Research to Practice

# Safety Eyewear

## *How much coverage does it provide?*

***By James R. Harris, Richard Whisler, Douglas E. Ammons, Jim Spahr and Larry L. Jackson***

IN 1980, BUREAU OF LABOR STATISTICS (BLS, 1980) released a special report on eye injuries among high-risk workers. In this study, approximately 40% of injured workers were wearing some form of eye protection, but in many cases an object or substance went around or under the protection being worn. This study had a significant influence on the development of ANSI Z87.1-1989, American National Standard Practice for Occupational and Educational Personal Eye and Face Protection Devices. That standard strengthened the requirements for side protection and was promulgated for general industry in OSHA 29 CFR 1910.133, Eye and Face Protection, in 1994. If a hazard from flying objects exists, the regulation requires employers to ensure that workers wear eye protection with side protection [29 CFR 1910.133(a)(2)].

**James R. Harris, Ph.D., P.E.,** *is a research safety engineer in NIOSH's Division of Safety Research. Harris holds a B.S. and an M.S. in Mechanical Engineering from West Virginia University (WVU), from which he also holds a Ph.D. in Occupational Safety and Health. He is a member of the Accredited Standards Committee (ASC) on Safety Standards for Eye Protection (Z87), a member of American Society of Mechanical Engineers and a professional member of ASSE and its Northern West Virginia Chapter.*

**Richard Whisler** *has an associate's degree in Computer Information Management from the International Academy of Design and Technology as well as an associate's degree in Computer Animation and Multimedia from the Art Institute of Pittsburgh. He is currently running a NIOSH anthropometry laboratory in Morgantown, WV.*

**Douglas E. Ammons** *holds a B.S. in Computer Engineering from WVU and a B.S. in Electronics from Fairmont State University. He is currently running a NIOSH virtual reality laboratory in Morgantown, WV.*

**Jim Spahr** *is a commissioned officer in the U.S. Public Health Service currently serving as a supervisory safety and occupational health researcher at NIOSH. He holds an M.S. in Public Health (International Health) from Johns Hopkins University. Spahr has completed two postgraduate fellowships in institutional environmental health and community injury prevention. He is also a registered sanitarian, Diplomat of the American Academy of Sanitarians and a certified healthcare environmental manager. Spahr is a professional member of ASSE and its Northern West Virginia Chapter.*

**Larry L. Jackson, Ph.D.,** *is a research epidemiologist and chief of the Injury Surveillance Team in NIOSH's Division of Safety Research. He maintains the collection of data on nonfatal occupational injuries and illnesses treated in emergency departments through the occupational supplement to the National Electronic Injury Surveillance System. In addition, Jackson specializes in the epidemiology of occupational eye injuries and is the NIOSH representative to the Z87 ASC, Prevent Blindness America's Eye Safety Advisory Committee and National Eye Institute's Healthy People 2010 Vision Workgroup.*

Although improvements have been made in the consensus manufacturing standard for safety eye protection and workplace regulations, an estimated 283,000 (±66,000 95% confidence bounds) work-related eye injuries were treated in U.S. hospital emergency departments in 1999 (NIOSH). More than 90% of these eye injuries resulted from contact with hazardous objects and exposure to hazardous substances and environmental conditions.

Anecdotal evidence from workers, emergency department charts and injury investigations indicate that eye injuries continue to occur while workers are wearing eye protection. One can cite many reasons that these injuries can occur—the eye protection not fitting properly; the protection not being positioned properly in front of the eyes; a lack of protection while the eyewear is being donned or doffed; wearing an improper type of protection for the hazards present; and eye protection that may not offer complete eye coverage.

This article addresses the issue of eye coverage within the context of safety eyewear requirements of ANSI Z87.1 and other international standards. A new measurement technique is described that provides a quantitative evaluation of coverage for specific eyewear. No attempt is made to define *sufficient* coverage, but the information from this type of methodology should be valuable when designing and selecting safety spectacles and when establishing test performance requirements or criteria included in eyewear standards.

### Coverage Requirements

In the U.S., design and performance of safety eyewear including safety spectacles, goggles, face shields, welding helmets and full-face respirators are guided by the 2003 revisions to ANSI Z87.1 (ANSI, 2003). For safety spectacles, the U.S. standard provides no minimum dimensions (with the exception of lens thickness) or shape requirements for the safety lenses other than those inferred for a product to meet various testing requirements, particularly high-velocity impact testing (Table 1).

For high-velocity impact testing of safety spectacles with side protection, ANSI Z87.1-2003 requires eight test shots for each lens to be fired in a horizontal reference plane (pupillary plane). This plane passes through the center of the headform eyes (nominally the pupils) at a focal point 10 mm posterior to the corneal vertex of the Alderson 50th percentile male headform. Figure 1 (p. 24) shows headform rotation including 15° to the nasal and from 0° through 90° temporally. Two additional shots are required at the 90° temporal axis along horizontal planes 10 mm above and below the horizontal reference plane through the pupils.

From a frontal view, these testing requirements do not define a minimum lens height beyond the physical requirements of the lens material to stop a 6.35 mm diameter steel ball at 45.7 m/s. From a temporal view, side protection is required with a minimum height of 20 mm (nominal) at a point 10 mm posterior to the corneal vertex. In the 1989 version of the standard (ANSI Z87.1-1989), the focal point for impacts was the corneal vertex, and not 10 mm posterior to the surface of the eye as in the current standard. For safety spectacles without side protection, shots are to be minimally at 15° to the nasal, 0° and 15° to the temporal, with additional shots in 15° temporal increments until the product is no longer impacted. Thus, eyewear dimensions with or without side protection are dictated by the structural performance requirements to pass the test and the practicality of manufacturers to have a reasonable, saleable product that minimizes hazards to the worker and liability to the manufacturer.

Although ANSI Z87.1 does not specify minimum eye coverage requirements, standards from other countries and standards-setting bodies do prescribe minimum lens dimensions (Table 1). Standards from Canada (CSA Z94.3-02), Europe (BS EN 166:2002, BS EN 168:2002) and Australia/New Zealand (AS/NZS 1337:1992) require various safety spectacle lens widths and heights as outlined in Table 1. Only the

**Abstract:** *More than 200,000 eye injuries occur in U.S. workplaces each year. Many of these workers were wearing some form of eye protection. Coverage provided by safety eyewear can be difficult to quantify. NIOSH researchers have developed methods for estimating coverage—information that should be valuable when designing and selecting safety spectacles and when establishing test performance requirements or criteria included in eyewear standards.*

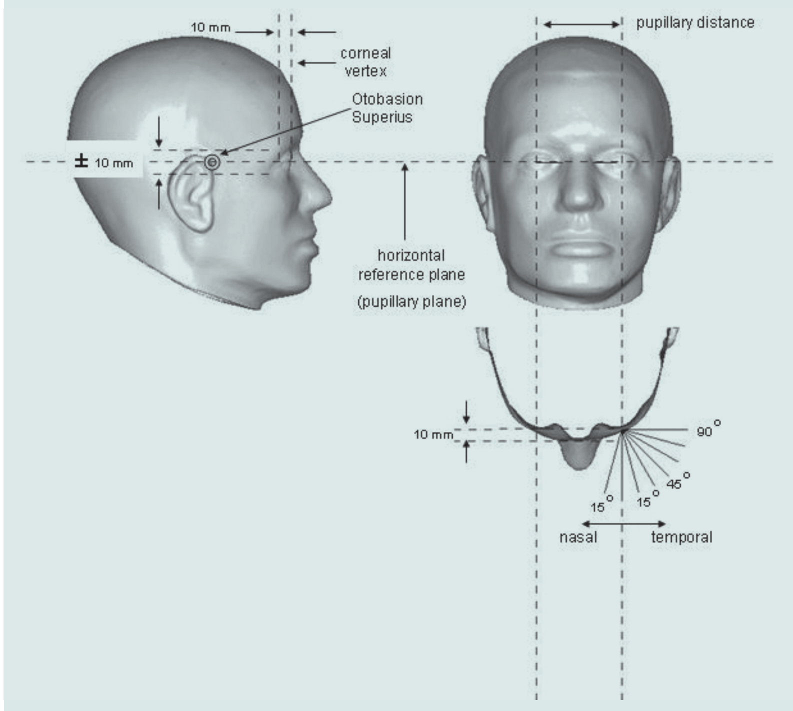
## Table 1

## International Consensus Standards for Safety Eyewear

| Standard | Min. lens dimensions | | Min. side protection dimensions | | Headform | Frontal impact | Temporal impact |
|---|---|---|---|---|---|---|---|
| | Width | Height | Width | Height | | | |
| U.S. ANSI Z87.1-2003 (with side protection) | -- | -- | -- | -- | Alderson 50th percentile male | **Target point/area:** a point 10 mm posterior to the corneal vertex in the pupillary plane<br>**Horizontal trajectory:** in pupillary plane<br>**Impact angles:** 15° to the nasal, 0°, 15°, 30°, 45°, 60°, & 75° temporally<br>**Impact locations:** 7 | **Target points/area:** points 10 mm posterior to the corneal vertex in the pupillary plane and parallel planes 10 mm above and below the reference plane<br>**Horizontal trajectory:** in pupillary plane & parallel planes at ±10 mm<br>**Impact angle:** 90° temporally<br>**Impact locations:** 3 |
| U.S. ANSI Z87.1-2003 (without side protection) | -- | -- | -- | -- | Alderson 50th percentile male | **Target point/area:** a point 10 mm posterior to the corneal vertex in the pupillary plane<br>**Horizontal trajectory:** in pupillary plane<br>**Impact angles:** 15° to the nasal, 0° & 15° temporally, plus 15° increments temporally until the lens is not impacted<br>**Impact locations:** 8 maximum | (By definition, temporal impact not possible without side protection) |
| CSA Z94.3-02 | 40 mm in front of each eye; field of view ≥ 45° temporally in horizontal meridian | 33 mm in front of each eye; field of view ≥ 80° total in vertical meridian | 20 mm | ±16 mm at corneal vertex<br>±10 mm at 20 mm posterior to vertex | Alderson 50th percentile male or CSA adult male | **Target points/area:** midpoint between pupils, point in front of each pupil, points at temporal edges (15 mm temporal from pupil center), & point of attachment of endpiece to the eyewire (one side)<br>**Horizontal trajectory:** in pupillary plane<br>**Impact angle:** 0°<br>**Impact locations:** 6 | **Target points/area:** points 10 mm posterior to the corneal vertex in the pupillary plane and parallel planes 10 mm above and below the reference plane<br>**Horizontal trajectory:** in pupillary plane & parallel planes at ±10 mm<br>**Impact angle:** 90° temporally<br>**Impact locations:** 3 |
| BS EN 166: 2002<br>BS EN 168: 2002 | Ellipse field of view with horizontal axis of 22.0 mm at 25.0 mm from surface of eye | Ellipse field of view with vertical axis of 20.0 mm at 25.0 mm from surface of eye | Both height and width controlled by lateral protection assessment criterion; minimum size covers frontal and temporal impact target areas | ← | European 50th percentile male | **Target points/area:** circle with 10 mm radius centered on pupil<br>**Horizontal trajectory:** in horizontal planes ≤ 10 mm above or below pupillary plane<br>**Impact angle:** 0°<br>**Impact locations:** 1 | **Target area:** circle with 10 mm radius centered on intersection of pupillary plane & vertical plane 45 mm posterior to the apex of the nose<br>**Horizontal trajectory:** in horizontal planes ≤ 10 mm above or below pupillary plane<br>**Impact angle:** 90° temporally<br>**Impact locations:** 1 |
| AS/NZS 1337:1992 | 42 mm[§] | 32 mm[§] | -- | -- | European 50th percentile male | **Target points/area:** point 32 mm temporally of the sagittal plane & 99 mm from the top of the headform (i.e., nominally the pupil)<br>**Horizontal trajectory:** in pupillary plane<br>**Impact angle:** 0°<br>**Impact locations:** 1 | **Target points/area:** corneal vertex in the pupillary plane<br>**Horizontal trajectory:** in pupillary plane<br>**Impact angle:** 90° temporally<br>**Impact locations:** 1 |

Figure 1

## ANSI Z87.1-2003 Headform Rotation/Translation Requirements for Impact Testing



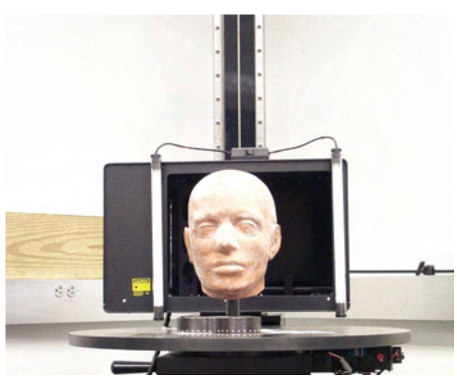



**Photo 1: Alderson headform prepared for laser scanning.**

Canadian standard has mandatory dimensions for side protection. Side protection must be at least 32 mm high at the corneal vertex and extend at least 20 mm posterior to the vertex with a minimum posterior height of 20 mm. As noted in Table 1, the BS EN standards include a test for lateral protection assessment. This assessment involves horizontal probing with a 2 mm diameter rod in an attempt to touch impact point regions on the headform.

The international standards cited have similar requirements for high-velocity impact testing in that spectacles are tested in place on a 50th percentile male headform by impacting the lens with a steel ball ~6.4 mm in diameter at a velocity ranging from 40 to 46 m/s. However, their impact points are slightly different (Table 1). The impact points for the high-velocity test do create defacto minimum lens and side protection dimensions, but for the non-U.S. standards the minimum required dimensions are still the controlling factor for lens size.

Whereas the testing and minimum required dimensions implicitly address coverage, these requirements offer no discriminatory factors between spectacle products. Additionally, the standards do not explicitly address typical coverage problems or gaps along the brow, the temporal area of the cheek bone or the transition area from lens to side protection. These issues are often expected to be addressed by the employer or worker in the selection and fitting of spectacles.

With current U.S. safety spectacle trends moving to smaller frames and more wraparound styles, a lack of minimum dimensions in the ANSI Z87.1 standard and/or criteria for eye coverage may present an unacceptable risk to the user by leaving significant portions of the eye area unprotected from projectiles. Balance must be achieved between having a fashionably small lens and providing the end-user with sufficient coverage.

It is important to note that change may be on the horizon as the 2003 ANSI Z87 standard is revised to the 2009 ANSI Z87 standard. The 2009 proposal has minimum lens dimension requirements for each lens to cover an elliptical area centered on the geometric center of each lens 40 mm in width and 33 mm in height. Additionally, new high velocity impact sites have been proposed. Note in Figure 1 that ANSI Z87.1-2003 impact points occur in 15° increments.

### Digital Coverage Assessment

The authors developed a technique for digitally evaluating coverage provided by safety eyewear. Laser scanning equipment produced digital eyewear models as well as digital standard headform models (Photos 1 and 2). A Cyberware 3030 scanhead on a Cyberware MS platform was used to project a low-intensity laser on the object of interest to create a lighted profile. High-quality video sensors evaluated this profile from two viewpoints to determine 3-D shape to an accuracy of 0.1 to 0.4 mm.

The digital eyewear models were then placed on the digital headform models using Imageware software (Photo 3). Each eyewear model was fit to a headform twice by each researcher. Two researchers were used for the digital coverage assessment.

The eyewear was not scanned while on the headform since eye area information could be blocked from the scanner by the eyewear.

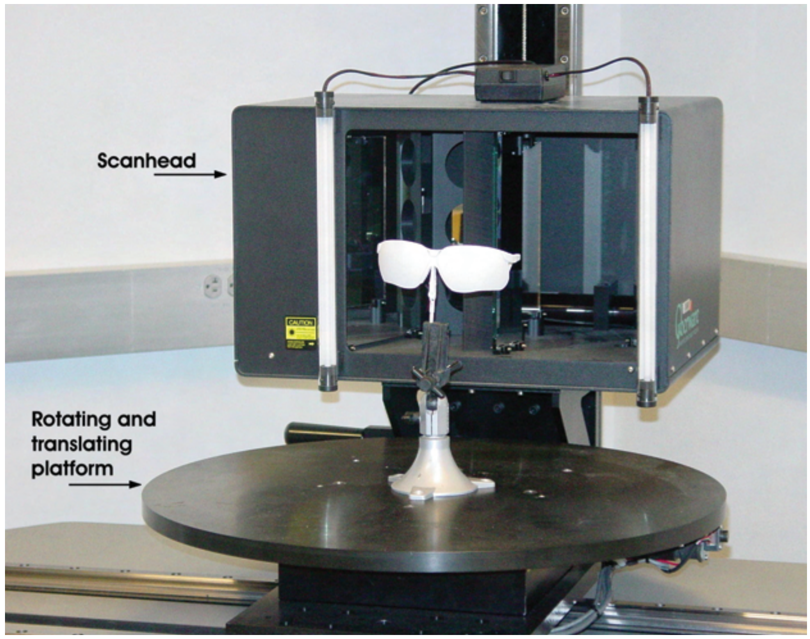



Photo 2: Spectacles prepared for laser scanning.

This study utilized 25 pairs of eyewear and eight different international headforms. For presenting results, the eyewear were grouped according to design. Group I had independent side protection (i.e., side protection separate from the lenses). Group II had integral (but discernible) side protection. Group III had wrap-around protection. Photo 4 displays examples from each group. Five pairs of eyewear were categorized as group I; 7 pairs as group II; and 13 pairs as group III.

The eight headforms used included the Alderson (5th percentile, 50th percentile, 95th percentile), CSA (child, juvenile, adult), BS EN and National Operating Committee on Standards for Athletic Equipment (NOCSAE).

To measure coverage, NIOSH researchers developed a measurement called the coverage coefficient. This is a number ranging from 0 to 1.0 that represents the portion of all particles destined for the eye area which are blocked by eyewear. The particles originate from a hemisphere of radius 300 mm and centered on either the left or right eye. The eye center is considered to be located 10 mm behind the front of the eye as defined in ANSI Z87.1-2003. The hemisphere is a 3-D expansion of impact testing along the horizontal reference plane described in ANSI Z87.1-2003. Particles are located every 15º along the hemisphere and are directed toward the eye center (Figure 2, p. 26).

The eye area is defined as the soft tissue area inside the bony socket surrounding the eye. For the headforms, this area was approximated. Photo 5 (p. 26) shows this area for an Alderson headform. Table 2 (p. 26) lists the eye area dimensions for each headform evaluated.

The authors developed custom C++ software code to perform the digital coverage coefficient calculation. As shown in Figure 2, virtual particles move from a hemispherical surface toward the center of the eye. Similar to the ANSI Z87.1-2003 requirements, particle trajectories are spaced 15° apart. This results in 145 trajectories per eye. Some theoretical trajectories were blocked by body parts such as the brow, nose and cheek, and these particles were not considered in the coverage coefficient calculation. Consequently, the actual number of trajectories that could impact the eye area on the Alderson

Photo 3: Example of eyewear scan digitally fit to headform scan for coverage coefficient calculations.

Photo 4: Examples of eyewear test samples by style grouping (Top = Group I; Middle = Group II; Bottom = Group III).

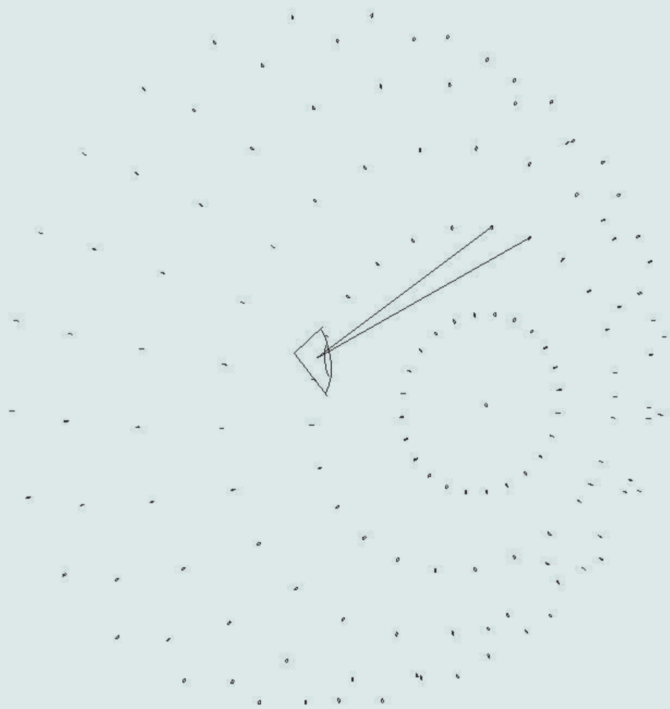
50th percentile male headform was 97 for the right eye and 98 for the left eye (not equal due to asymmetry of the eye areas and the headform). Figure 3 (p. 27) presents the average coverage coefficient results by group for each headform. The graph whiskers show high and low values.

### Physical Coverage Assessment

NIOSH researchers also developed a laboratory-based method and test fixture for determining the coverage coefficient of existing eyewear product (Photos 6 and 7, p. 27). The test fixture was designed

### Figure 2

## Sample Projectile Paths

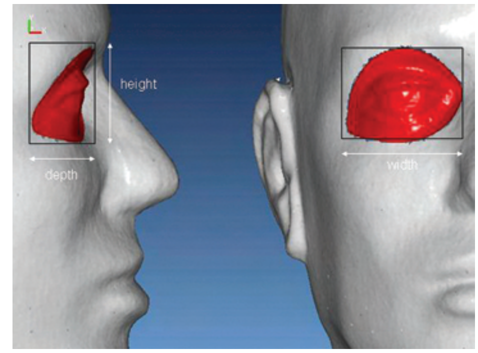


*Note.* *Sample projectile paths from surface of the half-sphere toward the eye center for calculating coverage coefficient.*

to sample at 15° intervals to mimic the ANSI Z87 standard and digital coverage assessment. The headform was positioned so that the rotation center was 10 mm behind the front of the eye.

Low-powered laser light from a laser pointer determined whether a particle from each sampled location would have contacted the eye area, safety eyewear or some other portion of the headform. As with the digital coverage assessment, the headform was first evaluated without safety eyewear to determine how many particles would have contacted the eye area (and not be blocked by another portion of the headform). The procedure was repeated with eyewear in place. Figure 4 lists the results of the physical coverage assessment.

**Photo 5: Approximate soft-tissue eye area on Alderson 50th percentile headform with maximum height, width and depth dimensions shown.**




For the physical coverage assessment, only the 50th percentile eyewear evaluation headforms were used (i.e., Alderson 50th percentile, CSA adult and UK/EN).

### Practical Implications

Many safety eyewear manufacturers design prototype safety eyewear using computer software. The coverage coefficient calculator software developed by NIOSH allows safety eyewear designers to estimate coverage provided by safety eyewear before fabricating physical prototypes. A method to quantify coverage provides additional information to safety professionals responsible for dispensing PPE. It can also provide information to the user interested in additional information concerning coverage performance. For existing prototypes or safety eyewear product, an experimental technique is suggested for calculating the coverage coefficient.

Existing safety eyewear products provide limited information to the user regarding the level of coverage protection provided. The coverage coefficient quantifies coverage for the user. Indeed, this study found a large variation in the level of coverage provided by ANSI Z87 safety eyewear. Coverage coefficient values as high as 1.0 were recorded for some eyewear/headform combinations, while values as low as 0.35 were also recorded.

Additionally, if coverage coefficient information is provided for standard headforms of varying sizes, workers can find coverage information that may be more applicable to the particular size of eyewear they need. For example, larger individuals may want to compare coverage coefficient values for eyewear on the Alderson 95th percentile headform to determine the best coverage option for them.

Those responsible for select-

### Table 2

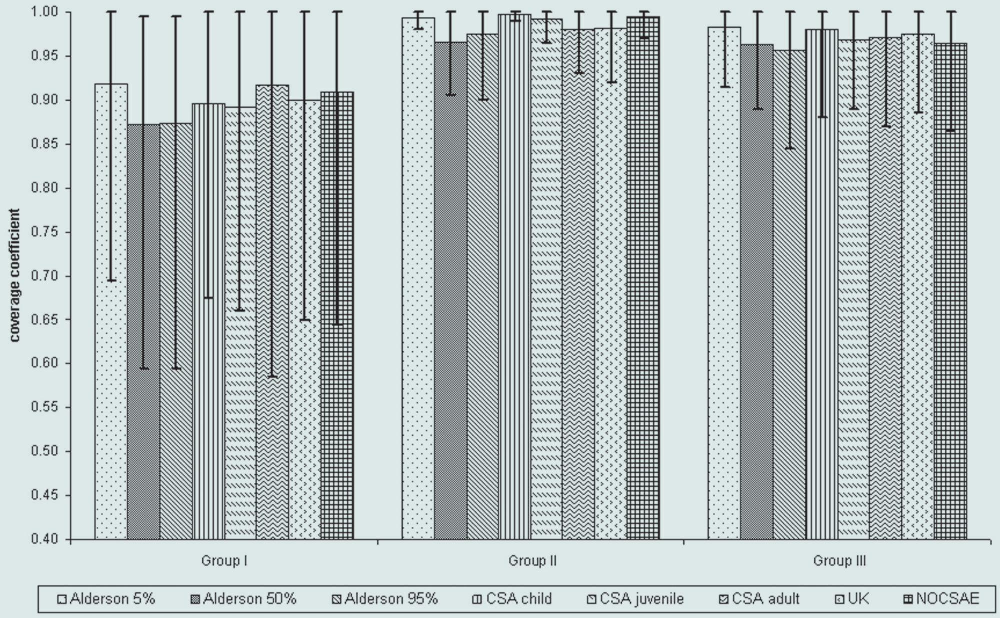
## Approximate Soft-Tissue Dimensions for International Headforms

| | Height | Width | Depth | Depth at corneal vertex |
|---|---|---|---|---|
| Alderson 5th | 31.4 | 42.5 | 19.4 | 15.0 |
| Alderson 50th | 33.2 | 42.6 | 23.6 | 19.5 |
| Alderson 95th | 41.5 | 51.3 | 29.0 | 19.8 |
| CSA Child | 31.1 | 37.2 | 15.6 | 10.0 |
| CSA Juvenile | 32.0 | 43.0 | 21.3 | 13.2 |
| CSA Adult | 33.5 | 48.7 | 21.2 | 13.9 |
| European 50th | 26.4 | 43.7 | 21.0 | 13.2 |
| NOCSAE | 33.5 | 46.5 | 19.9 | 12.8 |

*Note.* *Measured in mm.*

**Photos 6 and 7: Physical coverage assessment test fixture.**

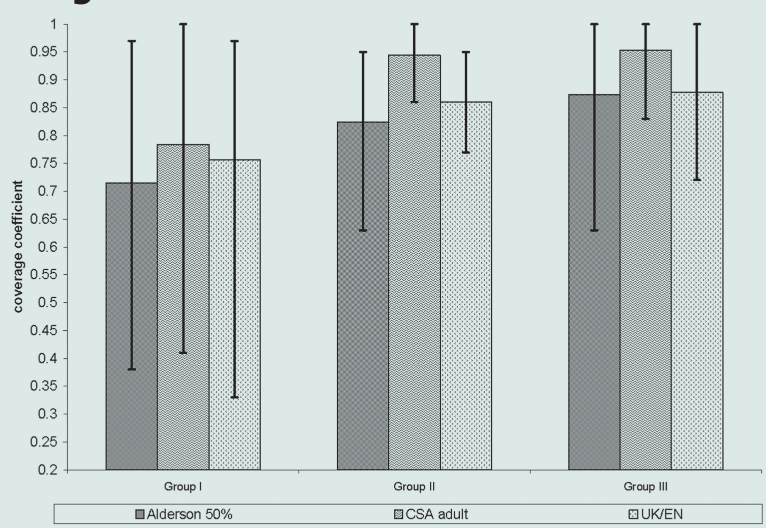
## Figure 3
## Digital Assessment




***Note.*** *Average and high/low coverage coefficients by spectacle style and headform from digital assessment (Group I:* n = 5, *Group II:* n = 4, *Group III:* n = 10*. Groupings were not selected to yield equal sample sizes).*

ing and/or dispensing safety eyewear for their company should consider that all eyewear is not created equal as far as coverage is concerned. Special consideration should be given to potential gaps in coverage provided by the eyewear. Areas of particular concern include the side shield area and potential gaps at the top and bottom of eyewear. The responsible safety person may want to procure samples of safety eyewear styles under consideration and try the product on different individuals to gauge coverage provided. Perhaps in the future, coverage coefficient values will be provided by manufacturers in their packaging materials. ■

## Figure 4
## Physical Assessment




***Note.*** *Average and high/low coverage coefficients by spectacle style and headform from physical assessment (Group I:* n = 5, *Group II:* n = 4, *Group III:* n = 10*).*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