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SPH-4 Aircrew Helmet Impact Protection Improvements 1970-1990

By

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The Sound Protective Helmet-4 (SPH-4), a derivative of the Navy SPH-3, has been used by the Army since 1970. As our knowledge of crash environments and human impact tolerance has increased through analyses of aircraft accidents and laboratory research, the performance of the standard SPH-4 helmet has been continuously reappraised, and the helmet's shell, liner, retention, earcups, and suspension have been upgraded to provide more impact protection. This report includes a discussion of improvements made in the SPH-4 helmet and the effects these improvements have had on its performance. The SPH-4, SPH-4B, and HGU-56/P are compared in terms of major design features, impact protection, and retention capabilities. The development of helmet impact testing methodology used at the U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama, also is discussed.

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Table of contents

List of figures

List of tables

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Introduction

In 1970 the U.S. Army fielded the Sound Protective Helmet No. 4 (SPH-4) as its new aircrew helmet and, with improvements, it has been used continuously since that time. The SPH-4, a single visor, lighter weight version of the Navy SPH-3, replaced the two Army aircrew helmets then in use: The Navy-developed Aircrew Protective Helmet-No. 5 (APH-5) and the Army-developed Antifragmentation Flight Helmet-No. 1 (AFH-1). Both helmets were deficient in noise attenuation and retention capability. The SPH-4, which was specifically designed for sound protection, provided (and still provides) superior sound attenuation, but the 1970 version provided no more impact protection than the APH-5. As the sciences of crashworthiness and head injury prevention developed, it became evident that head injuries could be reduced by modifying the SPH-4. This report will review the major developmental changes that have improved the impact protection provided by the SPH-4 and have led to the development of the Head Gear Unit-56 for Personnel (HGU-56/P). Improvements in aircrew helmet retention, the prerequisite of impact protection, also will be reviewed.

Establishment of USAARL helmet impact test criteria

The impact protective performance of the SPH-4 is assessed according to specific impact test criteria. Three factors have been involved in the establishment of these criteria. First, a means to estimate head injury potential was required; traditionally, head deceleration has played this role. Second, an accurate understanding of the forces to which an aircrew member is subjected during a survivable crash was needed in order that a minimum level of head impact protection be specified. Third, a suitable test method was required. The U.S. Army Aeromedical Research Laboratory's (USAARL) test method employs acceleration as a measure of head injury potential and it ensures the helmet meets the level of head impact protection specified in terms of contact velocity and headform deceleration.

The search for a precise measurement of head injury potential has been a long process. Thirty years ago, Gurdjian, Lissner, and Patrick (1962) introduced the Wayne State tolerance curve (WSTC). Linear skull fracture data obtained from impact tests of nonhelmeted, embalmed human cadavers were plotted as a function of average deceleration and decelerative pulse duration. The data showed high decelerative loads could be tolerated for very short periods without skull fracture, whereas low decelerative loads could be tolerated for longer periods. Later, Gadd (1966) linearized the WSTC and found the slope of the resulting line to be -2.5. Using 2.5 as a weighting factor, Gadd created an index formula known as the severity index (SI). The purpose of the SI was to standardize head deceleration pulses of differing shape, amplitude, and duration so they could be compared in terms of head injury potential. According to Gadd (1966), an SI value of 1000 represented the danger-to-life threshold. The SI considers the entire head deceleration pulse in its calculation.

More recently, investigators have desired to identify, for a given deceleration pulse, the specific portion of the pulse that provides the greatest potential for head injury. In order to accomplish this, Versace (1971) modified the SI. This modified form of the SI has become known as the head injury criterion (HIC). Calculating the HIC for a given pulse requires a time interval be determined within the pulse such that the deceleration that occurs over that interval gives the maximum possible HIC value for that pulse. An HIC value of 1000 is considered to be the threshold for life-threatening head injury (Versace, 1971). The HIC has been popular among researchers in the automotive industry since most automobile accidents involve head impacts with unhelmeted heads.

Although much thought has gone into the development of the SI and the HIC, these methods of predicting head injury potential have proven not to be entirely suitable for aircrew helmet impact testing. Both methods are based on the WSTC. The WSTC examined the combined effects of decelerative load and load duration on linear skull fracture in nonhelmeted human cadavers and did not evaluate the effects on brain injury per se. Brain injury frequently occurs in the absence of skull fracture (Slobodnik, 1980; Melvin and Weber, 1985; Ommaya, 1988) and, conversely, skull fracture can occur in the absence of brain injury (Melvin and Weber, 1985; Ommaya, 1988). Also, Slobodnik (1980) showed in Army helicopter accidents concussion occurred at HIC values below 1000. Alem, Nusholtz, and Melvin (1982), showed the HIC should not be used for assessing head injury potential of crown impacts. Apparently, when subjected to a crown impact, the head usually can transmit the force of the impact to the structurally weak neck. As a result, a severe neck injury can occur although the HIC value remains below 1000 and no head injury occurs.

Pulse duration is another factor which limits the use of HIC for helmet impact testing. Decelerative pulse durations for aircrew helmet impact tests range from 10 ms for high velocity (25 fps) drop tests of helmets with 0.5-inch thick foam liners to 25 ms for low velocity (12 fps) drop tests of helmets having thicker foam liners. HIC normally is not used for assessing head injury potential for pulses with durations longer than 15 ms (Melvin and Weber, 1985). This is because no deceleration pulses with durations in excess of 15 ms existed in the database from which the HIC was derived (Melvin and Weber, 1985). In view of these factors, USAARL has elected to use peak head deceleration as its indicator of helmeted-head injury potential as does the American National Standards Institute (ANSI) in Specifications for Protective Headgear for Vehicular Users (ANSI Z90.1-1971). Likewise, the Snell Memorial Foundation (1985) uses peak headform deceleration as the predictor of head injury potential.

The establishment of helmeted-head impact test criteria based on human tolerance to head impact has been an arduous and uncertain task. When Army aircrew helmets first came into use during the late 1950s, little was known about human tolerance to head impact. Early helmeted-head (accident) impact simulations with rigid magnesium head forms (Snively and Chichester, 1961) indicated humans could survive peak head decelerations up to 450 g. Later, ANSI Z90.1-1971 specified peak headform decelerations should not exceed 400 g with an impact energy of 50 ft-lb, i.e., an 11-lb headform with an impact velocity of 17.1 fps at a drop height of 4.54 feet for a 1.9-inch radius spherical impact surface. The publication of the ANSI specifications roughly coincided with the introduction of the SPH-4, and the official impact protection standards set for the helmet in Military Specification MIL-H-43925 (Department of the Army, 1975) actually were derived, with certain exceptions, from ANSI Z90.1-1971.

While accepted at the time, some researchers questioned the protection provided by a helmet that exposed the head to such high levels of impact force. Haley et al. (1966) stated peak headform deceleration should not exceed 160 g, based on WSTC data (for pulse durations greater than 10 milliseconds). During the early 1980s, research at USAARL demonstrated peak head decelerations far less than 400 g produce concussive head injuries which can leave the Army aircrew member incapacitated following a crash (Slobodnik, 1980). Incapacitation can leave the military aircrew member exposed to fire, drowning, or enemy action following a crash. These disconcerting results left USAARL researchers with questions that could be answered only by actual and simulated crash data.

To what level of impact energy should helmets be designed? What is the helmeted-head impact environment of very severe, yet potentially survivable aircraft crashes? The U.S. Army's Aircraft Crash Survival Design Guide (Simula, 1989) is a good source document to elucidate the survivable crash scenario. A review of Volume IV (Aircraft seats, restraints, litters, and cockpit/cabin delethalization), chapter 8.5.2, "Dynamic Test Requirements for Seats," shows the seat must sustain a velocity change of 50 fps for a triangular input deceleration of 30 g. The velocity of the helmeted head of anthropomorphic dummies used in testing such seats has been recorded as nearly equal to that of the input velocity of 50 fps (Melvin and Alem, 1985).

Even though the linear velocity of the helmeted head relative to the seat structure may range upward to 50 fps at a point from 1-to-2 feet away from the seat headrest, the head is moving on an arc both forward and downward and is more likely to strike an object with a tangential (glancing) impact rather than a head-on (perpendicular) impact as practiced in the ANSI test method. Aircraft accident head injury studies support the theory that most helmeted head impacts occur with less than a 90-degree impact angle, but the exact angle is never easily determined and usually is recorded as an abrasion (Reading et al., 1984). If one assumes the angle of impact falls halfway between a perpendicular (90°) and a tangential (0°), i.e., 45°, the effective head velocity is reduced to: V_E = 50 fps x sin 45° = 35 fps. Protection from a head impact velocity of 35 fps would require approximately 2.5 inches of energy-absorbing material (if the helmet struck an unyielding structure), an unreasonably large helmet.

Of course, the helmeted head may be struck by an overhead structure during a rollover crash or by a collapsing cockpit structure, or by intruding tree limbs. Since the area immediately in front of the flailing helmeted head usually is clear of obstructions, it may not be logical to use the flailing head velocity as a design value for impact protection. A review of actual head injuries sustained by pilots wearing the current SPH-4 and the impact velocity relative to those injuries is pertinent. Slobodnik's pioneering study in 1980 entitled "SPH-4 helmet damage and head injury correlation" provides useful data on 14 helmet impacts; one fatal case may be eliminated and seven other cases of no injury or very minor concussive injury (dazed for several minutes) also may be eliminated. The remaining six cases required a drop height of 1.52m, 1.91m, 2.29m, 1.52m, 1.22m, and 1.68m of the deformable headform to duplicate the same helmet damage as seen in the head injury case. The average of the above values is 1.69m (5.54 feet); this height yields an impact velocity of 18.9 fps in a free fall. These six cases represented injuries ranging from basilar skull fracture to several days coma, i.e., these energy levels (head mass of 11.0 lb x 5.54 ft = 60.9 ft-lb) were <u>survivable</u> with the current SPH-4 and the same energy should be handled by a new design helmet without injury. The one fatal case required a drop height of 3.28m and, if included, the average drop height and impact velocity would increase to 1.9m (6.23 feet, and 20.02 fps, respectively). Thus, a drop height of 6 feet yielding an impact velocity of 19.65 fps has been selected as a reasonable design value for new flight helmets. The SPH-4B is designed so the impact test headform shall never exceed 250 g at this drop height and the HGU-56 is designed never to exceed 175 g at this drop height.

The SPH-4 helmet is volume-limited to a foam thickness of 5/8-inch while the HGU-56 helmet design is 3/4-inch foam. The fielding of these improved helmets is expected to dramatically reduce the incidence of basilar skull fractures due to excess force transmitted through the skull.

Table 1 shows the USAARL helmet impact testing specifications. Typically, the SPH-4 and the SPH-4B provide peak headform decelerations that are somewhat lower than the specified requirements for these helmets. This, of course, is highly desirable. The SPH-4B and the HGU-56/P are tested at a drop height of 6 ft as opposed to the 4.8 ft drop height used for the current SPH-4.

Table 1.

USAARL helmet impact testing specifications.

Helmet type	Impact location	Drop ht (ft)	Velocity (fps)	Design peak G	Observed peak G in tests
Original SPH-4 1970	1.0" above foam edge (0.38" foam)	4.8	17.6	400	300
Current SPH-4 1982	Headband region and crown (0.50" foam)	4.8	17.6	400	250
SPH-4B 1990 estimate	Headband region and crown	6.0	19.7	250	190
	Earcup region	6.0	19.7	175	150
HGU-56/P 1993 estimate	Headband region	6.0	19.7	175	150 est.
	Crown	3.9	15.8	150	120 est.
	Earcup region	6.0	19.7	150	135 est.

The purpose of the impact test is to accurately simulate a helmeted-head impact, within the laboratory, such as might occur during a survivable crash. There are three criteria that a suitable helmet impact test method must meet. It must be accurate, repeatable, and simple. The role test methodology has played in the development of the SPH-4 is that it has ensured the helmet has met the impact test criteria established for it.

Although a number of different test methods exist, USAARL measures the level of helmet impact protection using a monorail vertical drop tower (Figure 1). Helmets are placed on the rail-mounted magnesium headform, raised to a prescribed height to attain a predetermined impact velocity, and dropped on a flat rigid surface. Headform deceleration is measured via a uniaxial accelerometer mounted within the headform. A 1600-Hz filter, as specified in SAE J211 (1980), is used before recording the headform acceleration signal.

The monorail vertical drop tower arrangement has two drawbacks. First, friction develops between the rail and drop mass and slows the descent of the helmeted-headform which, in turn, reduces the level of impact velocity attained. However, this is a minor problem and it is solved by the use of a slightly higher drop height which produces the required drop velocity. The second drawback is that this test method can be used only to study perpendicular impacts. USAARL currently is developing a free-fall drop tower which will eliminate the problem of friction and also will allow evaluation of tangential impacts as well as perpendicular impacts.

Since 1980, USAARL testing of aircrew helmet impact protection has been done in accordance with ANSI Z90.1-1971 with three exceptions: Aircrew helmets are not drop-tested using the hemispherical impact surface, the penetration striker is not used, and only one drop test is made per impact location. These omissions were made for practical reasons. Penetrating-type head injuries rarely occur in actual survivable Army helicopter crashes due to the low incidence of helmet damage caused by hemispherical or sharp, rigid surfaces in the cockpit. Flat surfaces are the major impact surface types found in Army helicopter cockpits (Slobodnik, 1980; Haley et al., 1983; Reading et al., 1984; and Vyrnwy-Jones, Lanoue, and Pritts, 1988) (see Table 2). In order to pass the hemispherical surface impact test and the penetration test, it is necessary for the aircrew helmet to possess a relatively thick and rigid shell as well as a relatively high density foam liner. Both these characteristics are undesirable in an aircrew helmet as they increase the weight of the helmet and reduce its energy-absorbing capability for flat surface impacts. Prior to 1980, USAARL testing included the hemispherical surface impact test on the SPH-4. Data obtained from Army helicopter accidents have shown that in most survivable crashes an aircrew helmet usually sustains only one severe impact (Reading et al., 1984). Therefore, performing one drop test per impact location appears to be a good representation of what occurs in most survivable crashes. By not requiring aircrew helmets to pass these three standard ANSI Z90.1-1971 tests, a thinner, lighter weight shell and a lower density foam liner can be incorporated to reduce weight and provide greater impact protection against the frequently encountered impact surfaces.

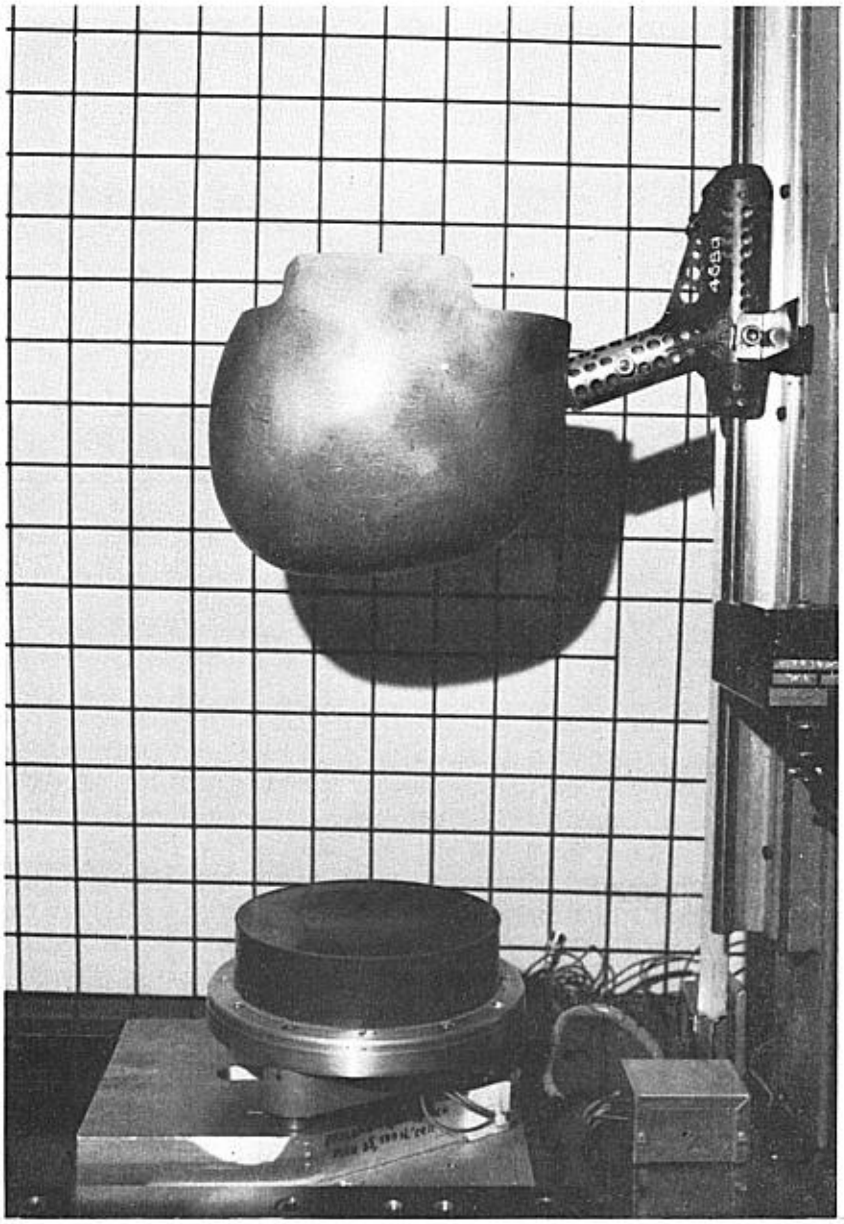


Figure 1. Vertical monorail drop tower.

Table 2.

Distribution of cockpit impact surface types.

Impact surface	Frequency	Percentage
Flat	119	49.0
Concave	24	9.9
Rod	20	8.2
Box corner	15	6.2
Wedge	15	6.2
Hemisphere	8	3.3
Unknown	42	17.3
Total	243	100.0

History of impact protection improvements

Head injury in aircraft accidents has been a major medical concern for several decades (DeHaven, 1952). One of the primary functions of an aircrew helmet is to protect the wearer's head from injury during a crash. With the introduction in the mid 1950s of the APH-5, the Army's first aircrew helmet, the number of head injuries incurred during aircraft accidents was reduced by half compared to the number of head injuries incurred before helmets were used (U.S. Army Board for Aviation Accident Research, 1961). This was a dramatic reduction three decades ago; but, today head injury in Army helicopter accidents continues to be a problem. In fact, head injury rates in Army helicopter accidents are higher now than they were during the era of the APH-5; Shanahan and Shanahan (1989) recently have pointed out some reasons for this increase. Helicopters now in use by the Army fly faster and lower than their predecessors. Consequently, aircrew members are subjected to greater impact forces due to accidents at higher airspeeds and sink rates. As a result, the head (and extremities) flails more violently during a crash sequence. This, in turn, increases the likelihood for head injury as contact between the head and the cockpit interior is more likely to occur. Other body regions are less affected by the more severe crashes due to the use of better restraint harnesses and stronger energy-absorbing seats. Considering the changes that have been made in the types of aircraft flown by the Army, it is likely the incidence of head injury in Army helicopter accidents would be much greater if improvements in SPH-4 impact protection had not been made. Table 3 outlines the changes that have taken place in SPH-4 design and also describes how the SPH-4 differs from the future HGU-56/P. Figure 2 shows the components and construction of the 1970 version SPH-4. Figures 3, 4, and 5 show the 1982 (current) version SPH-4, SPH-4B, and HGU-56/P, respectively.

After the introduction of the SPH-4 in the 1970s, two potentially preventable types of head injury continued to occur. These were incapacitating concussive head injury and basilar skull fracture.

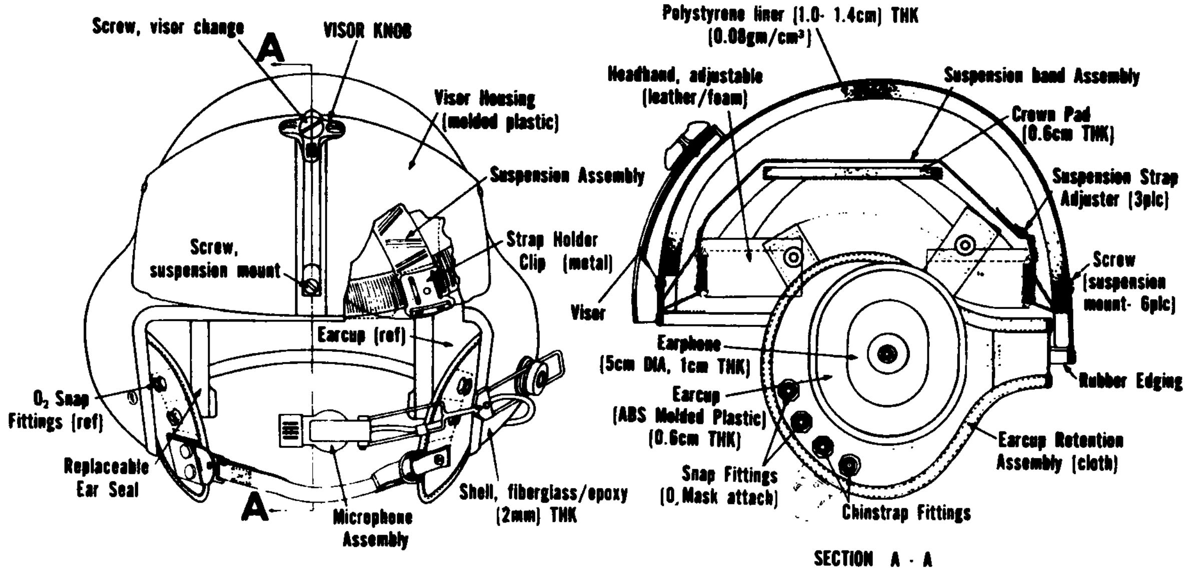


Figure 2. SPH-4 helmet assembly.

Table 3.
Helmet descriptive data.

Component		Helmet identity: Original SPH-4 1970	Current SPH-4 1982	SPH-4B 1990 (est.)	HGU-56/P 1993 (est.)
Helmet weight (lb), complete with visor and communications		Regular 3.4	Regular 3.4	Regular 2.9	Regular 2.9
Suspension type		Sling	Sling	TPL™	TPL™
Visor type		Single integral	Single integral	Double integral	Double integral
Shell material		Epoxy and fiberglass cloth layers	Epoxy and fiberglass cloth layers	Epoxy and Kevlar™ cloth layers	Epoxy and fiberglass, graphite, and ballistic nylon cloth layers
Liner foam	Material	Polystyrene	Polystyrene	Polystyrene	Polystyrene
	Density (lb/ft^3)	5.2	4.5 (1982)	2.5	2.4
	Thickness (inches)	0.38	0.50 (1974)	0.63	0.75
Retention harness type		Chinstrap-to-earcup-to shell	Chinstrap-to-earcup-to shell	Chinstrap-to-"yoke"-to shell	Chinstrap-to-"yoke"-to shell
Napestrap type		Napestrap-to-earcup-to-chinstrap	Napestrap-to-earcup-to-chinstrap	Napestrap-to-shell-to-earcup-to-chinstrap	Nape plate-to-shell-to-earcup-to-chinstrap
Chinstrap design strength (pounds)		150	300	440	440
Chinstrap maximum elongation (inches) (ANSI test method)		No requirement	No requirement	1.12	1.12
Chinstrap type		1 snap on each side	One side secured to retention assembly 2 snaps on other side	Modified yoke retention assembly with D-rings	Modified yoke retention assembly with D-rings
Earcup type		Rigid plastic 6 mm thick	Rigid plastic 6 mm thick	Crushable plastic 3 mm thick	Crushable flexible plastic 3 mm thick

Figure 3. Current 1982 version SPH-4.

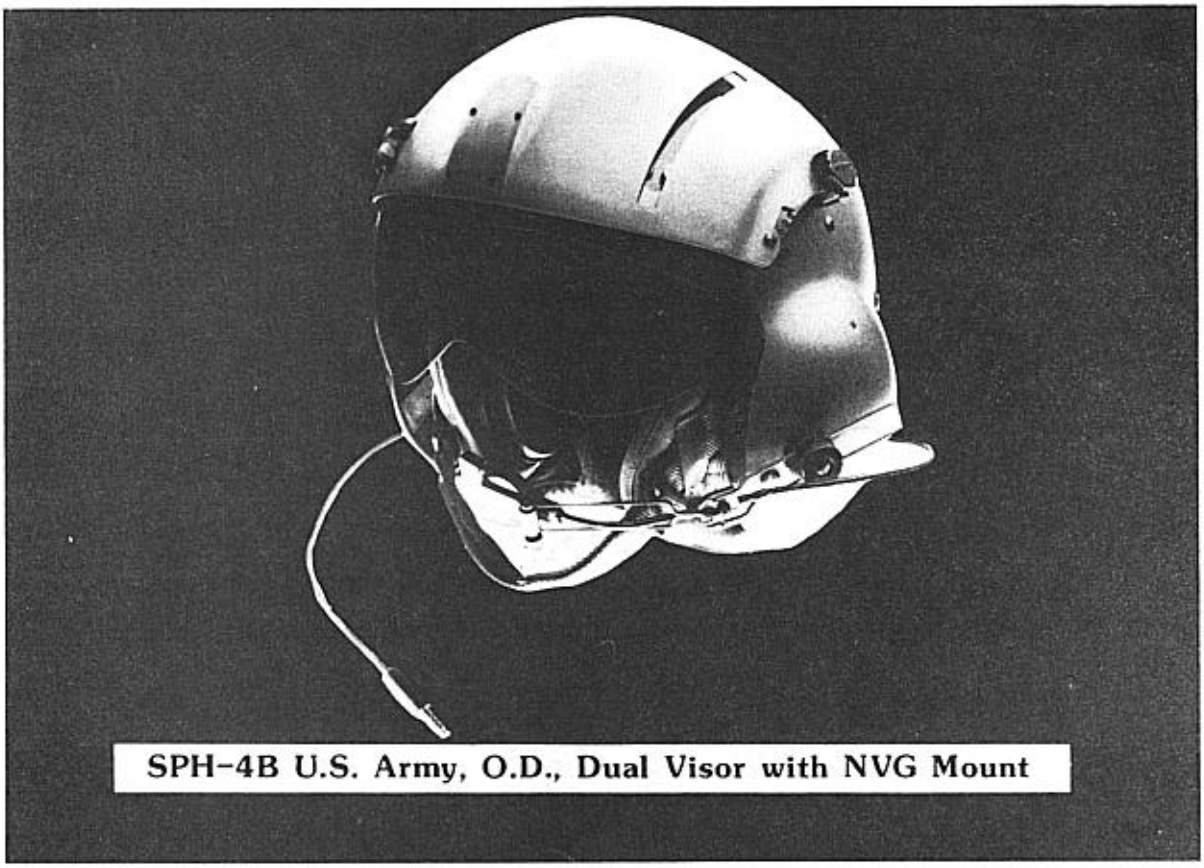


Figure 4. SPH-4B helmet (courtesy Gentex Corporation).

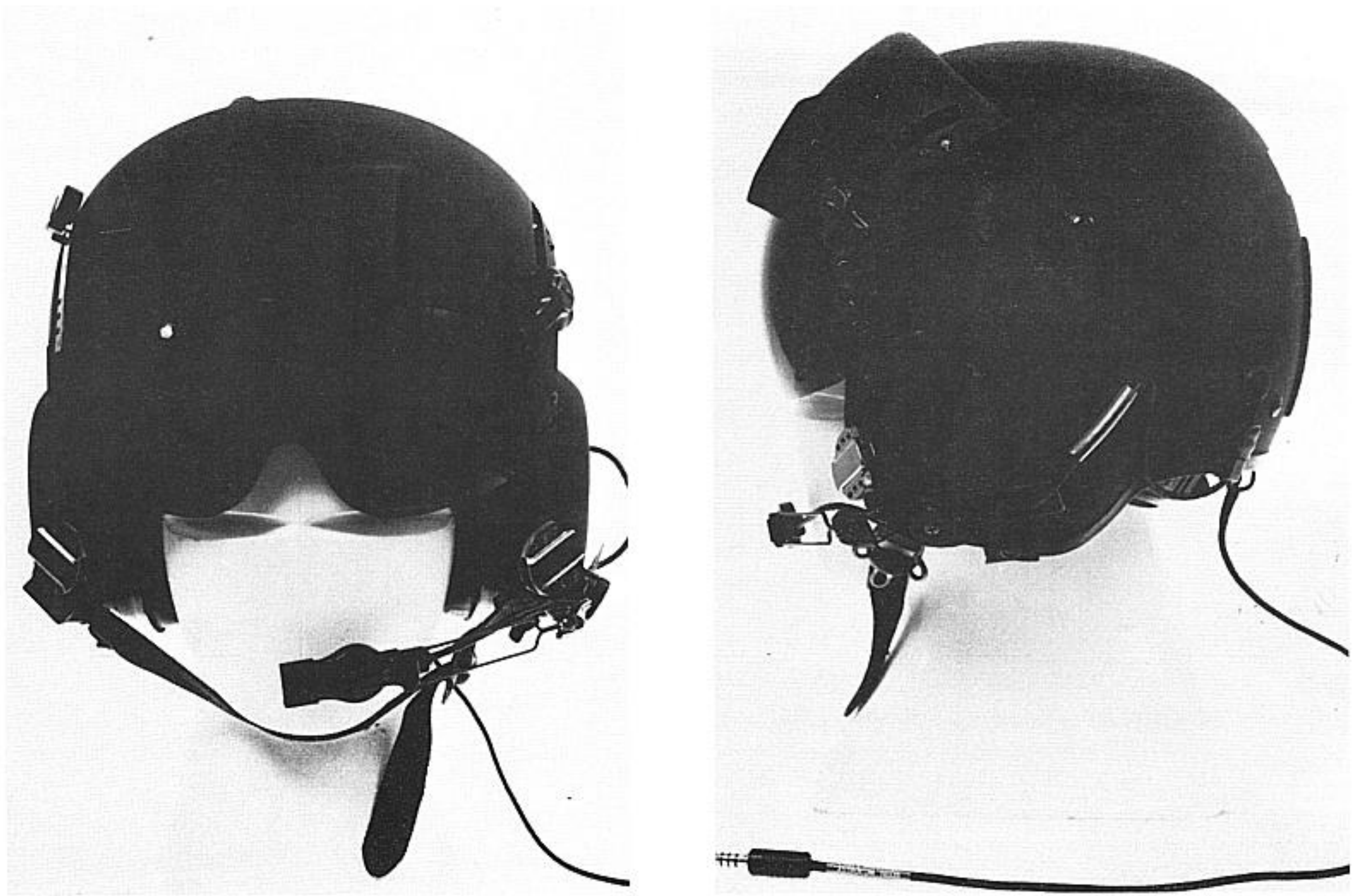
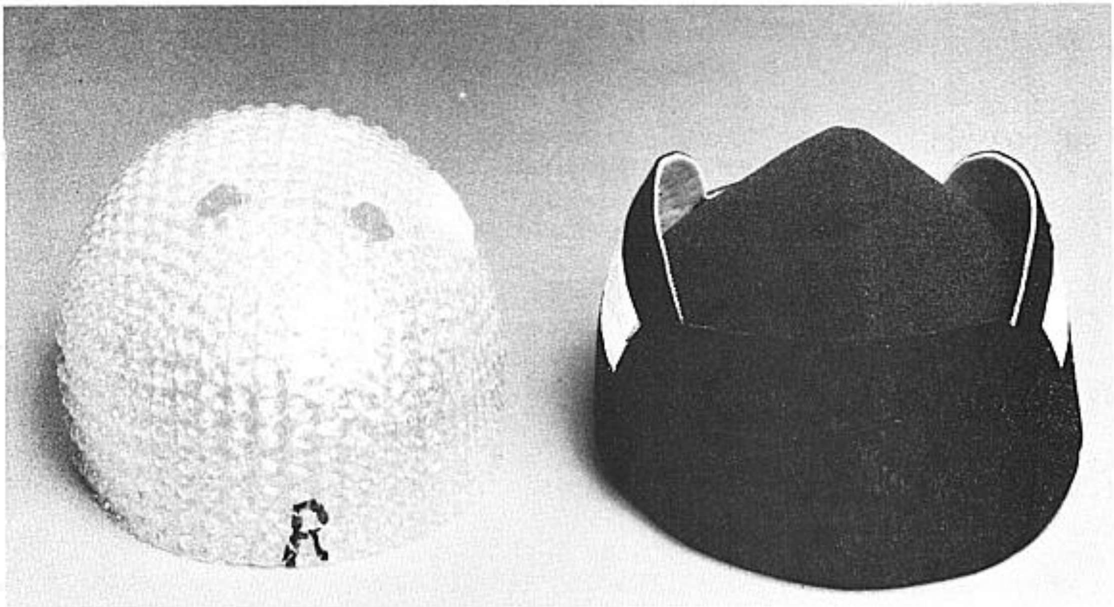


Figure 5. HGU-56/P helmet (courtesy Gentex Corporation).

Attempts were made to reduce the incidence of concussive head injury in Army helicopter accidents by improving the impact protection provided by the SPH-4. Research at USAARL showed the impact protection provided by the SPH-4 could be increased significantly by reducing the density of the polystyrene liner and increasing the liner thickness (Haley and Hundley, 1978; Haley et al., 1983 and 1988). Reducing the density allowed the foam liner to compress more easily, and thus, absorb impact energy more readily (conversely, higher density foams tend to transmit higher pressure with concomitant higher impact force). Increasing the liner thickness increases the stopping distance, reduces the occurrence of total foam compression or "bottoming out," and provides for a greater (survivable) velocity of impact.

In 1974, the thickness of the SPH-4's liner was increased to 0.50 inch from 0.38 inch after field studies revealed the 0.38-inch thick liner "bottomed out" and transmitted excessive impact force in some crashes. A lower density, 4.5 lb/ft^3 foam liner was incorporated in the SPH-4 in 1982. Although the impact test standard in MIL-H-43925 was not changed (Table 3), the impact protection of the 1982 SPH-4 was increased by about 33 percent over that of the original 1970 version. This line of work was carried further with a Gentex Corporation-developed helmet called the SPH-5™. This helmet, which was not procured by the Army, incorporated a 0.63-inch foam liner having a density of 2.5 lb/ft^3 in addition to a thermoplastic liner (TPL™) as shown in Figure 6. The SPH-5™ produced peak headform accelerations of about 190 g at a 6-ft drop height (Haley et al., 1988). This helmet was the forerunner of the proposed Army SPH-4B.

The Army SPH-4B is intended to replace the standard SPH-4 soon. The currently fielded SPH-4 may be converted to the SPH-4B (with the exception of the lightweight Kevlar™ shell) by installation of a retrofit kit which will contain a TPL™ and a 0.63-inch thick, 2.5 lb/ft^3 foam liner (Figure 7). In addition, USAARL has recommended the kit contain a modified "yoke" retention assembly and Gentex AL14 ABS plastic crushable earcups, both of which will be discussed later. As can be seen in Table 3, the SPH-4B will be intermediate between the current SPH-4 and the HGU-56/P in terms of impact protection. An obvious question that may be asked is why the SPH-4B is not designed to limit head deceleration to 150 g or less at a drop height of 6 feet. The answer is there are only two SPH-4 shell sizes available so the helmet volume is fixed. To further increase the impact protection provided by the SPH-4B would require using a thicker foam liner. This, in itself, is not a problem. However, since there are only two shell sizes available, using a foam liner thicker than 0.63 inches (in addition to the TPL™) would present serious fitting problems for individuals with large head dimensions.



TPL Foam and cloth carrier

Figure 6. View of the four-layer TPL™ removed from the 5 mm thick soft foam and cloth carrier.

0.63 inch foam liner TPL

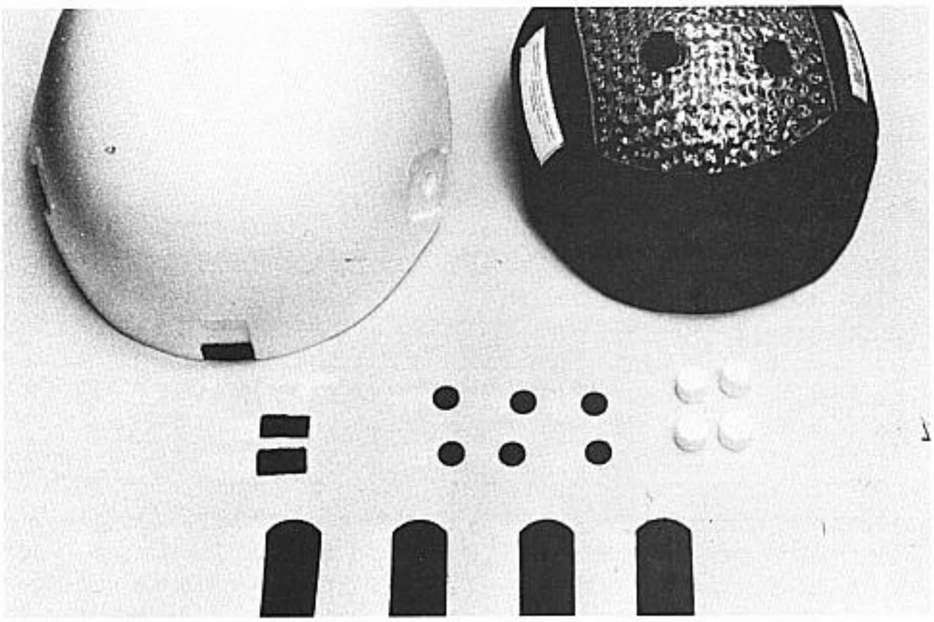


Figure 7. TPL™ retrofit kit for the SPH-4 helmet.

The only solutions in this case are: Increase the number of SPH-4 shell sizes available and then increase foam liner thickness as necessary, or use a more efficient foam liner. Currently, there are no plans to increase the number of SPH-4 shell sizes. Other types of foam liners have been investigated; however, polystyrene appears to be the best foam overall due to its fairly good energy-absorption characteristics, excellent shelf life, excellent wear characteristics, light weight, and relatively unchanged impact performance at various temperatures.

The HGU-56/P, which will have a 0.75-inch thick liner with a density of 2.4 lb/ft^3, will surpass the SPH-4 in impact protection as reflected in Table 3. This helmet will be available in not fewer than four shell sizes. The higher level of impact protection provided by the HGU-56/P definitely should reduce the incidence of concussive head injury in many Army helicopter crashes.

The TPL™ (Figure 6) primarily was designed to be a more comfortable alternative to the sling suspension; in essence, it is a "custom-fitting" pad. Nonetheless, it has a small but positive direct effect on impact protection being roughly equivalent to 1/8-inch of polystyrene foam. The TPL™ also has a significant indirect effect on impact protection because the sling suspension is removed and the vacated space occupied by energy-absorbing foam. Removal of the sling suspension also allows the use of a 25 percent thicker foam liner with 20 percent more cranium coverage. Figure 8 shows the head coverage provided by the SPH-4 foam liner in the 1970 and 1982 versions.

The second major head injury problem found in Army helicopter accidents, basilar skull fracture, was detected in the mid-1970s. Epidemiological studies showed a high frequency of basilar skull fractures associated with the use of the SPH-4 (Slobodnik, 1980; Haley et al., 1983; Shanahan, 1985). Army helicopter accident data have shown 26 percent of all impacts to the SPH-4 have occurred in the earcup region and impacts in this area result in more serious injuries than impacts to other regions of the helmet (Shanahan, 1985). Figure 9 shows the distribution of severe head injuries with abbreviated injury scale (AIS) $\geq$ 4 by impact location (Shanahan, 1985). Table 4 shows the distribution of basilar skull fractures by primary impact location in 175 helicopter accidents (Shanahan, 1985). The problem of basilar skull fractures was deemed to be due to the lack of energy attenuation capability in the earcup region (see Figure 8) associated with the rigid plastic earcup used in the SPH-4 (Slobodnik, 1980; Haley et al., 1983; Shanahan, 1985).

Figure 8. Head coverage with standard SPH-4 foam liner. (The dashed line shows the lower contour of the SPH-5 and SPH-4B foam liners.)

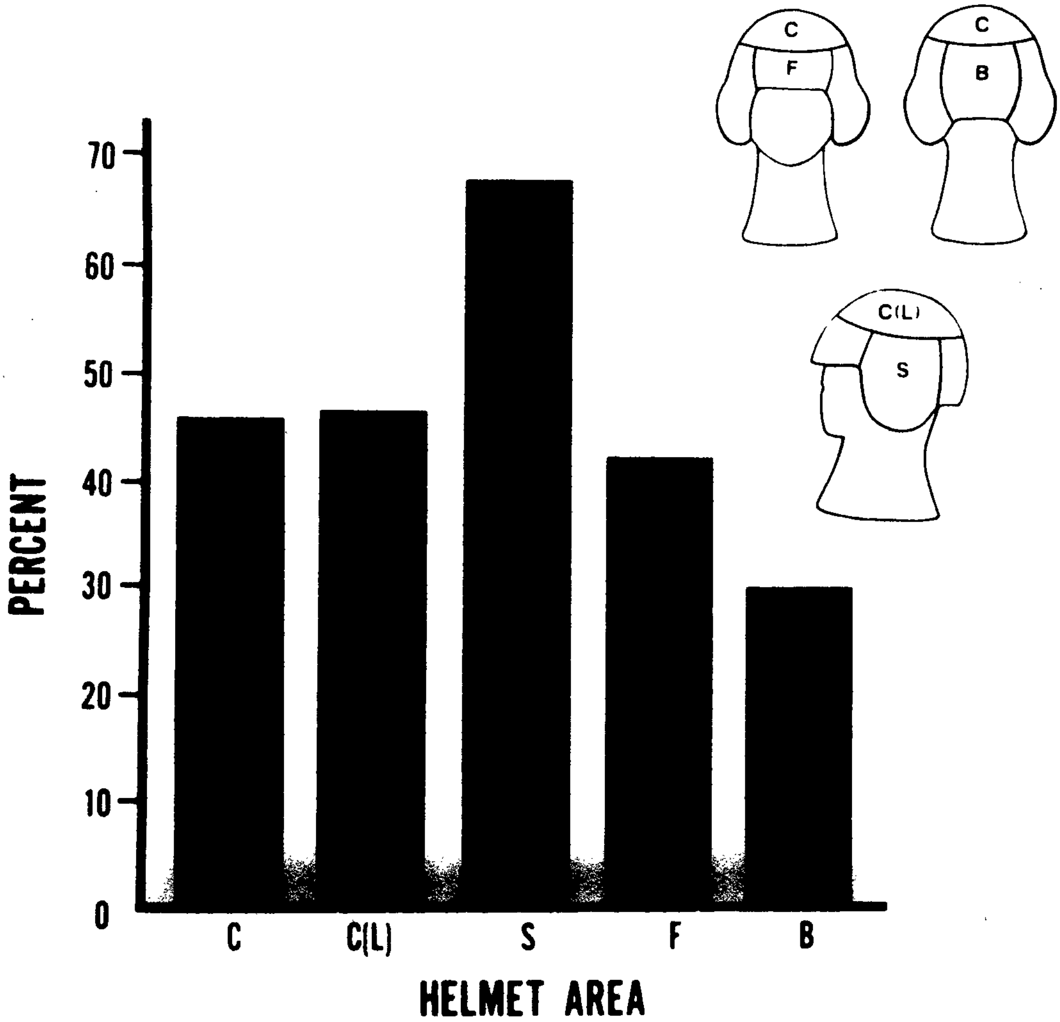


Figure 9. Percentage of serious (AIS ≥4) head injuries by impact location. C=crown, C(L)=crown (lateral), S=both sides, F=front, B=back. From Shanahan, 1985.

Table 4.

Distribution of basilar skull fractures by primary impact location (from Shanahan, 1985).

Primary impact area	Number of cases	Frequency of basilar skull fracture	Percent basilar skull fractures
Crown	28	4	14
Crown(lateral)	15	7	47
Sides	45	19	42
Front	69	14	20
Back	18	3	17
Total	175	47	–

While the SPH-4's rigid plastic earcup provided excellent sound attenuation, it also could withstand a 5000-lb load without failure (Shanahan, 1985). On the other hand, the temporoparietal region of the human skull can fracture under loads half as great (Chamouard et al., 1986). The combination of no impact attenuating foam in the earcup region and the rigid earcups allowed lateral impact forces to be transmitted directly to the temporoparietal region of the wearer's skull resulting in linear fractures which extended to the base of the skull (Shanahan, 1985). This finding led to the development of an energy-absorbing, crushable earcup which would yield at loads low enough to minimize basilar skull fracture (Shanahan and King, 1983; Hundley and Haley, 1984).

Figure 10 compares the force transmitted by the rigid plastic earcup with that of a prototype crushable aluminum earcup developed by Simula Inc. The ABS plastic AL14 crushable earcup was designed and implemented in the Gentex SPH-5™ in 1988. This earcup will be a part of the SPH-4B retrofit kit when fielded. Another plastic crushable earcup, which was designed under contract to the Army by Gentex, will be used in the HGU-56/P. This flexible plastic earcup currently provides about 10 percent more impact protection than the AL14 earcup.

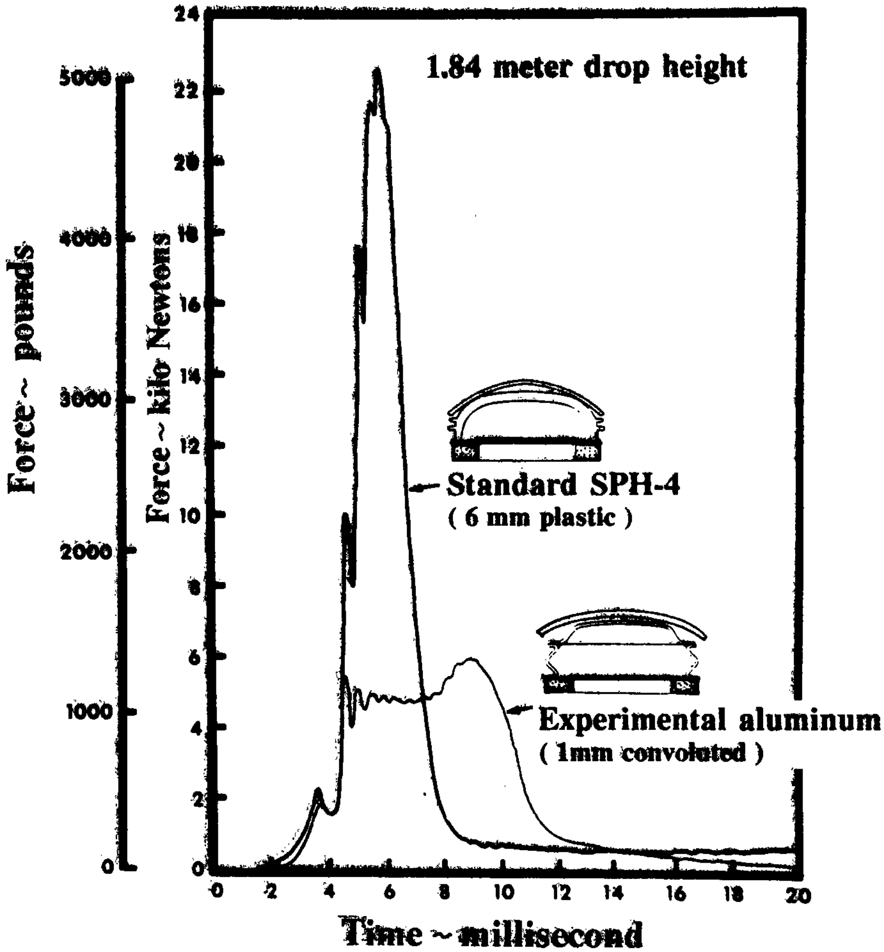


Figure 10. Comparison of force transmitted to standard SPH-4 earcup and a crushable earcup

History of helmet retention improvements

Helmet retention is crucial to head injury prevention in Army helicopter crashes. An aircrew helmet can provide impact protection only if the helmet remains firmly on the wearer's head for the duration of the crash and postcrash sequences. If the helmet comes off or rotates excessively during this time, the wearer's cranium can be exposed to impact and, subsequently, head injury can occur.

The SPH-4 retention assembly is made up of two components (Figure 11). They are the chinstrap-napestrap combination and the earcup assembly. The HGU-56/P differs in that it has a nape plate that ties in directly to the back of the shell; this feature helps to prevent rotation of the shell relative to the retention assembly. The nape plate increases the area of contact between the back of the wearer's head and the napestrap. This improvement was introduced to minimize helmet forward and rearward rotation on the head by increasing contact area between the nape and the retention assembly, and by a direct connection from the plate to the shell. Currently, aircrew helmet chinstrap strength is measured according to ANSI Z90.1-1971. The method entails static loading of the chinstrap and measurement of its resulting elongation and strength. Figure 12 shows the USAARL chinstrap test device.

Although not used at USAARL, a dynamic "drop test" to evaluate chinstrap strength and elongation is now specified by ANSI. However, this dynamic test falls short of evaluating the effectiveness of the retention system to prevent rotation on the head.

Figure 11. SPH-4 earcup retention assembly with (a) current chinstrap, 1980, (b) double Y-chinstrap, 1978, (c) single snap chinstrap, 1970.

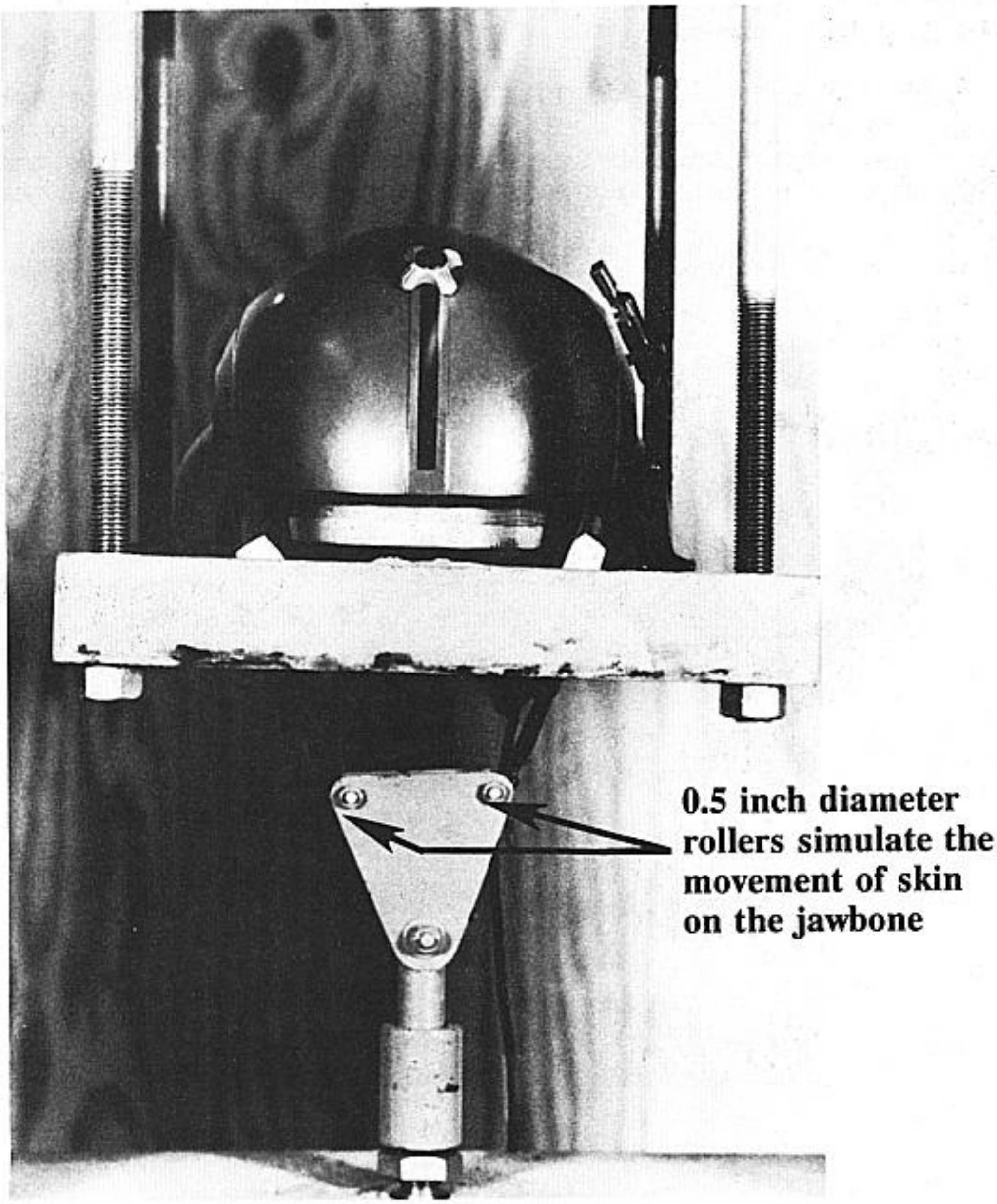


Figure 12. USAARL chinstrap test device.

Excessive helmet rotation and helmet loss have been a problem with the SPH-4 (Reading et al., 1984; Vyrnwy-Jones, Lanoue, and Pritts, 1988). More recently, Reading et al., and Vyrnwy-Jones, Lanoue, and Pritts stated about one in every five Army aircrew members involved in a severe crash loses his helmet. These losses primarily have been due to failure of the snap fasteners (Reading et al., 1984). However, many SPH-4 chinstrap failures observed in this laboratory during routine chinstrap strength tests have been due to stitch failure in the tabs that connect the retention assembly to the helmet shell. Excessive helmet rotation, which can leave portions of the wearer's cranium exposed to impact, occurs in about 20 percent of Army helicopter crash victims (Vyrnwy-Jones, Lanoue, and Pritts, 1988).

Various attempts have been made to strengthen the SPH-4 chinstrap. The 1970 version had a chinstrap with single snap fasteners on each side and was designed to withstand a load of 150 lb. In 1978, a double-Y chinstrap with two snap fasteners on each side was incorporated to reduce failures. This chinstrap had a failure limit of 250 lb based on the adjustment buckle strength. The current SPH-4 chinstrap was implemented in 1980. It is fastened to the earcup assembly on one side with a small screw and a T-nut, and the other side is attached with two snap fasteners. This chinstrap has a failure limit of 300 lb as stated in MIL-H-43925, but some snap fasteners fail at 280 lb. Figure 12 shows these three chinstrap configurations.

During the last few years, USAARL researchers have been evaluating a new test method to assess helmet rotational movement under dynamic conditions. This method, which uses a pendulum device, recently was described (Vyrnwy-Jones, Paschal, and Palmer, 1989). With this method, an aircrew helmet is placed on a "Humanoid" headform-neck assembly which, in turn, is mounted on a pendulum beam (Figure 13). The pendulum beam swings downward from its gravitational force and is subjected to a rapid deceleration after passing through the vertical position. The deceleration is created by an energy-absorbing material (i.e., paper honeycomb, foam, etc.) which represents the forces acting on a restrained torso during a forward impact. On impact, the head and neck flail forward simulating an actual crash. The forces of the simulated crash can be altered by changing the pendulum beam drop height and/or the type of impact crushable material used. The simulated crash sequence is recorded using high-speed video equipment. Helmet rotation is calculated after digitization of the video data.

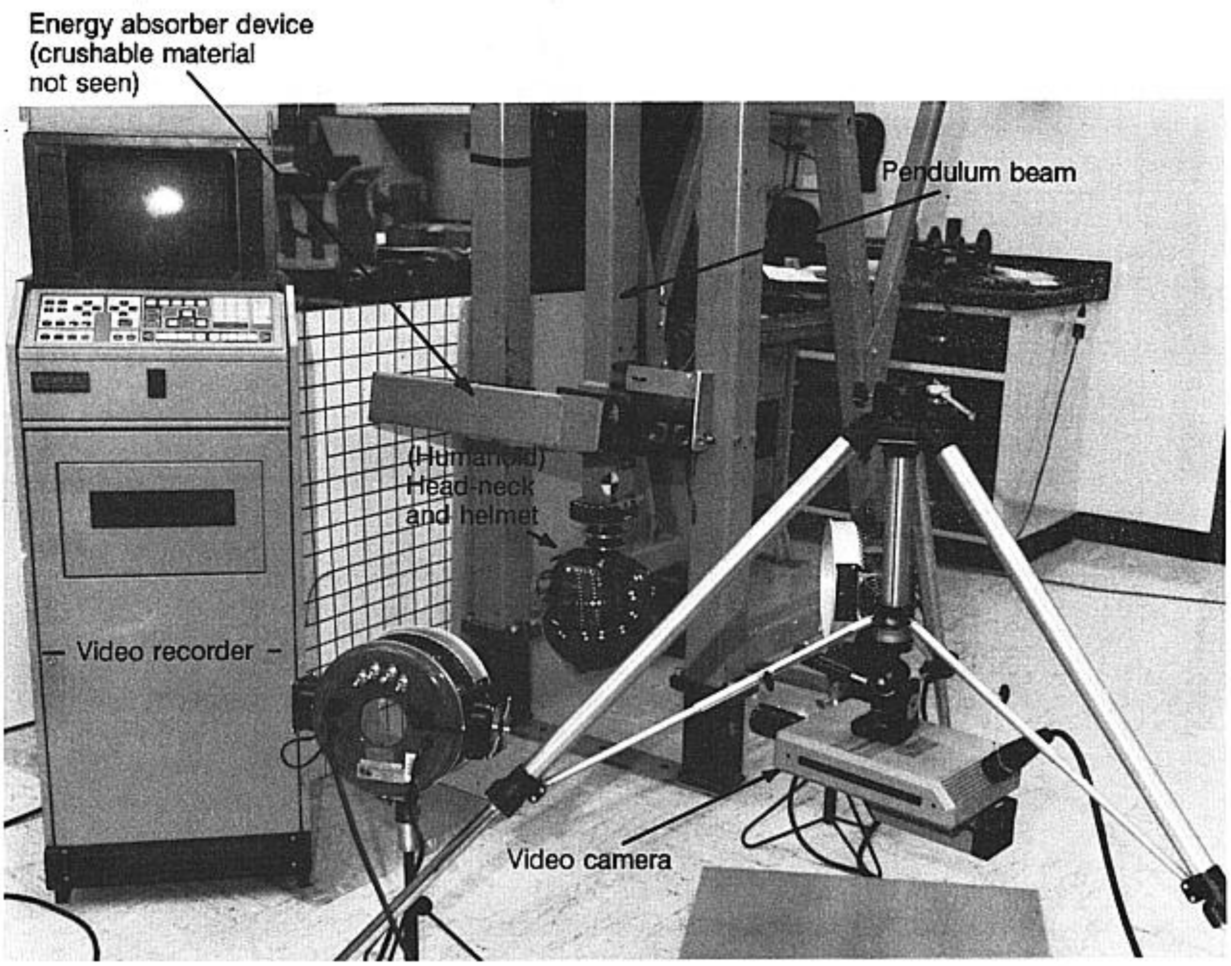


Figure 13. Pendulum device and high-speed video recorder.

Testing of the standard SPH-4 on the pendulum device showed its retention assembly allowed an alarming amount of forward and rearward rotation to occur. This marked rotation appeared to be due to excessive elongation of the retention assembly under load (Vyrnwy-Jones, Lanoue, and Pritts, 1988). Subsequently, it was found with minor modification the standard SPH-4 retention assembly could withstand loads up to 450 lb and its elongation under load could be reduced by about 50 percent (Palmer and Haley, 1988). Based on this work, the modified yoke retention assembly (MYRA) (Figure 14) was designed (Hines et al., 1990). The MYRA differs from the standard SPH-4 retention assembly in that the chinstrap of the MYRA is a continuous extension of the helmet shell attachment tabs. The attachment tabs of the standard retention assembly are prone to failure because the four tabs are individually stitched to the earcup retention cloth. In the MYRA, these tabs have been replaced with three lengths of tubular nylon. The tubular nylon is attached to the earcup retention cloth at three points on either side and spans across the earcups (Figure 14). The tubular nylon is reinforced with Kevlar™ tape and stretches less than the retention cloth which acts to reduce the entire retention assembly elongation. The chinstrap of the MYRA will have a 440-lb design (failure) limit, but it has been shown to withstand a 600-lb load without failure (Hines et al., 1990). A high-strength chinstrap such as this is desirable because, theoretically, it can be shown that loads of up to 400 pounds can be exerted on the chinstrap in a 95th percentile crash. The chinstrap may be loaded either by inertial force or by tangential impacts; the tangential impact at relatively flat angles easily can result in 400-pound loads when the impact vector is 1500-2000 pounds. The 440-pound design value includes a 10 percent increase to account for degradation with age. The chinstrap strength and reliability are improved because it is attached directly to the helmet shell and because there are no snap fasteners used. In addition to increased strength and reduced elongation, the MYRA includes a Gentex-developed tie-down napestrap to attach directly to the shell. The above noted MYRA features allowed much less rotation than the standard SPH-4 retention assembly allowed when tested dynamically using the pendulum device (Table 5).

A variation of the MYRA will be used in the HGU-56/P. The HGU-56P retention assembly differs in the way the crushable earcups are installed.

Summary

The SPH-4 aircrew helmet has been used by the U.S. Army for 20 years. Increased severity of Army helicopter crashes due to changes in Army aircraft and mission requirements has resulted in an increase in head injury frequency. This, in turn, has necessitated improvements in SPH-4 impact protection. Two preventable major head injury problems have been identified in the last 12 years: Incapacitating concussive head injury and basilar skull fractures. In order to reduce the incidence of incapacitating concussive head injury with the SPH-4, the area of "crushable" foam coverage is increased by 20 percent in the SPH-4B, the foam thickness increased by 25 percent, and the foam density reduced by 45 percent. With the introduction of the TPL™, the amount of head surface area covered by energy-absorbing foam has been increased as well. The frequency of basilar skull fractures caused by sideward impacts will be reduced by the implementation of an energy-absorbing earcup.

Figure 14. Modified yoke retention assembly.

Table 5.

Change in angular rotation.

Helmet type	Maximum forward rotation (degrees)	Maximum rearward rotation (degrees)
SPH-4 with TPL™ and standard retention assembly	16.3	40.9
SPH-4 with TPL™ and modified yoke retention assembly	9.0	23.1

Helmet retention, so necessary for impact protection, also will be improved in the SPH-4B. This situation will be improved by implementation of the MYRA. The MYRA is stronger and stretches less under load than the standard SPH-4 retention assembly. The MYRA also reduces helmet rotation on the head and should reduce the occurrence of cranial exposure.

The HGU-56/P, a lightweight, new technology helmet will offer significantly better impact protection than the SPH-4 due to the use of a thicker, lower density foam liner and the best currently available "crushable" earcup. The improved stability with the "floating" nape pad also is expected to make the use of helmet-mounted visual enhancement devices more comfortable.

Conclusions

1. The impact protection provided by the current SPH-4 has been significantly improved compared to the original 1970 version.

2. The problem of incapacitating concussive head injury in U.S. Army helicopter accidents can be further reduced by decreasing the density and increasing the thickness of the SPH-4's energy-absorbing foam liner. The amount of head surface area covered by the foam liner should be increased as well.

3. The incidence of basilar skull fracture in survivable Army helicopter crashes can be reduced by replacing the SPH-4's rigid earcups with energy-absorbing (crushable) earcups, and increasing the cranium coverage of the foam liner.

4. The introduction of the MYRA (yoke chinstrap) in the SPH-4 will reduce the incidence of helmet rotation and helmet loss in Army helicopter crashes, and improve the stability of the helmet when worn with visual enhancement devices.

5. The new HGU-56/P, when fielded, will provide better impact protection than the SPH-4 due to the thicker, low density foam liner and to the improved energy-absorbing earcups. Indeed, it is anticipated this new aviator flight helmet will provide the best impact protection of any in use worldwide. In actual fact, this new technology helmet will be nearly equal to the best commercial "crash" helmet in impact protection, but will weigh no more than many fixed-wing helmets giving less impact protection.

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