Chapter 26

THE DEVELOPMENT OF EYE ARMOR FOR THE AMERICAN INFANTRYMAN

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"If protection of the eyes of combat soldiers were a simple affair, that protection would have been provided long ago."

—J. Fair, 1952[1]

INTRODUCTION

Attempts to protect the soldier's body in war have been made at least since the fifth millennium BC.[2] Although many energetic and creative individuals have attempted to develop eye armor, the great majority of emmetropic American infantrymen, the soldiers most at risk, continue to enter combat with their eyes as exposed to the hazards of war as were the eyes of the first bellicose hominid. The following is an account of the development of eye protection for the American infantry, a twenty-year effort which culminated in the production and distribution of such eye armor for the emmetrope and ametrope, protective against the small missile and blunt-force threat, and against some of the eye-threatening laser wavelengths. This article will be concerned primarily with the protection of the eyes of infantrymen, the soldiers who suffer by far the preponderance of injuries in war and who are "the most valued component of the military force."[3]

It is necessary to define *eye armor* as the term is used in this report because the eye is vulnerable to many threats, but protection against only some of them is necessary and possible. The major threat to the eye of the infantryman in combat is the small missile, as has been true since World War I.[4] *Eye armor* is defined primarily, though not exclusively, as that component of personal body armor that can protect the eyes of the infantryman from such a threat.

EYE INJURIES IN WAR

Injuries to the eye and its adnexal structures are of increasing significance in war. The incidence of eye injuries sustained by our forces has increased 18-fold since the US Civil War, reaching 9% in the Vietnam War (see Table 26-1). Conflicts since Vietnam have continued to demonstrate the increasing

TABLE 26-1

OCULAR WAR INJURIES AS A PERCENTAGE OF TOTAL WAR INJURIES

War	Year(s)	Percentage	Soldiers Involved
Crimean War	1854–1856	0.65	British
		1.75	French
US Civil War	1861–1865	0.5	American
Franco–Prussian War	1870–1871	0.86	Prussian
		0.81	French
Russo–Japanese War	1904–1905	2	Russian
		2.22	Japanese
World War I	1914–1918	2	American
World War II	1939–1945	2	American
Korean War	1950–1953	2.8	American
6-Day War	1967	5.6	Israeli
Yom Kippur War	1973	6.7	Israeli
Vietnam War	1962–1974	9	American
Lebanon War	1982	6.8	Israeli
Desert Storm	1991	13	American

Data from Belkin M, Treister G, Dotan S. Eye injuries and ocular protection in the Lebanon War, 1982. *Isr J Med Sci* 1984;20:333-338. Heier JS, Enzenauer RW, Wintermeyer SF, Delaney M, La Piana FG. Ocular injuries and diseases at a combat support hospital in support of Operations Desert Storm and Desert Shield. *Arch Ophthalmol* 1993;111:795-798. Wong TY, Seet MB, Ang CL. Eye Injuries in twentieth century warfare: A historical perspective. *Surv Ophthalmol* 1997;41:433-459.

frequency of ocular injuries on the battlefield. Data derived from experience in highly mobile armored combat (Yom Kipper War, 1973) show that 6.7% of all combat injuries were isolated ocular injuries. This compares to figures of 2.0% in WW II and 2.8% in Korea. In the Yom Kipper War 70% of the eye casualties were among tank crews and armored infantry, whereas only 44% of the total war casualties served in the armored corps.[5] Ocular injuries accounted for 13% of the patient volume at a major combat support hospital during the ground phase of the recent Gulf War.[6] Making these figures even more ominous is the finding that 20% to 50% of ocular injuries are penetrating or perforation globe injuries and up to 28% are bilateral (see Fig. 26-1).[7,8] Eye injuries are a common occurrence on the modern battlefield.

Not only are ocular injuries common in combat they are also devastating. A soldier who sustained a penetrating wound of the globe in combat in Vietnam had a 50% of losing the eye no matter how prompt and expert the care.[6] This figure should be compared with the dramatic decrease in the percentage of wounded dying from their wounds (from 14.1% in the US Civil War to 4.5% in World War II, 2.5% in the Korean War and 2.6% in the Vietnam War).[3,9] Only 25% of the Vietnam eye casualties could return to active duty, while 83% of all surviving wounded could do so.[10,11] The Wound Data and Munitions Effectiveness in Vietnam (WDMEV) team determined that 7.4% of interviewed casualties reported "eye disability" after wounding.[12] Of these eye casualties, 79% were partially disabled and 21% completely disabled (at least temporarily).

The cost to our society of eye injuries (both combat-related and during peacetime) is significant, both monetarily and medically. For example, a 20-year-old E-4 (corporal) who loses one eye in the line of duty will receive at least $189,000 over his expected lifetime, and an O-5 (lieutenant colonel) with 18 years of service will receive at least $477,000.[13] Fortunately the great majority of these accidents can be prevented.[14] This fact has resulted in the general requirement of the American National Standards Institute (ANSI) Z-87.1-1979 standard that "...eye protection shall be required in hazardous environments where there is a reasonable probability that injuries can be prevented by the use of such protection."[15] It would seem appropriate that the same concern about eye injuries in the civilian workplace should exist for the soldier in combat.

Despite the obvious concern for ocular injuries on the battlefield, it must not be forgotten that soldiers are at risk for eye trauma even during peacetime. Tarabishy in 1983 reported that 40% (75 of 157) of injuries sustained by soldiers from four types of automatic weapons over a six-year period in peacetime were to the eye.[16] McMarlin and Connelly reported that 5% of injuries seen in a Army field hospital during a military training exercise were to the eyes.[17]

Fig. 26-1. Vietnam eye injuries. (**a**) Fragment (probably aluminum) on anterior lens capsule. (**b**) Fragment of rock on iris, air bubbles in anterior chamber, and iris prolapse through wound of entry. (**c**) Penetrating wound of globe from "mud blast" injury. Photograph: Courtesy of Richard M. Leavitt, MD.

ELEMENTS IN EYE ARMOR DEVELOPMENT

The development of eye armor was begun during World War I but did not reach fruition until just prior to the Gulf War, in large part because of the complexity of the task. Five elements must be considered: 1) the tasks of the infantryman; 2) the ocular threats; 3) the mind-sets of those to be protected and of those in positions of leadership; 4) the materials available to provide protection; and 5) available funds to support the costs of development, testing, modification, provision, maintenance, and replacement of eye armor.

The missions of an infantryman in combat can be reduced to firing his weapon or weapons, moving, identifying friend or foe, estimating range, communicating, and surviving. His eyes are his primary fire control mechanism and are important in maneuvering (as he is often the hunted as well as the hunter), and in communicating (a significant amount of which is done primarily with the eyes). The sine qua non for eye armor for the infantryman is that it must not only protect his eyes against several threats but must neither interfere with his ability to accomplish his missions nor with his chances of surviving them unharmed. Because the infantryman trains and fights under the most rugged conditions, equipment provided him must be simple and very rugged. It must also be compatible with his equipment (eg, helmet and weapon). Eye protection suitable for a pilot who fights seated and protected by his aircraft canopy may not serve for the infantryman who often must run, jump, and hit the ground hard and often. The detection of movement in the periphery of his visual field is of such great importance to the infantryman, correlating directly with his chances of survival, that he will reject any eye armor that interferes with his peripheral vision. This fact has been appreciated for at least 70 years – "...the fighting man must keep his whole visual acuteness, or at least have it but slightly modified by the protecting apparatus placed before the cornea; the visual field must not be manifestly narrowed."[4]

In the 20th century, body armor (except for the helmet) has been worn mostly by those on the defensive.[18] If eyes are unprotected, soldiers on the defensive suffer more eye injuries than do those on the offensive.[19] Since the head and neck region of the soldier are the "locus of the major sensory equipment in the human ... continuous appraisal of his situation vis-a-vis the enemy forces the foot-soldier to expose his head more often than any other part of his body."[3] Even taking this into account, an infantryman's eyes are injured at a frequency at least ten times higher than might be expected based on target size alone.[20] Eye injuries, furthermore, are always important; a small corneal abrasion can completely incapacitate a soldier in combat and penetrating injuries of the globe require medical evacuation.

In wartime, the major ocular threat is from fragments generated by detonating munitions (see Table 26-2), and we must expect that laser weapons will also be employed against our soldiers' eyes in any future conflicts. Eye-hazardous laser range finders and target designators are widely deployed now. The problem of protecting the eye against even a few wavelengths in such a way as not to impair the soldier's performance is a monumental task. The advent of the frequency-agile laser on the battlefield will only increase the problem.[21] Other significant immediate or potential threats to the eye are fragments from improved conventional munitions, flechettes (dart-like missiles released from artillery projectiles), ultraviolet light, flash from nuclear weapon detonation, sunlight, wind, dust, microwaves, particle beams, blast, heat, and poison gases. There is no way to protect against all of the threats all of the time, but it is now possible to protect against the small missile, the ultraviolet light, and blunt-force threats very well, and also against some of the eye-hazardous laser wavelengths. An analysis of ocular injuries to American servicemen in Vietnam estimated that the wearing of 2-mm poly-

TABLE 26-2

CAUSES OF NONFATAL WOUNDS

Agent	World War II (%)	Korean War (%)	Vietnam War (%)
Bullets	19.7	27	30
Fragments*	66.1	65.5	68
Other	14.2	7.5	2

*Fragments generated from explosive projectile shells, rockets and bombs, grenades, booby traps, land mines, and other munitions

Data from Reister FA. *Battle Casualties and Medical Statistics: US Army Experience in the Korean War.* Washington, The Surgeon General, Department of the Army, 1973, pp 48, 51. *Evaluation of Wound Data and Munitions Effectiveness in Vietnam.* US Departments of the Army, Navy and Air Force, Washington, 1970 (Vol 1), p D-51.

carbonate eye protection would have prevented fully 39% of all ocular injuries.[13]

The element in eye armor development that has been least appreciated is the mind-sets of both those who need protection and those who lead the Army. The complexity of the objective has frequently been ignored and the infantryman has often been regarded as just another industrial worker needing eye protection. In fact, the infantryman is usually young, emmetropic, unsophisticated, skeptical, denial-practicing, and body-image-conscious, with a variety of highly dangerous tasks to perform (most of which require unimpeded vision) and burdened already with much personnel equipment. He tends to regard ametropia for what it is, an eye abnormality. He is likely to reject eye protection that resembles ordinary spectacles, both because of the implications of wearing it and the interference with his field of vision produced by the spectacle frame. Only three of the 92 American soldiers treated for ocular complaints at one combat support hospital in the Gulf War were wearing their eye protection at the time.[6] It is important, therefore, not only to provide the infantryman with eye protection that provides a nearly unimpeded field of vision, but also to term it "eye armor" rather than "goggles" or "spectacles."

The mind-sets of those in senior positions are also of critical importance. Senior officers have often regarded eye injuries as being of little overall consequence and not preventable. The threat of injury to the infantryman's eyes has been in part consciously and in part unconsciously denied because to recognize it would saddle the Army with a major additional task that in the past could not be accomplished. Certain groups of combatants have, however, been judged to need eye protection (eg, aviators, tankers), reflecting the elitist division between cavalry and infantry known since antiquity. Sometimes it is the developers of eye armor who have failed to involve the user of the armor in its planning and development.[22]

Materials available for the production of soldier-acceptable eye armor have been readily available for only a relatively short period of time. Eye armor development was retarded by the belief that the generation of secondary missiles by shattered glass lenses made their use for the protection of emmetropes unwise. The plastic lens, CR-39, was easily scratched, and neither glass nor plastic could be formed in a configuration that would protect the temporal potion of the glove without obstructing peripheral vision. The development of injection-moldable optical-grade polycarbonate and scratch-resistant coatings has obviated all of these problems.

Fortunately for the US soldier, Army leadership has made available the monies required for the development, testing, and initial procurement of eye armor. Polycarbonate is intrinsically inexpensive and the cost to the US taxpayer for the infantryman's eye protection will be far less than the cost of his boots. The elements that have been of greatest importance in the successful development of eye armor are the availability of injection-moldable polycarbonate, the decision of the Infantry School to make eye armor a requirement for the infantryman, and the fear of laser weapons.

THE HISTORY OF EYE ARMOR DEVELOPMENT IN AMERICA

Pre-Colombian Period to World War I

The Incan and Aztec warriors of pre-Colombian America wore quilted cotton jackets and padded helmets that did not incorporate eye protection.[23] The Colonial period saw the gradual abandonment of the metal body armor that the earliest settlers had brought with them from Europe because it was "...too burdensome for the long treks and rapid movements of woodland warfare"[24] despite its effectiveness against Indian arrows.[23] "Soft" armor of buckram (a stiff armor of cotton or linen and silk covered with leather), fustian (a type of cotton or linen fabric), or canvas was also used by the colonists but was discarded because it was hot and uncomfortable.[25] Though eye protection for the helmet wearer was attempted in the 15th century by means of "metal-rimmed protective lenses of glass ... hinged to drop over the eyes,"[26] such eye protection was not present on helmets worn in the New World. Some of the Spanish infantrymen who accompanied DeSoto wore a type of helmet called a salade or sallet, some of which bore a hinged visor, and others themselves covered the face, in which case vision was provided for by means of a slot (ocularium).[24] These partial eye protective devices were abandoned in part because the limitation of visual field they produced prevented the effective handling of pistols. Dupuy and Dupuy comment that "by 1650, European armor, although effective against Indian projectiles, had been largely abandoned … and was replaced by lighter and less cumbersome protective garb of cloth and leather."[27]

In the American Revolutionary War and the War of 1812, the cavalry continued to wear leather helmets and a few combat engineers wore steel breastplates.[18,23] Breastplates were also worn in the American Civil War by combatants of both sides, although they were never formally authorized.[28] The Indian and Spanish-American Wars were fought apparently without body armor of any kind, though "push-shields" were considered for use in the latter.[18] The American Indians, however, "...used buffalo-hide shields and breastplates of bone tubes strung together, both of which were a good defense against arrows and lances, and were even able to stop a half-spent bullet."[23] By the onset of World War I, the use of body armor was regarded as "dead as Queen Anne."[25]

World War I and the Interwar Period (1914–1940)

Although all belligerent nations embarked on World War I providing little if any body armor for their infantrymen, almost all (including the United States) made efforts during that war to develop and distribute armor, including eye armor. The head was protected first, largely through the efforts of General Adrian of the French army, but ophthalmologists soon attempted to stimulate and assist in efforts "...to try and realize for the eye sockets what has been obtained for the skull."[4,18] Unfortunately, no acceptable eye armor could be developed and development of eye armor for the infantryman practically stopped at war's end.

The major impetus for the interest in the development of body armor early in World War I was the employment by all armies of munitions generating a myriad of small fragments upon detonation, the extensive use of the machine gun, and the rapid replacement of a war of maneuver with a war of position ("trench warfare"), which made many combatants especially vulnerable to small fragment injuries. The trench war became a war of artillery and over half the casualties were caused by shellfire.[29] The static war of the trenches led to a peak of 8% of injuries being eye injuries, and 10% of all patients seen in base hospitals required eye examinations and treatment.[9,30,31] Three-quarters of the casualties were due to missiles of low velocity, less than a thousand feet per second.[25] A British 1917 attempt at eye armor (see Fig. 26-2) was based upon a French automobile driver's goggle. Because of the inherent visual field limitations of these "lunettes," however, they would not have to be worn by soldiers, except when the wearer was "...under bombardment or menaced by bullets."[32]

Senior American Army ophthalmologists, such as Wilmer and Greenwood,[33] were familiar with the various types of eye armor developed by our allies and with their deficiencies. Wilmer, at the request of the Ordnance Department, had developed an eye shield of Hadfield (manganese) steel with a single horizontal stenopeic slit and a circular opening below to permit a view of the ground (see Fig. 26-2). The idea for the shield came to Wilmer from the "single slotted eye shield which is used against snow blindness by the Indians of our northwest."[18] Greenwood devised an "eye shield" with two stenopeic slits, one vertical and one horizontal, but concluded that Wilmer's shield, designed to be compatible with the standard British helmet, was superior.[30] The US Army ordered 30,000 of Wilmer's shield but they were rejected by the headquarters of the American Expeditionary Force because they were "not readily kept in position."[18] This unfortunate result mirrored the fate of all body armor (except the helmet).

Although visors of different types were tested on experimental helmets of many different designs, all visors were rejected and the helmets that became standard at the outset of World War II made no provision for eye protection. In fact, many line officers in positions of authority during this period of time

Fig. 26-2. World War I eye armor. (**a**) British, 1917. (**b**) US Wilmer-type, 1918.

believed that eye protection would "spoil the image of the soldier" who was apparently expected to be farsighted in every sense of the word (personal communication, Lowrey, 1979). Efforts did continue to improve flying goggles for the Army and Navy aviators, for "it had long been realized that the task of flying was more dependent on vision than on any other of man's senses."[34] It is interesting, though not surprising, that many of the issues dealt with by developers of better eye protection for military aviators in the 1920s and 1930s (field of vision, peripheral protection) are the same issues dealt with in the 1970s and 1980s for the infantryman.

Methacrylate (plastic) lenses (Lucite, Plexiglas) were introduced in the United States in 1937, but their softness and discoloration led to their rejection and they were not manufactured in this country after 1939.[26,35]

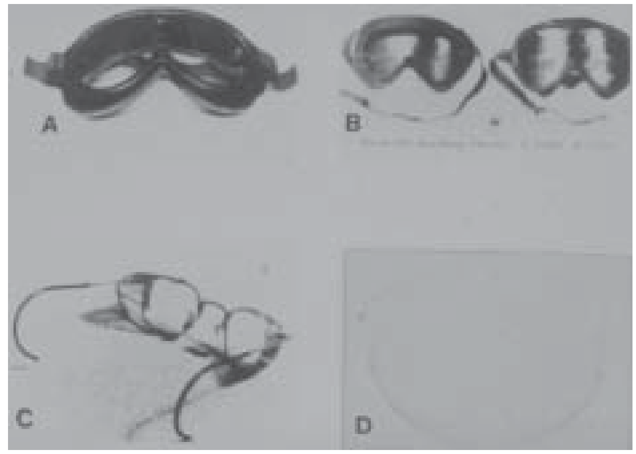

Fig. 26-3. US military eye protective devices. (**a**) World War II sun-wind-dust goggle, M1944. (**b**) World War II mine-clearance goggle, T45. (**c**) Korean War, Fair-type eye armor. (**d**) Vietnam War, polycarbonate eye shield (component of Army aviator's helmet).

World War II and the Interwar Period (1941–1949)

In contrast to the many efforts made in World War I, relatively few such efforts were made towards eye protection in World War II. Those in senior positions considered the incidence of eye injuries to be too low to necessitate eye armor development. Military planning in the pre-World War II period posited a war of movement, of maneuver, to obviate a recurrence of the static trench warfare of World War I. Body armor (except for the helmet) was believed to hinder the infantryman so much as to be ill advised.[22] In short, it was decided not to "sacrifice freedom of body movement for protection."[36] Hence, although the prevention of industrial eye injuries was well advanced, the United States entered World War II with no eye armor for its infantrymen.[37,38]

Eye injuries were again very significant.[20] As had been true in World War I, the devastating effects of miniscule fragments upon soldiers' eyes prompted attempts at eye armor development. Town[39] described a "metal eye protector," then in use by Soviet Union forces, which weighed 5 ounces and provided for vision through crossed stenopeic slits. Stieren[40] described a "metal safety and glare goggle" of aluminum (reminiscent of the British World War I eye armor in Fig. 26-2). An eyeshield of cellulose acetate was provided for members of the Chemical Corps for wear when they were in the vicinity of toxic gasses, and some soldiers employed this eyeshield as a dust protector. A sun-wind-dust goggle, M1944, bearing 1-mm cellulose acetate lenses (see Fig. 26-3) was provided to tankers and certain vehicle operators, but its size and shape made it unsuitable for use by foot soldiers. Towards the end of the war a metal eye shield, T45, was developed for engineers engaged in mine clearance (see Fig. 26-3).[22,41] It was composed of a plate of manganese steel bearing vision slits (similar to those of the World War I British eye armor in Fig. 26-2) mounted in a rubber sun-wind-dust goggle frame, and weighed 7 ounces.

United States Army Air Force aviators wore several types of eye protection and different types of sunglasses, but the restriction of visual field was a major problem.[34,42] The US Navy considered a visor for the standard M1 helmet to protect the face, but it was not fielded. Ironically, but not surprisingly, "industrial type" eye protection was provided to some soldiers performing equipment maintenance, and successful efforts were made by the US Armed Forces to protect the eyes of those working in defense industries.[43,44] The glass spectacles worn by ametropic soldiers were not case-hardened and secondary missile injuries occurred with enough frequency to stimulate a recommendation that increased protection be provided the ametrope: "Ordinary spectacles should be made of armor plate or shatter-proof glass."[20] Body armor, especially in the form of thoraco-abdominal protection, was investigated for infantry. "Flak suits" were developed for and extensively and effectively used by US Army Air Force flying personnel. Eye protection for these airmen was nonetheless suboptimal and many eye injuries occurred.[22]

The British did make efforts to develop eye protection for the infantry. Cruise,[45] who had developed a form of helmet-mounted eye armor termed the "chain mail veil" in World War I, had continued to work on such a protective device in the inter-war period. In 1940 he advocated a helmet-attached perforated visor of 22-gauge duraluminum that could, if necessary, be adjusted over spectacles. The visor "acted as a multiple stenopeic disk, and in that way vision would be improved for the people with refractive errors without their glasses."[46] The visors used by knights in the Middle Ages were also believed to correct refractive errors in a similar fashion. By 1941, three types of eye armor had been evaluated by the British military: 1) a perforated metal visor of the Cruise type; 2) slotted and round holed metal visors; and 3) methyl methacrylate and cellulose acetate plastic visors and goggles.[47] Cellulose acetate, 2 or 3 mm thick, was found superior to methyl methacrylate on impact resistance evaluation. The latter's proclivity to spall was to cost some airmen their sight during the war. The scratchability of the plastic was identified as a serious problem. Despite the efforts made to develop and field eye armor, British soldiers were provided no protection to the eye beyond cellophane anti-gas shields similar to the cellulose acetate shield provided US ground forces.

The Korean War and the Interwar Period (1950–1962)

The Korean War evolved from a war of maneuver to a war of position, and the resulting eye injuries again stimulated US Army ophthalmologists to attempt to enhance eye protection. King,[48] a US Army ophthalmologist, called for the provision of case-hardened lenses to ametropic combat arms soldiers and considered an eye shield that could be attached to the helmet. He recommended the testing of plastic lenses in front-line companies and stressed the importance of gauging the soldier's acceptance or rejection of eye armor.[49]

Freed, the inventor of the metal device described by Town,[39] attempted to interest the US Army in it without success. Fair[50] made the major eye armor development effort by advocating a "spectacle-type goggle with tempered glass lenses and side shields" (see Fig. 26-3). He noted that, "the only real problems foreseen are making the goggles acceptable to the soldier who has never before worn spectacles and providing lenses for the soldier with a significant refractive error."[50] Unfortunately for thousands of US soldiers, accomplishment of these objectives required 30 additional years. According to Stokes, "...although the eye armor that [Fair] was working on might be beneficial in decreasing eye injuries, it so impaired a soldier's peripheral vision and his ability to defend himself otherwise, that it was not practical in battle" (personal communication, Stokes, 1986). Despite the proposal to test various types of commercial safety glasses, no trials were conducted in Korea.[51]

The next significant attempt was made in 1962 by McNair, who advocated the development of a polycarbonate eye protective device for the infantryman based on the polycarbonate lenses provided to aviators (see Fig. 26-3).[52] This attempt was rejected by US Army commanders, who stated that "the line officers had enough trouble getting the foot soldier even to wear his helmet let alone to have him wear protective glasses or a shield" (personal communication, McNair, 1987). Nonetheless, in 1962, a joint effort by the Quartermaster and the Army Medical Department to develop eye armor was begun. It was to be an optically clear device suitably curved to provide maximum protection with minimum interference with soldiers' activities and include provision for optical correction. A major shortcoming of this effort was the absence of a formally approved Army statement of need for eye armor, and in fact such a "requirement document" was not generated until 1984.

Scientific studies of great relevance were conducted during this period by Stewart and Rose[53,54] and Williams[55] who, disturbingly, demonstrated that non-heat-treated glass lenses were more protective than heat-treated ones against small missiles and that, under some circumstances, eyes were probably safer uncovered than "protected" by glass lenses. Bryant[56] substantiated the greater impact resistance of plastic (allyl resin) lenses compared to tempered glass lenses. Fackler et al[57] studied wound ballistics and Davis[58] made valuable observations regarding the optical factors of plano lenses. The major development of the period, however, was the production of optical-grade polycarbonate by General Electric.[59] The marked advantage of polycarbonate over other lens materials was promptly appreciated and it has become the eye and face protective materials of choice.[60,61] Polycarbonate could withstand the impact not only of molten metal but also of a quarter-inch diameter steel ball moving at velocities of up to 500 feet/second (ft/s).[62] Such lenses of 2.47 mm thickness resisted the impact of 545 mg lead spheres and slugs with pointed heads traveling at 595 ft/s.[63]

The Vietnam War Era (1962–1969)

The overwhelming majority of emmetropic infantrymen entered combat in Vietnam without eye protection of any kind. Some drivers of large vehicles and helicopter loaders were provided the US M1944 sun-wind-dust goggle which, as had been true in World War II, provided only minimal protection from the small fragment threat because its lenses were made of 1 mm thick cellulose acetate. When struck with a fragment, this material readily disintegrated into small sharp-edged fragments (spall) which could themselves damage the eye.[64] The US Army aviator's visor was attached to the standard M1 helmet by Navy researchers in an attempt to protect the eyes of sailors serving on patrol boats in the Delta region of South Vietnam.[65] The visor was judged to be sailor-acceptable, protective, and capable of satisfactorily withstanding the deleterious effects of salt air and intense sun. Although US Army personnel were also equipped with the M1 helmet, no effort was made to evaluate the effectiveness of the helmet-mounted visor for them.

Once again the ocular threat came predominantly from small, low-velocity missiles (see Fig. 26-4). Bryant,[66] studying the lens retention of safety frames, concluded, "Polycarbonate plastic lenses exhibited a highly significant increased fracture resistance compared to industrial or dress thicknesses of tempered glass and CR-39 plastic lenses." Later reviews of wound data and foreign bodies from Vietnam led to the conclusion that the majority of foreign bodies which resulted in eye injury would have been stopped by 2-mm thick eye armor.[67–70] Thus, polycarbonate plastic lenses appeared to have a great potential for truly effective eye protection against flying missiles. Solution of the lens retention and scratch-resistance problems, among others, had to be achieved to permit a complete realization of this potential.

Modern Eye Armor Development—1969 to Present

The modern development of eye armor began by the testing of the Postoperative Eye Guard (Younger Manufacturing Company, Los Angeles, CA) by La Piana (see Fig. 26-5). Intended to protect an eye that had recently undergone cataract extraction, the protective qualities of these devices was demonstrated in demolition tests. Further testing conducted on soldiers during combat training exercises in Vietnam revealed a general dissatisfaction with the plastic ring on the back surface of the Guard (the ring was designed to hold the aphakic correction) because of its interference with their peripheral vision. Other frequently expressed complaints were of distortion in the far peripheral field (due to the cylindrical lens power in the lateral portion of the shield) and lack of firm stabilization of the shield on the face when sweating occurred (unpublished data, 1970).

An effort was made in 1971 to interest first the Army and then private industry in the development of eye armor, without success. Part of the problem was political: the failure to interest civilian industry may have been influenced by the widespread anti-military sentiment at the time. In fact, eye armor in the form now being manufactured (in-

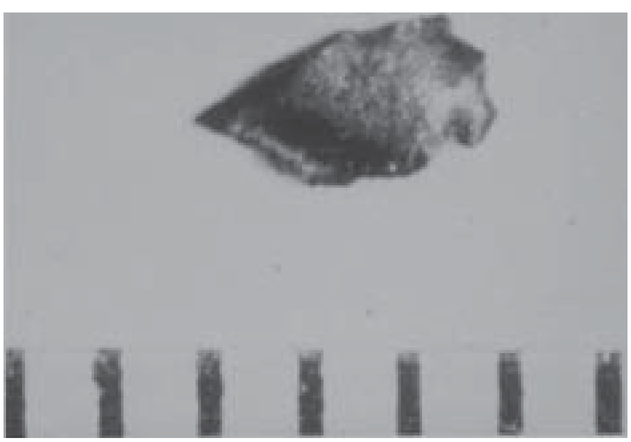

Fig. 26-4. Typical intraorbital foreign body removed in Vietnam weighing 12 mg (millimeter scale).

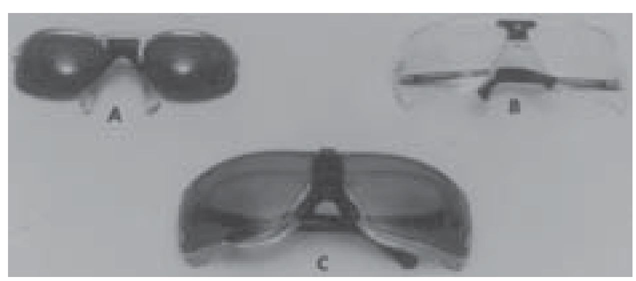

Fig. 26-5. Contemporary forms of eye armor. (**a**) Prototype eye armor-1 (PEA-1). (**b**) Prototype eye armor-2 (PEA-2). (**c**) Definitive eye armor (ballistic and laser protective spectacle [BLPS]) complete and assembled.

jection-molded polycarbonate in a toric-wrap configuration) could have been manufactured in 1971 (personal communication, LaMarre, 1987). Eye armor development was therefore in a sense another casualty of the Vietnam War, reminding us of Hirschberg's observation that "the history of medicine is part of the history of the entire civilization."[71]

Much effort has been devoted to convincing US Department of Defense (DOD) workers involved in eye armor development that the threat to the eye of the soldier in peace and in war is overwhelmingly from small missiles of 100 mg or less and that eye armor should be developed to protect against this threat (see Figs. 26-4 and 26-6). Many DOD workers were unrealistically calling for eye armor that could also protect against larger missiles, including bullets. In Desert Storm, not a single bullet injury was noted in a series of 160 American eye casualties.[72] Such unrealistic demands on the performance of eye armor only delayed the deployment of protection from the much more likely small-missile threat.

In the 1970s, studies had demonstrated the superior impact-resistance of polycarbonate but also demonstrated degradation in its strength when a scratch-resistant coating was applied.[73] This was a matter of great importance since polycarbonate must be so coated because it is easily scratched. Further studies demonstrated that polycarbonate lenses could protect the wearer from the small missile threat.[67–70] Among the findings, it was demonstrated that at 30 meters from a munitions burst, a polycarbonate eye shield could protect a soldier's eye from most (about 80%) of the fragments.

Fig. 26-6. Some of the intraocular and orbital foreign bodes removed by two military ophthalmologists in Vietnam from 1968 to 1969. Photograph: Courtesy of H. Dale Sponaugle, MD, and Robert T. McKinley, MD.

Prescription polycarbonate lenses became available in 1977 and their advantages over lenses made of glass or CR-39 were noted, including greater impact resistance, higher refractive index (making possible stronger lenses with either less curvature, thinner edges, or both), and low specific gravity (making polycarbonate prescription-bearing lenses approximately one-half the weight of an equivalent strength glass lens).[74] The increased lateral chromatic aberration of polycarbonate was a relative disadvantage, however, because patients wearing lenses greater than 2D may appreciate colored fringes along black-edged borders.[75]

A major conference on Combat Ocular Problems was held in 1980, and much attention was paid to the protection of the soldier's eye from all identified threats.[76] Partially as a result of this conference, the three following important decisions were made: 1) to link laser eye protection to missile and blunt force protection, 2) to make polycarbonate the material upon which all development efforts would center, and 3) to provide protection against the missile and blunt-force threat as soon as such became available, and not delay its provision until laser protection became available, as it was judged that the latter required much more time and effort than the former.

The need to protect the soldier's eye from laser wavelengths has concerned the US Army since the advent of this powerful and versatile directed energy source.[77] Many medium-power laser systems are being used in tactical military ground and airborne applications, which include range finding, target designation, ordnance guidance and, during periods of darkness, night vision illuminators. Viewing the collimated laser beam or the specularly reflected beam through a telescope or binoculars can increase the retinal irradiance considerably. Thus at locations where a laser might be considered safe to view by the unaided eye, it may not be safe when viewed through optical devices. Damage to the eye on the battlefield or the training ground can occur at distances of 400–4000 meters depending on the wavelength and power employed, whereas the M-16 rifle (the standard infantry weapon) is effective to only 400 meters (personal communication, Stuck, 1986). The inherent ability of polycarbonate to block ultraviolet and far infrared light (such as emitted by the CO_2 laser) added to its attractiveness. The spectral attenuation of a polycarbonate lens in the visible and near-infrared is insignificant, however, and of no value for laser protection in the retinal hazard region (400–1400 nm).[78]

A major stimulus to eye armor development was provided by the appearance on the commercial market of Gargoyles (Pro-tec, Inc., Kent, WA; see Fig. 26-5). Gargoyles are fabricated of optical-grade polycarbonate, the thickness of which varies from 2.5 mm in the optical center to 1.8 mm in the periphery, and weighs only one ounce. They are impact resistant, efficient UV absorbers, and cosmetically acceptable—a very important characteristic because "protective head gear and eyewear will be worn only if the design appeals to the intended wearer."[79,80] Gargoyles, or some variation of them, seemed to be an ideal foundation for the development of troop-acceptable eye armor. Some continued to propose the sun-wind-dust goggle fit with 4 mm thick polycarbonate, this despite the fact that the restriction of visual field caused it to be rejected by even many tank crewmen and a similar goggle was rejected by Israeli infantrymen engaged in combat.[64]

Testing of Gargoyles on US Army soldiers and Marines began in 1983. Initial results were encouraging, with high troop-acceptance. Several modifications were deemed necessary, however. The nose bridge required strengthening. The distance between the brow and lens had to be increased to minimize fogging. The integrated front had to be extended at least 8 mm posteriorly to provide full protection to the eyes of soldiers with large heads and widely spaced eyes. A polycarbonate lens cleaner was needed because soap and water often are not available in the field.

Because eye armor must protect the ametrope as well as the emmetrope, it was necessary to know the incidence and range of ametropia within the US Army. It had been stated that approximately half of the Army wore glasses,[81] but the incidence and degrees of ametropia in different types of units had not been studied adequately. Studies were initiated to determine the incidence and range of ametropia in three Army infantry divisions, the results of which are summarized in Table 26-3. The studies substantiated the impression that the incidence of ametropia is lowest in combat arms units, those units whose members are at greatest risk of eye injury in war. This information provided an additional stimulus to work for the development of troop-acceptable eye armor, for is clear that those most at risk (emmetropic combat arms unit members) had the least, and in most cases no, protection.

TABLE 26-3

INCIDENCE OF AMETROPIA IN THREE ARMY DIVISIONS

Investigator	Unit Type	Percentage
Rimm (25th Infantry Division)	Combat Arms	15–20
	Combat Support	25–30
	Combat Service Support	45–50
Bussa (82nd Airborne Division)	Combat Arms	27
	Combat Support	24
	Combat Service Support	35
Tressler (4th Infantry Division)	Combat Arms	25
	Combat Support	49
	Combat Service Support	33

The emergence of low energy lasers as a significant ocular hazard on the modern battlefield gave additional impetus towards the development of eye armor. Whereas up until recently the major threats to the infantryman's eye were ballistic in nature, now electromagnetic energy, in the form of lasers, was a significant and increasing threat. There have been a number of well documented laser injuries, usually as a result of incorrect usage of laser range finders, target designators, or other common laser devices utilized by modern armies.[82,83] Added to these accidental exposures are a number of suspected intentional laser exposures over the past two decades, usually directed towards pilots and other aircrew members.[82] There were two documented laser eye injuries during the recent Gulf War (personal communication, Brown, 2000). A number of countries are known or suspected to have developed laser devices with the direct purpose of causing either temporary or permanent eye injury; these countries include the United States, United Kingdom, and the former Soviet Union.[82] Thus modern eye armor needs to protect against both the ballistic and laser threats.

Contracts were let with the American Optical (Southbridge, MA) and Gentex Corporations (Carbondale, PA) in early 1985, and the American Optical product selected for final development and testing of eye armor (see Figs. 26-5 and 26-7). The American Optical eye armor, termed the ballistic and laser protective spectacle (BLPS), is composed of an integrated front (see Fig. 26-7) of medium molecular weight polycarbonate containing ultraviolet wavelength inhibitors and coated with an

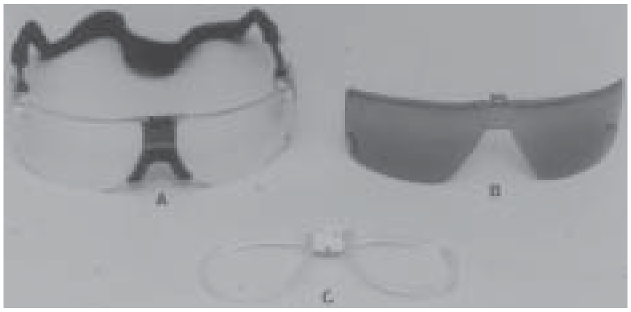

Fig. 26-7. Definitive eye armor (BLPS) components. (**a**) Polycarbonate eye armor. (**b**) Laser protective attachment. (**c**) Corrective lens carrier.

Fig. 26-8. SPECS. UVEX, Fürth, Germany.

organo-silane for abrasion and chemical resistance. Additional components include a laser-protective device of low molecular weight polycarbonate into which are incorporated specific laser wavelength absorbers, a lens carrier, and a retaining strap of neoprene and fabric (see Fig 26-7). Further testing determined that emmetropes preferred a new device manufactured by UVEX (Fürth, Germany), termed SPECS (see Fig. 26-8). Unfortunately, SPECS could not be modified to accept a spectacle correction and is unsuitable for use by ametropes. Thus the US Army is currently fielding two different forms of eye armor: BLPS for ametropes and SPECS for emmetropes.

CONCLUSION

The development of soldier-acceptable eye armor for the American infantryman, seemingly a straightforward, simple task has in fact required 70 years for successful realization. A thorough understanding of the elements of personal body armor development (missions of the infantryman, threats on the battlefield, materials available for eye protection, mind-sets of both the infantryman and his leaders, and monies for the development, provision and replacement of eye armor) and the sustained, dedicated efforts of many within and outside the Department of Defense have been required for the development of such eye armor.

In the *Iliad,* Homer sang, “Men grow tired of sleep, love, singing and dancing sooner than war.” As threats to the eye of the soldier (and quite possibly the civilian) evolve, eye armor must also evolve. The development of eye protection for the American infantryman will continue to be a work in progress.

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