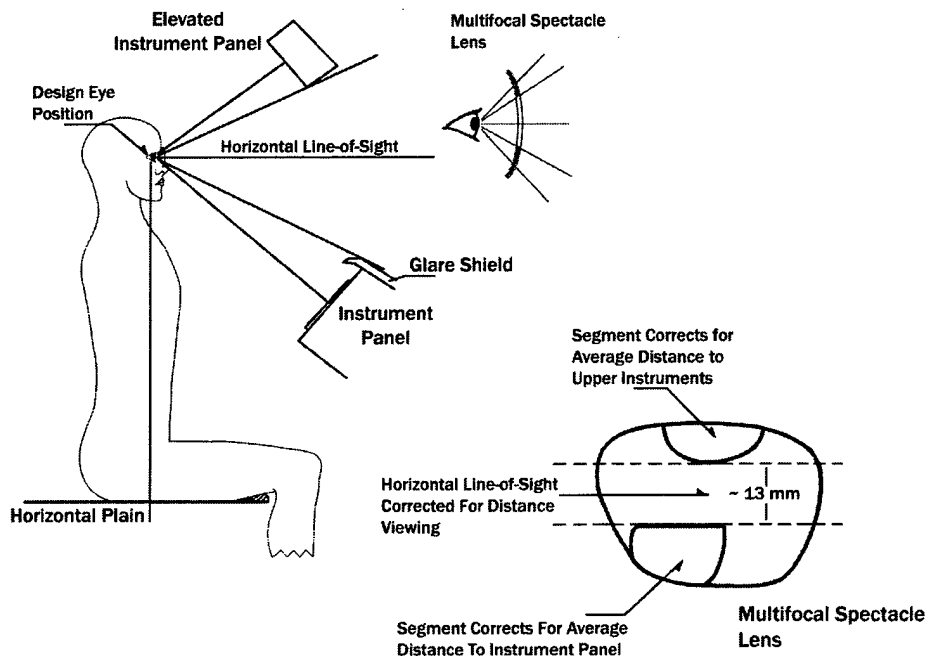


Figure 16. Multifocal spectacle lenses can be used by presbyopic pilots. When combined with the individual's depth-of-field, they can smoothly accommodate objects at multiple distances.

Spectacles pose complex issues for aviators using HMDs. Among these are discomfort when worn with the helmet, slippage, reduced FOV, and interfering reflections off the lens and frame.

Incompatibility with NBC protective masks and some forms of laser eye protection also have been problems. This was specifically illustrated by the AH-64 modified spectacles (Figure 11).

Spectacle lenses are held in a frame, supported on the nose. Two arms attached to the frame hold the assembly to the head. The distance from the back part of the correcting spectacle lens to the eye's corneal surface is called the vertex distance (Figure 17). It ranges from 8 to 18 mm. Lens thickness is usually several mm, depending on material, type of glass or plastic, and lens shape, determined largely by the amount of correction required (Benjamin, 1998). Consequently, the front of the lens forms a surface that is some distance from the face, limiting ability to position or place the eye. This necessitates increasingly required physical eye relief for many optical devices including HMDs (Licina, 1998; Rash and McLean, 1998; Melzer and Moffitt, 1997). If a pilot uses bifocals, the position of the head and eyes are restricted so that the region of the lens having the appropriate power (correction) is centered between the object being viewed and the pupil of the eye. However, in spite of some obvious limitations, eyeglasses work very well in most situations. They are cheap, durable, can be worn for extended periods of time, and are easy to manufacture and maintain. They provide excellent vision and a wide range of vision corrections.

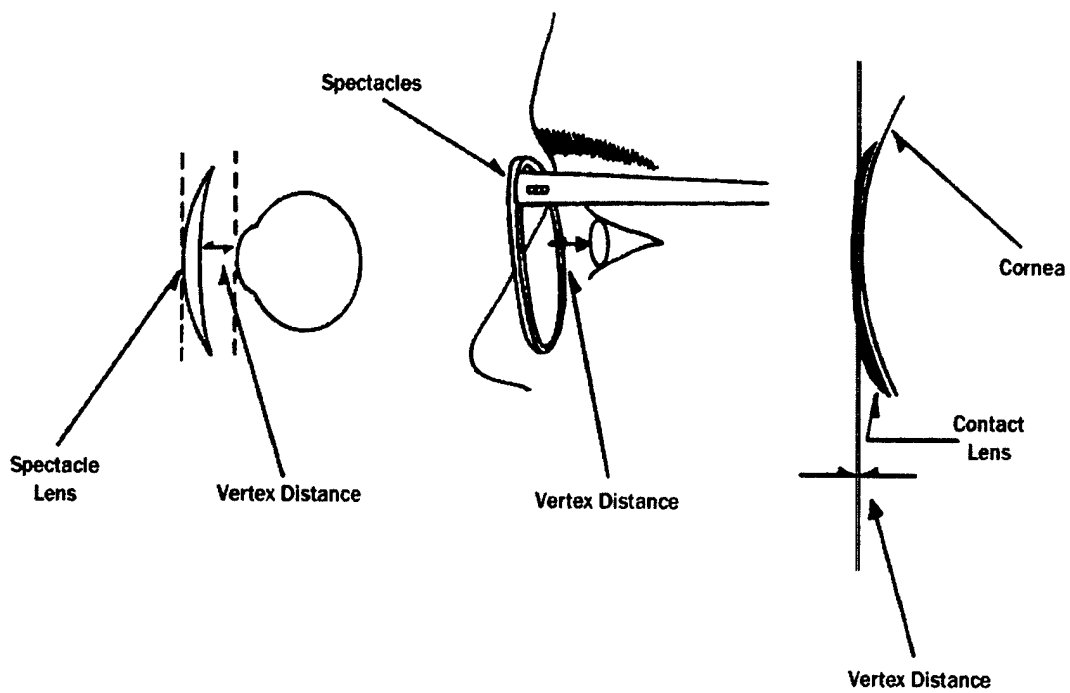


Figure 17. Vertex distance for spectacle lenses and contact lenses.

None-the-less, it is the problem with eyeglasses that have driven the search for other solutions to refractive error correction for pilots. Eyeglasses "present serious compatibility problems with

many advanced optical systems, life support equipment, night vision or laser protective goggles, chemical protective hoods, and other personal protective gear" (Polse, 1990). In addition, there can be problems with perspiration and fogging, G-forces, reflections, seeing in foul weather, and comfort problems/hot spots when worn with helmets.

Behar et al (1990) conducted a survey that isolated vision problems of Apache aviators. They found that spectacle frames specially modified to fit the Integrated Helmet Unit (IHU) were uncomfortable and slipped, regardless of spectacle frame adjustment. Many pilots had a sensation of pressure around the orbit and temples, often a problem associated with wearing a helmet- and helmet-mounted gear. Some pilots were unable to position the eye close enough to the Integrated Helmet Unit combiner lens to provide a full FOV. Consequently, they were unable to see all of the symbology. They also complained of frame reflections off the combiner that cut out some symbology. Bachman (1988) and Lattimore (1991a,b) expressed similar concerns. McLean and Rash (1984) investigated field-of-view losses while using specially modified spectacles with the IHADSS. They concluded that, with proper helmet fit, combiner extension, and central fixation, FOV losses could be eliminated or minimized. The problems associated with use of spectacles with the Apache HMD continue. In a recent survey, Rash et al. (2001) found Apache pilots wearing spectacle corrections expressing many of the same concerns as previously: Inability to properly position the eye when using the HMD/IHADSS/HDU, discomfort, and problems using bifocals with the IHADSS. These problems are exacerbated when a protective mask is worn. Walsh, Rash and Behar (1987) found that many individuals were unable to obtain a full field-of-view in the IHADSS when wearing the AH-64 protective mask without eyeglasses. The M-43 molded protective mask was developed in an effort to overcome restraints imposed by the HDU (Figure 18). Unfortunately, the molded face does not solve all compatibility issues.

**XM-43 NBC Mask**

**XM-48 Mask**

Figure 18. Using protective masks with "glue on" corrective lenses while using the IHADSS. "Glue-on" corrective lenses for the M-43 were shown to produce unwanted magnification and distortion (Crosley, Rash and Levine, 1991).

In summary, there are major problems associated with use of spectacle corrections in the military and by Army pilots in particular. Most of these problems stem from having a fairly large lens with a sizeable vertex distance and a frame that must hold the lens in position with respect to the face. Certainly these two account for incompatibility with many optical devices, reflection problems, pilot discomfort, fogging, reduced visual field, and inadequate poor weather performance. The use of "glue-on" corrective lenses with the M-43 protective mask has created additional problems.

Contact lens use by Army aviators

Use of CLs would appear to solve many of the problems experienced with spectacles, and, as it turns out, they do. Use of CLs to correct for refractive error solves the eye relief, spectacle comfort and reflection problems. Contact lenses are, simply put, more compatible with current optical devices like HMDs/HDUs in the cockpit. However, CLs have their own set of problems, making their use less than universal among aviators.

Many visual corrections involve changes at the cornea itself. The cornea is an unvascularized, transparent, dome-shaped, living tissue at the front of the eye globe (Figure 13). Through it you can see the pupil (opening of the eye) and the iris (a muscle that forms an adjustable aperture that changes the size of the pupil). The cornea averages 0.56 mm in thickness. The diameter of the domed cornea is about 12 mm. It depends on direct contact with the air and on the circulating fluid within the eye for most of its oxygen. The dioptric power of the cornea (a measure of its ability to bend light and focus an image) is around 45 diopters, considerably more than the internal crystalline lens, about 15 diopters, that provides the eye's ability to change focus (Bron, Tripathi and Tripathi, 1997).

CLs have been a popular alternative for vision correction, which solve many of the problems associated with spectacle wear (Figure 19). CLs are formed, circular pieces of bell- or dome-shaped, transparent material that will hold their shape while being held to the cornea of the eye by fluid attraction forces and/or the lid (Mandell, 1988). These small pieces of material vary in diameter from a little less than 7 mm to a little greater than 20 mm. A CL surface largely replaces the cornea optically providing refractive correction of the eye. Use of CLs to correct for refractive error solves the eye relief and spectacle comfort and reflection problems. The reason CLs solve the eye relief problem is because they are very thin, tenths of a mm, and rest on the cornea. This makes the vertex distance effectively zero (Figure 17). From the standpoint of eye relief, a CL on the cornea is virtually indistinguishable from the cornea without a CL. There is no frame used to support CLs, eliminating this source of discomfort and obstruction. The reflection characteristics of an in-place CL are very close to those of the natural, exposed cornea and do not provide any unusual viewing problems.

There are two basic types of CLs, hard and soft. In the 1800s, hard CLs were made of glass. Molded, hard plastic CLs were first made in 1938. Some were made of polymethyl methacrylate (PMMA), a lens material that is still used, albeit not often. These lenses do not absorb water and are impermeable to oxygen. They rest on a layer of tears between the back surface of the CL and the corneal epithelium (the surface cells on the cornea). The hard CL moves when the

wearer blinks, providing a pumping action that forces fresh, oxygenated tear between the cornea and the lens. Today, hard lenses called rigid gas permeable (RGP) CLs are more generally used. They are made from a variety of materials and, as their name suggests, are permeable to oxygen.

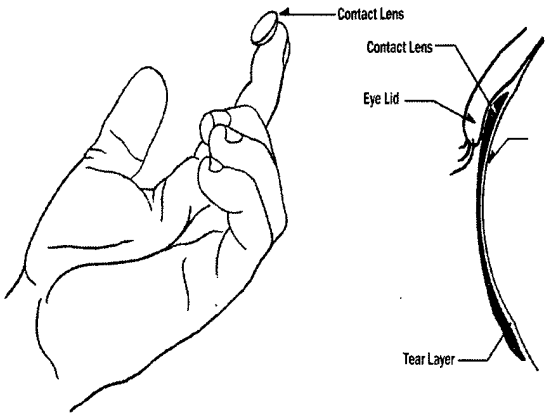


Figure 19. A contact lens can be placed on the cornea and correct refractive error.

A soft, flexible hydrophilic CL was first conceived in Czechoslovakia in the 1950s and introduced in 1968. Since that time many CL materials have been developed with varying flexibility, durability, water content, and oxygen transmissibility. Although soft CLs also move on the cornea, they tend to move less than hard C's and do not perform a tear pumping action. Consequently, the cornea depends, in part, on soft CL gas permeability to supply it with oxygen. Soft contact lenses have a certain water content that, along with thickness, is related to gas permeability. This is of concern, because hypoxia of the cornea, insufficient oxygen supplied to the tissue, can change its clarity and power.

Hydration of the CL is also important in maintaining soft CL shape and directly related to its optical power. Environmental effects can cause changes in CL water content, particularly with hydrogel lenses (Refojo, 1991). These CLs can dehydrate in dry air until they reach equilibrium with tear absorption. If the air is very dry and the individual is in a draft, the water content at equilibrium may be too low, resulting in reduced CL performance and reduced oxygen transmission (Josephson, 1991a,b; O'Neal, 1991; Polse, 1990). Thick CLs with moderate to low water content have a slower rate of evaporation (O'Neal, 1991; Refojo, 1991). Consequently, the U.S. Air Force approved CLs are 58 percent water content or less.

The advantages of CL use were outlined by Crosley, Braun, and Bailey (1974), Tredici and Flynn (1987), and revisited by the *Committee on Vision Commission on Behavioral and Social Sciences and Education National Research Council* (Polse, 1990) and the *Considerations in Contact Lens Use Under Adverse Conditions: Proceedings of a Symposium* (Flattau, 1991). Some of these advantages were: No interference when optical instruments (increased eye relief),

increased field-of-view, no lens fogging, elimination of reflections from spectacle lenses, elimination of some perspiration problems, and use for treatment of specific medical/optical conditions. Tredici and Flynn (1987) went on to list 16 disadvantages, which included: CL intolerance, dislodging (for a variety of reasons, including G-force), cornea (more) prone to edema, often poorer visual acuity than with spectacles, added health care burden, and difficulty of lens hygiene and professional care in the field (Table 3).

Even though great technical strides have been made in CL materials and design, the military has taken a very conservative stance regarding CL use in aviation, and they have done so for good reasons (Wiley, 1993). Military aviators must be able to perform continuously under very adverse conditions. Flight crews can be exposed to a variety of adverse environmental conditions: Chemicals, dust, heat, cold, altitude changes, high and low humidity, G-forces, and adverse weather. The list is lengthy. Further, CLs may have to be cared for under very primitive conditions and worn for extended periods of time. There may not be optometrists or ophthalmologists in a field environment to care for the variety of eye problems that can arise from CL wear. Some of these conditions and some of the more general problems associated with CL wear restricts their use in the military to this day.

There are a number of excellent papers chronicling the history of CL use in military aviation (Wiley, 1993; Lattimore, 1991b; Lattimore and Cornum, 1992; Tredici and Flynn, 1987). These papers give extensive reviews of the problems with CL wear in the military. The focus here will be on the main problems with CL wear associated with Army aviation.

In a recent survey of Apache aviators, Rash et al. (2001) found that almost 33 percent of AH-64 Apache pilots needing visual correction wore CLs while flying, sometimes in combination with spectacles. CL wear for army pilots is currently restricted to Apache pilots, because they must use the IHADSS, which is only marginally compatible with spectacle wear. Only one individual in the sample wore bifocal CLs. Although the number of injuries and diseases associated with CL wear was unclear, these problems were generally rare. They included scratches and abrasions, dry eye and infection.

Soft CLs are relatively resistant to minor dust problems. However, scratches and abrasions do occur. They can be a barrier to some chemical exposures, but can be a sink, absorbing chemicals, such as organic solvents, after a short period of exposure (Dennis et al., 1989a; Nilsson and Anderson, 1982). Consequently, chemical exposure can result in a toxic or allergy problem or simply an irritation. Even tearing can be a serious problem if it occurs at the wrong time in flight when both hands and feet are required to maintain control. As noted by the working group on Contact Lens Use Under Adverse Conditions (Polse, 1990), the cockpit can be a dusty and polluted environment. Although soft CLs are generally not recommended for highly polluted environments, they do seem acceptable in the cockpit (Lattimore and Cornum, 1992; Polse, 1990; Josephson, 1991b; Dennis, 1988; Dennis et al., 1989b; Dennis et al., 1988; Kok-van-Aalphen et al., 1985).

Table 3.

Rationale for and disadvantage of contact lens use in U.S. Army aviation.
(Adapted from Crosley, Braun and Bailey, 1974; Tredici and Flynn, 1987)

RATIONALE FOR CONTACT LENS USE
IN U.S. ARMY AVIATION

1. Increased field-of-vision
2. Good vision in inclement weather outside aircraft
3. No lens fogging
4. Elimination of reflections from spectacle lens
5. No interference with use of optical instruments (reduced physical eye relief)
6. Reduced perspiration problem
7. Compatibility with protective masks
8. Treatment of some medical/optical conditions

DISADVANTAGE OF CONTACT LENS USE
IN U.S. ARMY AVIATION

1. Some individuals cannot tolerate contact lenses (newer materials have improved comfort and accommodation/adaptation)
2. Often poorer visual acuity than with spectacles
3. Lenses can be dislodged (a greater problem with hard contact lenses)
4. Bubbles can form beneath the Contact Lens at altitude (central vision with hard lenses, peripheral vision with soft contact lenses)
5. High G-forces can dislodge contact lenses, particularly hard lenses (a greater problem with Air Force aviation than Army aviation)
6. More difficult and time-consuming to fit than spectacles (particularly binocular and toric lenses)
7. Added health care burden (increased cost from professional fitting, follow-up, care)
8. Foreign body problems (particularly with hard contact lenses in high-particulate environments, smoke)
9. Lens hygiene and professional care difficult in field
10. Increased corneal infection risk (greatest with extended wear lenses that are necessary in the field)
11. Edema with extended wear and altitude (can reduce visual acuity and comfort)
12. Extended wear can be a problem (corneal edema, increased infection risk, comfort, etc.)
13. Can act as a sink in chemical environment (increasing toxicity, irritation, allergic reactions)
14. Allergic reactions (GPC, increased concentration of environmental allergens)

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Levine, Lattimore and Behar (1990) evaluated the use of extended wear soft CLs (Vistakon Acuvue, 58 percent water content) with the Apache M-43 protective mask. Eight experimental and six control subject volunteers were evaluated on a number of cognitive, physiological and vision tests. Among the measures were: High and low contrast visual acuity, contrast

sensitivity, color vision, slit lamp/clinical impressions, and three tests from the physiological assessment battery (PAB). Experimental subjects wore the masks and CLs for 0, 1, 2, 3, and 4 hours. They found no significant changes in visual function, cognitive performance, nor in physiological function while wearing the mask. However, midday increases in conjunctival injection were noted. Bachman (1991) evaluated the effect of airflow in an M-43 protective mask on two soft CL wearers. The airflow is designed to prevent fogging, as the mask cannot normally be removed during an aircraft mission. The subjects wore the mask for 4 continuous hours. Although the subjects reported dry-eye symptoms, no degradation in tear breakup time was measured. Slit lamp examination did reveal severe injection. Neither of these studies dealt with actual chemical environments nor did they deal with practical problems like the dislodging of a lens during a mission. However, within the limits of these studies, it may be concluded that CL wear is compatible with wearing an M-43 protective mask.

Spectacle correction for astigmatism is easy and works very well because the lens is held in place by the frame. Soft CL correction for astigmatism, on the other hand, is not easy and does not work as well; holding the lens in place is problematical. Although rigid contact lenses can correct for astigmatism by completely replacing the cornea optically, they are not authorized for Army aviators. The only contact lens option that Army aviators have for astigmatism correction is a soft toric CL, as astigmatism shows through spherical CLs. The toric CL is specially shaped so that it both corrects the astigmatism and maintains a relatively constant axis orientation while on the cornea. This must all be done while the CL rests on a fluid tear layer and the individual is moving his eyes and blinking. A careful CL fitting by a skilled practitioner is required for this to work well. Acuity is often not quite as good or quite as consistent as with a spectacle correction. Still, it is a viable solution for many applications, particularly when spectacles cannot be used. As found in the survey of Apache aviators that use the IHADSS, pilots try every combination of solutions that they think might work (Rash et al., 2001). These include combining spectacle and CL use or even removing one spectacle lens.

Spectacle correction for presbyopia, though easy, works less well than it does for astigmatism. It's like false teeth, where one can chew, but not nearly as well as before. Depending on the individual, using CLs to correct for presbyopia is not a lot better, and even worse in many cases (Morse and Reese, 1997). The simplest CL solution is to correct one eye for distance vision and one eye for near vision (monovision). This, of course, eliminates binocular vision, which is critical for stereopsis, binocular acuity enhancement and fused single vision. Arguably, these issues are less important when using a monocular HMD. However, visual flexibility is reduced, and it is certainly not a good solution with binocular HMDs. Nakagawara and Veronneau (2000) and Nakagamara and Wood (1998) reported on the 1996 Delta Air Lines 554 accident at LaGuardia Airport. The National Transportation and Safety Board concluded that the, "probable cause of this accident was the inability of the pilot to overcome his misperception of the airplane's position relative to the runway, due to the use of monovision contact lenses." Another approach to CL correction for presbyopia is simultaneous vision (SV). SV requires that both near and distance correction be presented in the pupil at the same time (aspheric curved lenses, concentric zones, diffraction optics, etc.). With this solution, part of the light collecting power of the CL is used for near and part for distance vision. This approach also assumes that the entire correction is within and stays within the pupil. A fairly large pupil is required in order to have sufficient light collecting power. It should also be pointed out that the pupil tends to get smaller

with age, which can work against this solution for many individuals. A third approach, called alternating vision (AV) requires that a portion of the contact lens be used for distance correction and part for near. A combination of lid support with eye movement is used to bring the AV CL into place. A loose lid, common with aging, or any of a variety of environmental conditions that cause improper movement of the AV CL can reduce vision flexibility and dependability. The AV solution also is not viable with elevated instruments. A combination of these approaches can also be used.

Low-light vision, contrast sensitivity, acuity and low-contrast acuity are generally poorer with bifocal CLs than with bifocal eyeglasses (Morse and Reese, 1997). When clear, flexible, binocular vision can make the difference in a combat situation, it is clear that current CL correction for presbyopia does not provide a reliable vision edge. The trade-off is between two poor-to-fair solutions to presbyopia, CLs and spectacles.

A number of studies have shown that soft CLs can be worn for an extended period (Socks, 1991; Bachman, 1988; Leibrecht and Bachman, 1989; Leibrecht et al., 1990; Bachman et al., 1987; Nilsson and Persson, 1986). This is essential in operational settings where ophthalmic services are generally unavailable and hygienic care is difficult. An extensive study by Lattimore and Cornum (1992) recommended planned replacement daily wear paradigms for garrison (home station) use and disposable 3-day/2-night wear in the field. It must be added that extended wear increases risk of corneal hypoxia, edema, and infection. Using disposable CLs reduces, but does not eliminate, the increased risk. Current Army policy states that backup soft CLs need to be carried by pilots in the field, as well as backup spectacles.

Additional extreme conditions experienced by Army aviators include heat and facial perspiration, cold, low and moderately high altitudes, high humidity, turbulent air flow and vibration. Heat, per se, is not a problem when wearing CLs. However, resulting facial perspiration can cause sweat to enter the eye. It may not dissipate as rapidly with CL wear, continuing to be an irritant and distraction that cannot be attended to (Josephson, 1991a). Although high humidity does not have much direct effect on vision with soft CLs (Eng, Harada and Jarerman, 1982), it can exacerbate perspiration problems. There is little evidence that cold is a serious problem for CL wearers. Socks (1991, 1982) and Socks and Graton (1981) subjected CL-wearing rabbits to strong winds and very low temperatures for 3 hours. Only minor epithelial damage was experienced. A survey of military personnel assigned to cold geographical areas indicated that eye redness was the main complaint. Vibration, a constant with rotary-wing aircraft, also has little affect on vision performance with CLs (Josephson, 1991a, 1991b; Brennan and Girvin, 1985).

Some studies have shown that at hypobaric pressures neither the hydrogel CL fit nor its performance change (Lowther, 1991a, 1991b; Tredici and Flynn, 1987). O'Neal (1991) reviewed a number of studies that evaluated vision performance at aviation altitudes and found that, "In general, they report only minimal or no effect on visual acuity." He also reported that this did not preclude some swelling due to hypoxia. High altitude flight can result in bubbles forming under CLs. With hard CLs these bubbles form under the CL center and get larger with altitude. This will affect vision. Bubbles also can form under soft CLs at altitudes as low as 6000 feet, but they form at the periphery. They do not affect vision (Flynn et al., 1988, 1986).

Castren (1984) reviewed the literature on the effects of low pressures (high altitude) on soft CL wearers. He found effects ranging from changes in dark adaptation and stereoscopic vision (9-16,000 foot altitude) to corneal erosion and stromal opacities (3 hour exposure to a simulated 12,000 feet). Brennan and Girvin (1984) and Eng, Rascoe and Marano (1978) reported on use of high and medium water content soft CLs by subjects exposed to a simulated altitude of 27-30,000 feet. They found no biomicroscopic changes. Brennan and Girvin (1984) reported small decrements in acuity without measured change in contrast sensitivity, while Eng, Rascoe and Marano (1978) observed only scleral injection. It's clear from the literature that a number of factors combine to determine the effects of altitude on soft CL wearers. These include humidity, rate of ascent, water content of the lens, and time at altitude.

Hard CLs lenses are not allowed for Army aviators (AR 40-63 [Department of the Army, 1986]). This is in spite of their ability to correct for astigmatism; something spherical soft lenses do not do well. Accidental displacement, susceptibility to dust, smoke and chemicals, central bubble formation at higher altitudes, and inability to be worn for extended periods of time have been major reasons (Lattimore and Cornum, 1992; Josephson, 1991a, 1991b; Lowther, 1991a; Polse, 1990; Nilsson and Anderson, 1982).

Soft spherical CLs and soft toric CLs are presently acceptable for Army aviators. However, current Army policy states, "that contact lens wear will be prohibited during gas chamber exercises, field training, and combat." AR 40-63 further states "The issue of contact lenses is specifically prohibited for use in environments where exposure to smoke, toxic chemical vapors, or dust occurs."(Department of the Army, 1986) Strict guidelines exist for waivers to this policy, originally only for AH-64 Apache pilots due to protective masks/IHADSS incompatibility, more recently for all classes of aviation personnel. Current Army policy states that backup soft CLs, solutions and backup spectacles must be carried by aviation personnel in the field. Soft contact lenses should be worn primarily on a daily-wear basis (no more than 16 hours per day) and a minimum of 6 to 8 hours without contacts is recommended between periods of contact lens wear. Wear during sleep is discouraged, although operational conditions may preclude removal and therefore removal of contacts is recommended at the first opportunity in order to minimize the risk of complications.

## Summary

As the Working Group on Contact Lens Use Under Adverse Conditions (Polse, 1990) states, "...helicopter personnel currently face the greatest spectacle incompatibility problems of any aviators, even as they face the greatest possible stumbling blocks to the successful use of contact lenses." CL use solves the eye relief, reflection and discomfort problems arising from spectacle use with HMDs. However, they do not provide a particularly good, general solution to presbyopia or astigmatism, and present new issues of their own, i.e., logistics, hygiene, use under extreme conditions, etc. At best, CL can be used in situations where spectacles do not work well. At worst, they create more problems than they solve. In any case, they are here, probably to stay. Refractive surgery is the latest refractive option emerging and correction may provide an additional solution. A discussion of refractive surgery follows.

## Advanced techniques for visual correction

### Refractive surgery technologies

Refractive surgery includes any procedure that surgically modifies the optical power of the human eye in order to eliminate or reduce the need for spectacles or contact lenses. The earliest known corneal surgery was performed prior to the turn of the 20th century in 1894 by William Bates, who made nonperforating straight incisions in the cornea to reduce astigmatism (Elander, Rich, and Robin, 1997). Through the remainder of the 20th century, the most common use of surgical intervention to change the power of the eye was the use of incisions in the cornea to correct unwanted or induced astigmatism after cataract surgery. The large peripheral corneal incisions needed to extract the cataractous lens often led to significant unequal power of the postoperative eye and a few accurate incisions in the peripheral cornea easily reduced astigmatism with minimal additional intervention. However, it was not until the advent of radial keratotomy (RK) in the 1970s that refractive surgery entered the popular mainstream. Today's arsenal of refractive surgery techniques includes everything from incisions and laser reshaping of the cornea to ocular implants. Although most techniques have been successful in reducing the individual's need for spectacles or contacts, almost all techniques have side effects that to varying degrees may affect visual performance in the operational environment.

Refractive surgery is gaining increased acceptance in the general public as an alternative to glasses and contact lenses for the correction of refractive error. The most significant technological gain for this acceptance is the development of the excimer laser as an instrument to reshape the cornea. The precision of laser ablation of corneal tissue versus manual incisions results in more accurate outcomes with less fluctuation of resulting refraction than RK (Binder, 1994; Hjortdal et al., 1996; Seiler, Hell and Wollensak, 1992). In the United States, the excimer laser for photo-refractive keratectomy (PRK) received Food and Drug Administration approval in October 1995. The number of refractive surgery procedures being performed in the United States is increasing each year with 1.5 million procedures estimated for 2002.

### Corneal procedures

Since the cornea is the primary refracting surface of the eye and the most accessible, modification of its curvature can very successfully reduce or increase the power of the eye such that the individual is less dependent on glasses or contacts or may not need any further correction at all. The cornea can be modified through the placement of incisions, through tissue interaction with lasers, or through implants or inlays.

### Radial keratotomy (RK)

RK changes the refractive power of the cornea through incisions placed in a radial pattern in the corneal surface, often 8 incisions are used and each incision cuts up to 90 percent of the depth of the cornea. The cuts serve to weaken the peripheral cornea which causes it to bulge outward and the central cornea to consequently flatten (Figure 20).

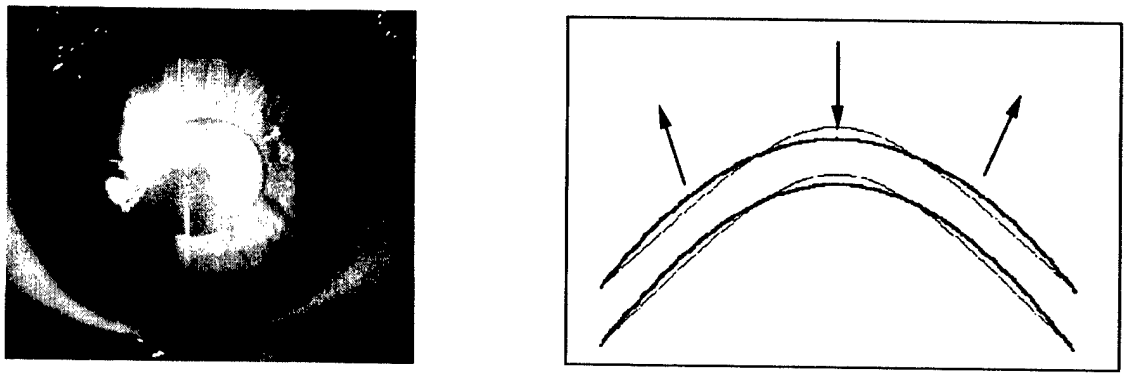

Figure 20. Corneal changes associated with Radial keratotomy

Advantages: RK can reduce myopia with as few as three radial incisions of the anterior cornea, and visual recovery is generally fairly quick. More incisions of the cornea can be made where insufficient refractive correction was initially achieved, although this practice is not always successful. RK is still periodically used for the correction of low amounts of myopia, due to its low cost and rapid recovery.

Disadvantages: Overcorrections, which leave the patient hyperopic, are not correctable through the addition of more incisions and often mean returning to contact lens or spectacle wear. The Prospective Evaluation of Radial Keratotomy (PERK) study and other studies have found that the most significant consequences of RK were unpredictability of results, diurnal fluctuations of refraction, long-term progression towards hyperopia, and visual disturbances including haloes and glare (Bourque et al., 1986; Bullimore, Sheedy, and Owen, 1994; Ginsburg et al., 1990; Lynn, Wayne, and Sperduto, 1987; Warin, Lynn and McDonnell, 1994). Numerous studies have shown that altitude and hypobaric environments can cause significant corneal thickening and curvature changes leading to visually disabling effects on eyes that have had RK, a situation with military-significant consequences (Mader et al., 1996; Mader and White, 1995; Ng et al., 1996; Simsek et al., 1998; Winkle et al., 1998).

Photorefractive keratectomy (PRK)

PRK is a procedure that changes the refractive power of the eye using laser energy to reshape the corneal surface (Figure 21). The corneal epithelium is removed and an excimer laser ablates a 6- to 7-mm diameter area of the central corneal stroma to reduce corneal curvature in myopic corrections. For hyperopic PRK, an annulus is ablated which results in an increase in central corneal curvature. After the procedure, the epithelium grows back over the corneal surface to reestablish corneal integrity.

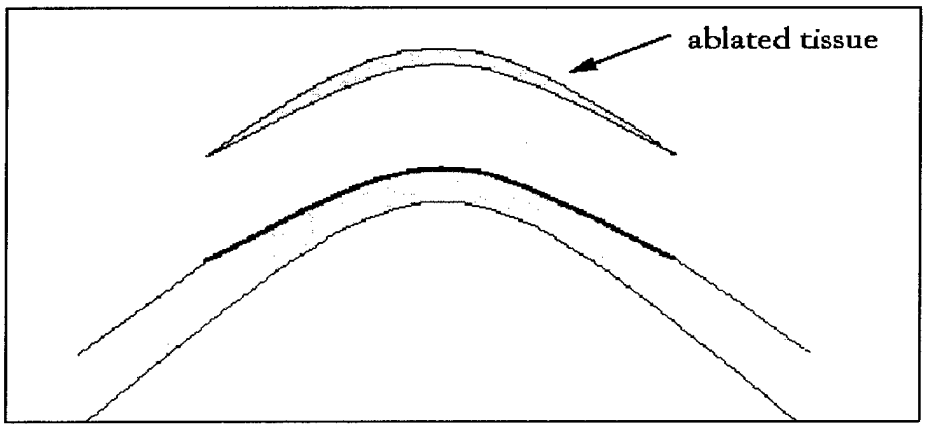


Figure 21. Corneal changes associated with myopic photorefractive keratectomy (PRK).

Advantages: The excimer laser used to reshape the cornea can very precisely sculpt the surface of the cornea to change its power. PRK can be used to correct myopia, hyperopia and astigmatism; and higher levels of myopic correction are possible than with RK.

Disadvantages: Since the epithelium has to be removed to resculpt the corneal stroma, during the healing process the individual can experience pain and sensitivity to light, much like experiencing a very large corneal abrasion. Also during the healing process, a subepithelial haze may develop, generally peaking at about 1 month postoperatively and dissipating by 3 months postoperatively. Corneal haze may affect visual performance, especially at its peak density. In about 2 cases in 1000, the cornea does not properly heal and the individual will lose 2 or more lines of best-corrected visual acuity.

Laser in-situ keratomileusis (LASIK)

LASIK also uses the excimer laser, but for myopic corrections, the plus lens is subtracted from the mid-stroma only after an 8- to 9-mm diameter corneal flap is created and the stromal bed is exposed. A microkeratome is used to split stromal lamellar layers and create a corneal flap of approximately 160 microns thickness with a hinge. The excimer laser ablates the stromal bed to remove a positive "lenticule" as is done in PRK. The flap is then repositioned over the ablation zone. Hyperopic corrections use an annulus ablation profile as in PRK. The flap generally has a hinge either nasally or superiorly so that after the ablation, the corneal flap is returned to its original position without rotation (Figure 22). The flap is held in place by surface tension forces until the epithelium reconnects at the periphery of the flap.

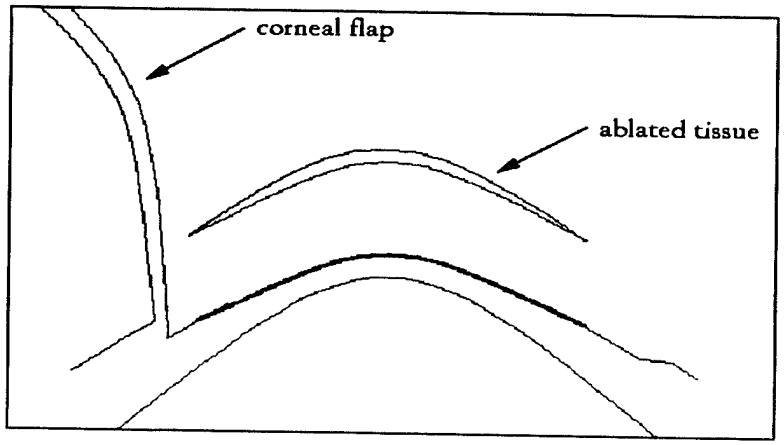


Figure 22. LASIK for myopia.

Advantages: The recovery time after LASIK is much shorter than after PRK. Patients often have excellent vision within hours of surgery and do not experience more than a little discomfort due to the procedure. LASIK is generally the procedure of choice for higher corrections, since the risk of corneal haze development is higher with PRK when more tissue is ablated at the corneal surface.

Disadvantages: Stromal healing in the interface is much slower than epithelial healing and may continue up to 18 to 24 months after the procedure. The greatest risk for displacement of the flap is in the first 3 months after the procedure, since the epithelial boundary is the primary factor maintaining the flap position. The disadvantage of LASIK in a military setting is the prolonged healing time of the corneal flap and the consequent increased possibility of flap displacement due to trauma. Slow flap healing is evidenced by the ability of corneal surgeons to lift the flap without special instrumentation up to 1 year postoperatively if a retreatment is desired. Besides the risk of traumatic flap displacement postoperatively, LASIK has an increased risk of intraoperative complications due to problems with the microkeratome used to cut the flap and the possibility of infiltration or infection under the flap. An additional concern is the reduction in the overall stability of the cornea by cutting a 160-micron flap and then further reducing the thickness of the central cornea with the laser ablations. If the residual corneal bed approaches 250 microns or less, the cornea becomes susceptible to iatrogenic ectasia (central steepening due to decreased biomechanical strength and decreased resistance to internal ocular pressure). The risk of loss of two lines of best-corrected visual acuity after LASIK is the same as that experienced after PRK; however the causes of visual loss are different for LASIK.

Laser-assisted sub-epithelial keratectomy (LASEK)

LASEK is a newly emerging alternative to PRK and LASIK, melding aspects of both procedures in an effort to reduce postoperative pain and healing time, minimize the development of corneal haze, and eliminate the complications associated with the LASIK flap. In LASEK, the corneal epithelium is "loosened" through the use of an alcohol preparation. The epithelium can then be rolled back to expose the anterior corneal stroma, which is then ablated and the epithelium rolled back into place.

Advantages: Visual recovery is faster than with PRK, but slightly slower than after LASIK. The epithelium acts as a natural bandage aiding in the healing process of the cornea, this may serve to minimize infections and reduce overall healing time. The other main advantage is that in cases where the thickness of the cornea is a concern, LASEK does not thin the cornea as LASIK does and there is a reduction in the development of haze as PRK produces in higher corrections.

Disadvantages: In some cases, the epithelium sloughs off and the procedure becomes a PRK. The long-term implications of the use of alcohol on the epithelium or the anterior corneal layers is not known; however, it is not anticipated to cause more than transient effects.

Intrastromal Corneal Ring Intacs®

Intrastromal Corneal Ring Intacs® is a system of two arcs that are implanted in the peripheral cornea at two-thirds the depth of the stroma. The arcs add thickness to the peripheral cornea causing a flattening of the central cornea and a correction of myopia or astigmatism, depending on the thickness and length of the arcs (Figure 23). Only low amounts of correction are possible with this surgical option.

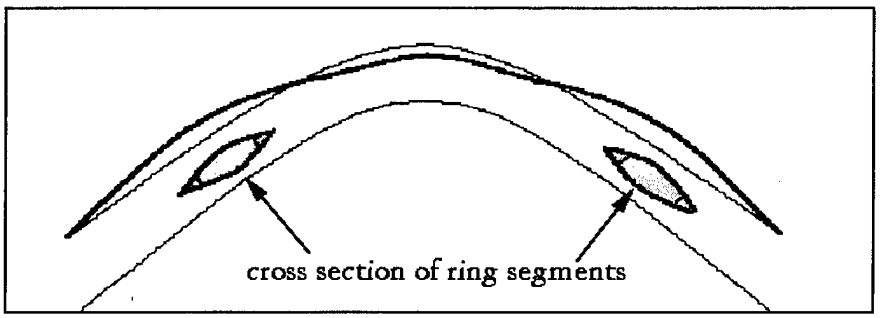


Figure 23. Intrastromal corneal ring segments

Advantages: This is the only corneal procedure that maintains the prolate shape of the anterior corneal surface, in that the central cornea is steeper than the peripheral cornea. The other advantage to the rings is that they are removable and/or replaceable if the desired correction or visual endpoint is not achieved. If the rings are removed, the cornea will return to its preoperative shape.

Disadvantages: This corneal procedure requires more surgical skill than the other procedures listed; the surgeon has to create two channels in the corneal stroma and then feed the arcs into position. Although the implants are placed outside the central corneal area, they can contribute to glare symptoms in patients who have large pupils, especially at night.

## Intraocular procedures

It is also possible to change the refractive power of the eye by altering the power of other refracting elements of the eye, particularly the crystalline lens. The most common intraocular procedures include clear lens extraction, cataract surgery and the implant of intraocular lenses, and the addition of phakic intraocular lenses into the eye. The general disadvantage of any intraocular procedure is the increased risk of intraocular infection, as with any invasive procedure.

## Clear lens extraction

The crystalline lens of the eye provides about one-third of the refracting power of the eye. Removing can therefore reduce a severely myopic eye by a significant amount of power such that the individual is able to see.

Advantages: Lens removal is relatively uncomplicated with today's small incision techniques and phakoemulsification of the crystalline lens.

Disadvantages: Once the crystalline lens is removed, the individual is no longer able to accommodate to focus on near objects, necessitating the use of bifocal lenses; the resulting power of the eye is difficult to predict, requiring a residual correction in most cases; the lens provides a buffer to movement of the intraocular contents, it's removal increases the risk of retinal detachment.

## Intraocular lens (IOL)

An IOL is commonly implanted into the eye after cataract surgery, which makes cataract surgery a form of refractive surgery. The IOL is placed into the capsule that remains after the cataractous portion of the lens is removed. IOL's can be single vision or multivision and, in some cases, are created with an aspheric design to minimize aberrations in the eye.

Advantages: The IOL is often significantly clearer than the natural lens and, as such, can provide an increase in image clarity to the patient. If a patient had a large refractive error prior to surgery, this surgery can often reduce or eliminate their need for glasses or contact lenses.

Disadvantages: Even with the addition of an IOL in the lens capsule, the eye is still at an increased risk for retinal detachment. If a lens if not properly centered on the visual axis, even an aspheric design lens will not correct the aberrations of the eye and the individual will have visual symptoms (usually glare or halos around lights).

## Phakic intraocular lense (IOL)

If the natural lens is left in place and an IOL is placed in the anterior chamber in front of the lens, this system can be used to correct very high amounts of refractive error.

Advantages: Since the crystalline lens is not removed, the individual is still able to change accommodative state to focus for near and distant objects.

Disadvantages: In some cases, the Phakic IOL or intraoperative instruments come into contact with the front surface of the natural lens causing a cascade of reactions to opacify (make opaque) that portion of the lens; in other words, the individual can develop a cataract necessitating cataract surgery.

Refractive surgery and ocular aberrations

Although great leaps have been made in the technologies surrounding refractive surgery and the outcomes have been much more precise, there are still problems associated with refractive surgery. Most notably, individuals may experience problems with night vision, the presence of halos or glare at night, increases in dry eye symptoms (especially after PRK or LASIK), and risks associated with surgeries that expose the eye to possible infections or reactions to agents used in the surgery (such as anesthetics). The problems with night vision, halos and glare have been mainly associated with an increase in the aberrations of the eye after refractive surgery. Aberrations due to changes in the shape of the cornea are most pronounced if the refractive correction is high, the ablation zone is small or the pupil is large (Applegate and Gansel, 1990; Applegate and Howland, 1997; Martínez et al., 1998; Oshika et al., 1999). Aberrations are generally minimal when the refractive correction is less than 6.00 diopters of myopia or 4.00 diopters of hyperopia. Most lasers ablate a zone larger than the daylight pupil size; however, in some cases, pupil size under low light conditions may exceed the ablation area and cause visual disturbances. In a normal eye, the aberrations of the anterior surface of the cornea are balanced by opposite aberrations of the remaining refractive surfaces in the eye, including the posterior corneal surface and the crystalline lens. The anterior surface of the cornea is the primary refracting surface of the eye; therefore, modifications at this surface have the greatest effect on the quality of the image formed by the eye. If the aberration balance of the eye is modified, there are various impacts on visual performance ranging from subtle visual disturbances to severe distortions.

A significant amount of work is being done to improve the outcome of refractive surgery. One main technology has contributed towards this effort, the capability to measure the higher order aberrations of the eye. Most refractive surgery technologies have increased the basic aberration level of the eye through the induction of shape changes or a mismatch between the optics of the added components and the optics of the eye. The most promising procedures for reducing the amount of induced higher order aberrations are the corneal refractive surgery procedures or custom implants. Using a scanning spot laser, very precise ablations can be applied to the cornea in either PRK or LASIK. The problem with PRK is that the cornea undergoes a certain amount of unpredictable healing as the epithelium regrows over the corneal surface and the anterior corneal stroma responds to the laser insult. This can result in an undoing of the precise ablations and a reduction in the overall desired effect of the correction. With LASIK, the replacement of the flap over the ablated area is much like putting a thick blanket over a precisely sculpted surface, the end result is not as finely sculpted as anticipated. Ocular or corneal implants may help to solve these problems; however, they too require a precision that may be too difficult to obtain at present. Although an implant may be accurately shaped to

counter the aberrations of the eye while correcting the refractive error, the implant has to be stable in the optical axis without any rotation or translation.

## Military studies of refractive surgery

Navy studies of PRK have been ongoing since 1994 (Schallhorn, 1994; Schallhorn et al., 1996; Schallhorn et al., 1998; Tanzer et al., 1998). Subjects in the early studies have been Navy SEALS and nonaviators. The results of the Navy SEALS study were excellent, although one SEAL had significant night vision disturbances and did not have the procedure completed on his other eye. Improvements in the laser ablation parameters, including a larger ablation zone and smoother surface, have led to a decrease in the incidence of night vision disturbances in subsequent studies. The general findings of all the Navy studies have been excellent in terms of efficacy and safety (Schallhorn, 1999). Refractions are stable after 8 to 10 weeks, corneal clarity has returned to preoperative levels in 3 months and over 99 percent of subjects are correctable to 20/20 by 6 months postoperative. Contrast sensitivity and the report of night vision disturbances return to preoperative levels between 2 and 3 months postoperative. Studies have shown that moderate altitude does not cause PRK and LASIK corneas to undergo the same significant corneal thickening and curvature changes as previously seen with RK (Davidorf, 1997; Mader et al., 1996; van de Pol et al., 2000b).

The Air Force efforts to evaluate refractive surgery have concentrated on determination of the effects of altitude, G-forces, and disability glare (commonly experienced by Air Force aviators). The study is examining 80 nonflying volunteers using clinical vision tests and operational tests for the three conditions listed. At this time, only PRK is being considered for aviation personnel, due primarily to the concerns about LASIK flap stability in the remote possibility of an aircraft ejection. Initial findings of Air Force studies have found a measurable change in contrast sensitivity after PRK; efforts are continuing to determine the operational impact of these visual changes in the flight environment (Ivan, 2002).

The Army is currently running a number of studies to evaluate refractive surgery for the aviation environment. The "accession study" will evaluate flight applicants who have had PRK or LASIK to determine whether visual or flight performance of 100 PRK and 100 LASIK candidates differs from a control group of 100 nonsurgical flight school candidates. The "rated aviator study" will measure the flight and visual performance of 80 UH-60 pilots before and after refractive surgery, 40 will receive PRK and 40 will receive LASIK surgery, to determine whether the surgical intervention has an impact on qualified aviators' performance. A final study is a "surveillance" effort in conjunction with the U.S. Army Aeromedical Activity (USAAMA), in which aircrew members, flight surgeons, flight medics and air traffic controllers are allowed to have refractive surgery (PRK or LASIK) under the provisions of an Aeromedical Policy Letter and the Corneal Refractive Surgery Surveillance Program. Their visual performance and surgical outcomes are maintained on file at USAAMA, and they must complete an annual eye exam as part of their flight physical.

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