



Ability of Ballistic Eyewear to Maintain Protection with Primary Blast Shock Waves

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14. ABSTRACT A helmet-wearing headform embedded with pressure sensors at the left (OS) and right (OD) corneal planes was exposed to blast pressures of 10, 20, 30, and 40 psi at orientations of 0, 45, 90, 135, and 180 degrees with respect to head rotation. Statistical comparisons were made among 3 groups: a baseline control with no protective eyewear (N=16), ballistic goggles (N=17), and ballistic spectacles (N=18). Adverse events were defined as eyewear breakage or displacement, helmet displacement, or chinstrap failure. A total of 51 records were obtained during 53 blast tests. The paired t-test and Pearson's Chi-Squared test were applied at a p<0.05 significance threshold. For the 0 degree orientation, both goggles (OD:p=0.031; OS:p=0.034) and spectacles (OD:p=0.044; OS:p=0.047) significantly reduced the peak corneal pressure compared to no protection, with goggles being more effective (p=0.004).					
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Results for other orientations lacked significance except at 135 degrees for the eye closest to the blast, which showed elevated corneal pressure behind the protective eyewear. Namely, peak corneal pressure was amplified for spectacles ($p=0.048$) and approached significance for goggles ($p=0.057$). Chi-Square testing showed that chinstrap failure was a mitigating factor for eyewear failures mainly for the 45 degree orientation ($p=0.018$ overall; $p=0.010$ with spectacles). Blast exposure risk plots indicated that goggles were more protective than spectacles. There was an unexpectedly high failure rate of approximately 83% for both types of eyewear. Blast testing protective eyewear reveals the risk for ocular trauma.

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Introduction

The risk of morbidity or death from an explosive device depends upon many factors including the type of explosive material, the distance to the explosion, the presence of surfaces such as floors and walls that can reflect or concentrate the blast energy, the presence of shrapnel or other ballistic debris, and the ability of protective armor to prevent or limit trauma.¹ In the current study, the ability of tactical goggles and spectacles to reduce the peak corneal pressure due to primary blast shock waves was evaluated. Additionally, the ability of protective eyewear to withstand the primary blast and block the secondary blast wave debris field was assessed. Primary blast injuries are distinctly different from the overt trauma induced by secondary blast damage due to ballistic shrapnel and debris causing large lacerations, contusions, or burns.^{2, 3} Primary blast injuries are also distinct from tertiary blast injuries such as a concussion sustained when the head impacts a surface after the primary blast event has passed.⁴

A primary blast wave is a shock wave caused by a high-energy explosion that propagates through space, and induces an abrupt change in pressure within a narrow span of time, usually within a few milliseconds (ms). Primary blast wave injuries were at one time not recognized clinically, but with the long-term follow-up of veterans exposed to blast energy in recent wars, it is now known that a primary blast wave can induce significant trauma at a microscopic scale. These injuries include cellular dysfunction, axonal damage, brain lesions, and retinal or choroidal lacerations.^{5 - 12} Over time, identifiable symptoms appear (e.g., visual scotomas) that can confirm a diagnosis of primary blast trauma.

Our understanding of the biomechanics and epidemiology of primary blast trauma to the human body remains incomplete, particularly with respect to vision. In part, this is due to limitations involving research on animal models, such as extrapolating the physics of low-energy blast events using a laboratory animal model to the high-energy blast events experienced by humans in combat. Additional research is needed to determine the etiology of primary blast injuries, what pressure thresholds induce trauma, and how various tissues can be better protected from blast energy. Primary blast wave research places a large technical demand on the ability to collect data during an event that lasts on the order of milliseconds. Computer simulations circumvent some of the technical demands associated with testing an actual blast event, but simulations have limitations including the lack of corresponding real world trauma data for validation, difficulties in modeling protective armor, the need for specialized software and training, and the need for substantial computing power.^{13 - 16} Therefore, the use of shock tube testing remains a gold standard for evaluating primary blast wave trauma. In addition, shock tube testing appears to be the most effective method of evaluating various types of protective armor, including eye armor and helmets.

Currently available tactical goggles and spectacles were never designed or intended to protect the eyes from a primary blast wave.¹⁷ They were designed specifically for protection from ballistic shrapnel or debris propelled by the secondary blast wind that follows the shock wave or from bullet fragments.¹⁸ Impact-based safety standards exist for ballistic eyewear, including ANSI Z78.1 – 2010 for civilian eyewear in the United States; MIL-PRF-31013 for U.S. military eyewear; and EN166, 169, 170 and 172 for European-based eyewear. However, no comparable safety standards exist for evaluating eye protection against shock waves.

The peak pressure arriving at the corneal plane is a potential metric of protection

efficacy, but it remains unclear exactly how peak corneal pressure varies with incident blast strength and with orientation to the blast source. When the head is oriented at oblique angles to the blast wave, right and left eyes should experience different amounts of blast energy due to occlusion effects by the shape and anatomy of the head. Furthermore, goggles and spectacles have inherently different shapes, structure, and mass, and are presumed to differ in their ability to deflect or absorb shock wave energy. Therefore, the main goal of this study was to compare protective capability of ballistic goggles and spectacles under varying conditions of blast pressure and orientation. A secondary goal of this study was to determine how well goggles and spectacles withstood blast energy. Endurance of ballistic eyewear during the primary blast event is a critical performance factor because it helps to determine the potential for ocular trauma due to secondary blast debris.

Methods

Tests were conducted with an ARA (Applied Research Associates, Inc.; Albuquerque, NM) portable shock tube located at the Virginia Polytechnic Institute and State University in Blacksburg, VA. All tests were performed with a human surrogate headform using a non-hinged neck mount that fixed the location of the head with respect to the shock tube centerline (Figure 1). Blast pressures were systematically varied so that the peak incident pressure measured at the splitter plate location adjacent to the headform was scaled to approximately 10, 20, 30, or 40 psi (pounds per square inch; where 1 psi \approx 6.89 kilopascals or 6.89×10^3 newton per square meter). Peak pressure is defined by the peak amplitude of the Friedlander waveform (Figure 2), and is associated with the near-instantaneous arrival of the positive phase of the shock wave at a pressure sensor (Figure 2). The range of induced pressures spanned the 50% survival ratings as described by Bowen Risk-Injury Curves (Figure 3), which are representative of those found with high-energy improvised explosive devices (IEDs).

The headform was modified to contain two pressure sensors (PCB Piezotronics; Model 113B26; Depew, NY) centered at the corneal planes of the left (OS) and right (OD) eyes. The pressure sensors had linear output and were factory calibrated. Pressures were recorded on separate data recording channels at a rate of 1,000 KHz over a period of approximately 36 ms during each blast test. Wiring of the sensors was through the base of the headform to prevent interference with the test environment. Note that the effect of impedance, which is the resistance experienced by the shock wave upon entering a denser medium, elevates the peak corneal pressure when compared to the peak incident pressure measured at the splitter plate. In addition, constructive or destructive wave interference may arise if the shock wave is focused or reflected back upon itself, leading to unanticipated changes in pressure.

All testing was done on the horizontal plane with no adjustments made for tilting the headform up or down. The angle of incidence of the shock wave with respect to the headform was controlled by rotating the headform to one of five orientation angles (0° , 45° , 90° , 135° , or 180°). A value of 0° indicated the blast wave was striking perpendicular to the coronal plane of the face (Figure 4). The orientation angle for the head rotated to the right was labeled positive (i.e., a clockwise rotation when viewed from above), and labeled as a negative angle for the head rotated to the left. No data were collected with the headform rotated to the left. Instead, we replicated the leftward rotation data based on the assumption that the bilateral symmetry of the headform and eyewear creates mirror-image symmetry of the peak corneal pressure data of the

two eyes, and the OS and OD data can be switched when crossing the midline.

Two types of protective eyewear were compared: the Arena Flakjak® tactical goggles (Arena Tactical; Orange, CA) and the Revision Sawfly® ballistic spectacles (Revision Military, LTD; Essex, VT) (Figure 5). A control group for statistical comparison had no ocular protection. All tests were performed with an Advanced Combat Helmet (ACH; Gentex Corp.; Simpson, PA) placed on the headform and secured with chin straps (Figure 2). Chin straps were inspected after each test and replaced if needed. A total of 51 useable tests (goggles = 17; spectacles = 18; control = 16) were obtained during 53 trials, with 2 tests lost due to sensor recording failures. Headform orientation, blast pressure, and test articles were randomly varied during testing. Adverse eyewear events were defined as eyewear breakage while located on the headform or eyewear displacement that was deemed sufficient to allow secondary blast wave exposure to one or both eyes. Eyewear breakage and displacement events as well as chin strap failures and helmet displacements were determined by reviewing high-speed video recorded at a resolution of 800 x 600 pixels using an exposure time of 990 μs, and a frame rate of 1000 pictures per second. The test articles were inspected after each blast. Damaged test articles were discarded, while undamaged articles were reused, as would be the case in combat use. All data were statistically analyzed and plotted with default mode settings using SigmaPlot 13 (SYSTAT, Inc., San Jose, CA). The threshold for statistical significance was set at $p < 0.05$.

Results

A contour plot of the blast test results for the control group condition is shown in Figure 6, and the corresponding contour plots for the goggle and spectacle test groups are shown in Figure 7. These graphs show data corresponding to the left eye; right eye data would be the mirror image of the left eye contour pattern. The vertical axis is a fixed scale for the independent peak incident pressure of the blast wave acquired by the splitter plate sensor. The horizontal axis represents the orientation angle of the head with respect to the blast wave. The color-coded contour scale is fixed for all plots and represents the dependent peak corneal pressure.

Results indicate that the greatest overall blast energy at the cornea occurs between $\pm 90^\circ$ for the unprotected control group (Figure 6), and that both goggles and spectacles appeared to be generally effective at reducing the peak corneal pressure with goggles out-performing spectacles (Figure 7). The asymmetry seen in the spectacle plot indicated that blast orientation was an important mitigating factor for determining the protection by this eyewear.

The peak corneal pressure plots alone do not indicate directly whether wearing eye protection is more beneficial than wearing no protection at all. This is particularly true for orientations where blast energy is blocked by head anatomy or where the shock wave can be trapped or reflected by the eyewear shape. Figure 8 shows contour plots in which the primary blast exposure risk for a given eyewear is defined as:

$$\text{Exposure Risk} = (\text{PCP}_{\text{eyewear}} / \text{PCP}_{\text{control}}) \times 100\%$$

where PCP refers to the peak corneal pressure. A value of 100% exposure risk (indicated by the bright yellow contour in each plot) means that wearing the eyewear is equivalent to the risk of wearing no protection at all. In other words, the eyewear provides no added benefit for the orientation and incident blast pressure. Examination of the plot shows that this happens typically when the back of the head is exposed to the primary blast. Values of exposure risk less than 100% (illustrated by blue and green contours) indicates the benefit of a reduced peak corneal pressure when wearing the eyewear. Optimum protection efficacy, where exposure risk is minimal, tended to be centered about the 0° orientation for both goggles and spectacles. In other words, blasts to the front of the head were protected by the eyewear and reduced the exposure risk. In general, the results indicate that goggles outperform spectacles in terms of protection, mainly because they have a larger overall range of orientations that result in reduced blast pressures at the cornea ($\pm 90^\circ$ for goggles vs. $\pm 45^\circ$ for spectacles). Orientations near $+135^\circ$ or -135° exhibited the highest exposure risk. This is particularly the case for spectacles with the head rotated 135° to the right.

A summary of shock tube parameters are listed in Table 1. The overall comparison between OD and OS pressures is shown in Table 2. The majority of the records showed no significant differences between fellow eyes; however, this data exhibited high variance due to combining data across all applied pressure levels and because of a low N-value for blast testing. The exceptions that showed a statistically significant difference were at 0° for the unprotected eyes, and at 90° for both the unprotected eyes and the spectacle protection group. Comparison of the goggle and spectacle data showed that both the OD and OS data for the spectacles always exceeded the corresponding peak corneal pressure behind the goggles at each orientation. In addition, the peak corneal pressure for the unprotected OD and OS groups tended to be higher than both the goggle and spectacle groups except for 90° and 135° orientations with spectacle protection and for the 135° orientation for goggle protection.

Table 3 and Table 4 show statistical comparisons between groups when performing a separate analysis for the OD and OS eyes. This was done to determine if occlusion by the bridge of the nose or the cheek played a role in reducing or increasing the peak corneal pressure. Surprisingly, the 0° orientation showed significant differences across all of the groups, while the 135° orientation showed significance for the spectacle versus in the OS eye, which was the eye exposed to more blast pressure.

Table 5 reports on all helmet adverse events. Statistical significance was evaluated by a Pearson's Chi-Squared test that showed that chin strap failures were associated with blast orientation, but helmet displacements that were large enough to interfere with eyewear had no significant association with the direction of the blast. Figure 9 shows two examples of chin strap failures, one in which the strap stitching was torn and another in which the chin strap had completely failed. The eyewear and helmet were both seen displaced over the top of the head in this example. In virtually all tests, some amount of helmet bounce was observed in the video, but it was not considered a true helmet displacement unless the helmet moved sufficiently to interfere with eyewear. Figure 10 shows pre- and post-blast photographs of an example test case where the helmet chin straps remained intact and undamaged, but the helmet was displaced fully to the side of the head. This type of event happened on multiple occasions.

Table 6 lists all failures of the goggles combined with corresponding helmet and chin

strap failures within the goggle protection group. There were no statistically significant associations; however, the 0° orientation did exhibit a large number of goggle displacements. This may be an artifact due to more tests being run at this orientation. An example of a goggle displacement in progress is shown in a series of photographs in Figure 11. The corresponding failures for the spectacle protection group are shown in Table 7. There were no statistically significant associations of spectacle breakage or displacement with a specific blast orientation; however the 0° orientation did produce more instances of spectacle breakage. Again, this may be an artifact due to sampling, but one would expect most breakage to occur at 0° because this is the orientation where maximum incident pressure occurs. Figure 12 shows a series of photographs in which spectacles were being pulled off the head by the blast wave. Table 7 shows that there was a statistically significant association of chin strap failure in the spectacle protection group, and in particular, there was a 100% failure rate for the 45° orientation.

Discussion

Military grade protective eyewear includes both tactical goggles and spectacles that are produced by various manufacturers to military ballistic protection specifications. An Authorized Protective Eyewear List (APEL) currently exists, which can be found at the Army Program Executive Office (PEO) Soldier website or through an Internet search. APEL goggles and spectacles are required to meet the ballistic impact standard. Spectacles are preferred by many military personnel because they can be removed and replaced easily, and have reduced issues related to fogging when compared to goggles. Relatively little is known about the capabilities of APEL eyewear to physically withstand high-energy primary blasts.

The failure rate of both goggles and spectacles in this study was extraordinarily high with approximately 83% failure in both protective eyewear groups (Tables 6 and 7). Failures tended to be distributed similarly with ~30% breakage events and ~50% displacement events recorded for both groups. Eyewear failure events were not associated statistically with a specific head orientation to the blast. Based on a review of the high-speed videos, spectacle frames were seen breaking or lenses were separating from the frame. Goggles also broke when lenses separated from the frame. These observations suggest that improvements could be made in the way protective eyewear is constructed, and that having the ability to easily replace lenses might be a detrimental feature of the eyewear when it comes to primary blast protection.

Attaching elastic straps onto spectacles may help with retention, but it would likely lower user acceptance. It should be noted that goggles with elastic straps had nine total instances of displacement in the study, which matched the same number of occurrences for spectacles without a retention strap. We speculate that the recorded instances of goggle displacements were initiated by helmet displacement because goggle straps are worn attached over the back of the helmet. If helmet movement is excessive during the blast, it is likely that goggle strap elastic tension cannot counteract this movement in a short period of time (<30 ms), and the goggles typically would fall away from the face. This was observed on multiple occasions during the course of the study, but there was no clear statistical correlation between goggle displacement and helmet displacement, at least with respect to a specific orientation of the blast or in comparison to spectacle movement (compare Tables 5 and Table 6).

In addition, chin strap failures occurred in roughly 25% of the tests, which contributed to helmet displacements (Table 5). Chin strap failures were significantly associated with blast

direction and tended to occur most often at 45° incidence in the spectacle group (Table 5). Perhaps the massive, ruggedized frame of the goggles helped to dissipate the shock wave and thereby reduced chin strap breakage in the goggle group.

From the peak corneal pressure results shown in Figures 6 and 7, and the exposure risk shown in Figure 8, it is clear that both the goggles and spectacles provided protection from a primary blast directed toward the front of the head, with the goggles outperforming the spectacles. However, for instances in which the blast comes from the side or behind the head, unanticipated increases in peak corneal pressure across a wide range of incident pressure occurred while wearing protective eyewear (Figure 8). This finding is in general agreement with two previous reports.^{17, 18} The increased risk from peak pressure was particularly true for the spectacle eyewear near an orientation of 135°. Goggles also showed a greater risk at this orientation due to loss of protection. One can speculate how exposure risk can rise above 100% by considering that: 1) blast wave energy can more easily enter between the eyewear and the temple of the head near the 135° orientation; 2) eyewear might be more easily pulled away from the face at this same orientation; 3) blast energy may be reflected off the back surface of the lens and toward the cornea once it is behind the eyewear; and 4) constructive interference may occur whenever multiple reflections of the shock wave converge within a volume of space, thus raising the local pressure magnitude. Clearly, additional information needs to be obtained about primary blast wave interactions with the eye and orbit in order to better understand how to increase protection. Recent studies that elaborate on specific details of the orbital and ocular anatomy help to point the way toward future studies.^{19, 20} In particular, future studies that can directly capture intraocular and intraorbital pressure data within physical fluid-filled models of the human eye during staged blast events will be helpful in bridging the gap between post-trauma clinical observations in humans and finite element modeling of human eyes.

A major limitation of this study was the small sample size. When data was combined across different blast tests, the resulting standard deviations were large. Nevertheless, the data are still useful for assessing variance and calculating sample sizes for future applications of the test protocol. In addition, some comparisons were found to be significant, and others nearly so. In general, because of the low N-values, caution should be used in interpreting negative significance of these results. Perhaps data that appear to be approaching significance ($p < 0.1$) should be given more weight, particularly when lower exposure to shock wave trauma is the goal.

In conclusion, our study provides evidence that ballistic goggles and spectacles were most effective at reducing primary blast energy from shock waves directed toward the front of the head, but the exposure risk increased as protection diminished for primary blast waves striking the side or back of the head. In particular, blast exposure risk was higher for spectacles than for goggles, and the lack of a fully face-conforming frame around the periphery of spectacles appeared to allow more blast energy to enter behind the lens where it can potentially reflect back toward the eye. A previous study indicated that spectacles fitted with foam appeared to raise protection.^{17, 21} The results also indicated that currently available eyewear has a high failure rate of approximately 83% over the range of primary blast pressures tested. This failure potentially exposes one or both eyes to secondary blast damage from shrapnel or debris.

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Appendix A:

Table 1. Shock Tube Parameters

	Minimum	Maximum	Mean	Standard Deviation
Splitter Peak Pressure (psi)	11.37	44.47	25.09	12.54
Positive Phase Duration (ms)	2.97	5.32	4.20	0.92
Positive Phase Impulse (psi * ms)	32.29	60.42	43.88	10.76

Table 2. Fellow Eye Comparison (OS vs. OD) of Mean Peak Corneal Pressure

Angle	No Protection (Control)			Goggles			Spectacles		
	OS	OD	p*	OS	OD	p*	OS	OD	p*
0°	65.106 (44.292)	68.109 (45.178)	0.028	18.686 (11.338)	18.909 (12.985)	0.789	27.280 (14.443)	27.985 (15.530)	0.585
45°	77.303 (59.892)	49.420 (34.012)	0.205	20.589 (10.176)	16.549 (4.039)	0.224	49.570 (27.780)	29.598 (12.648)	0.151
90°	30.575 (14.056)	21.199 (11.098)	0.034	17.974 (8.854)	16.286 (5.775)	0.458	42.223 (11.595)	21.879 (12.001)	0.051
135°	16.701 (8.172)	17.682 (7.159)	0.077	20.072 (7.264)	23.311 (9.607)	0.232	25.580 (10.219)	20.913 (7.544)	0.150
180°	25.510 (10.753)	25.082 (11.936)	0.899	20.954 (9.137)	19.574 (8.289)	0.412	26.629 (11.764)	26.806 (13.008)	0.904

*Paired *t*-test

Table 3. Between Group Comparison of OD Eye Mean Peak Corneal Pressure

Angle	No Protection "Control"	Goggles "G"	Spectacles "S"	Control vs. G p^*	Control vs. S p^*	G vs. S p^*
0°	68.109 (45.178)	18.909 (12.985)	27.985 (15.530)	0.031	0.044	0.004
45°	49.420 (34.012)	16.549 (4.039)	29.598 (12.648)	0.178	0.254	0.070
90°	21.199 (11.098)	16.286 (5.775)	21.879 (12.001)	0.252	0.329	0.261
135°	17.682 (7.159)	23.311 (9.607)	20.913 (7.544)	0.630	0.724	0.245
180°	25.082 (11.936)	19.574 (8.289)	26.806 (13.008)	0.153	0.282	0.171

*Paired *t*-test

Table 4. Between Group Comparison of OS Eye Mean Peak Corneal Pressure

Angle	No Protection "Control"	Goggles "G"	Spectacles "S"	Control vs. G p^*	Control vs. S p^*	G vs. S p^*
0°	65.106 (44.292)	18.686 (11.338)	27.280 (14.443)	0.034	0.047	0.004
45°	77.303 (59.892)	20.589 (10.176)	49.570 (27.780)	0.188	0.299	0.106
90°	30.575 (14.056)	17.974 (8.854)	42.223 (11.595)	0.052	0.097	0.068
135°	16.701 (8.172)	20.072 (7.264)	25.580 (10.219)	0.057	0.048	0.100
180°	25.510 (10.753)	20.954 (9.137)	26.629 (11.764)	0.214	0.746	0.066

Table 5. Helmet Results

Angle	Number of Tests	Chin Strap Torn* N (%)	Helmet Displacement* N (%)
0°	15	5 (33.3)	7 (46.7)
45°	11	6 (54.5)	8 (72.7)
90°	9	2 (22.2)	5 (55.6)
135°	9	0	4 (44.4)
180°	9	0	3 (33.3)
Total	53	13 (24.5)	27 (50.9)
Pearson's Chi-Squared		p = 0.018	p = 0.471

*These data include failures for the control group and the two protective eyewear groups.

Table 6. Protective Goggle Results

Angle	Number of Tests	Goggle Breakage N (%)	Goggle Displacement N (%)	All Goggle Failures N (%)	Chin Strap Torn N (%)	Helmet Displacement N (%)
0°	5	1 (20)	4 (80)	5 (100)	2 (40)	4 (80)
45°	3	2 (66.7)	0 (0)	2 (66.7)	1 (33.3)	2 (66.7)
90°	3	1 (33.3)	1 (33.3)	2 (66.7)	1 (33.3)	2 (66.7)
135°	3	0	3 (100)	3 (100)	0	1 (33.3)
180°	3	1 (33.3)	1 (33.3)	2 (66.7)	0	1 (33.3)
Total	17	5 (29.4)	9 (52.9)	14 (82.4)	4 (23.5)	10 (58.8)
Pearson's Chi-Squared		p = 0.476	p = 0.077	p = 0.519	p = 0.571	p = 0.611

Table 7. Protective Spectacle Results

Angle	Number of Tests	Spectacle Breakage N (%)	Spectacle Displacement N (%)	All Spectacle Failures N (%)	Chin Strap Torn N (%)	Helmet Displacement N (%)
0°	6	3 (50)	1 (16.7)	4 (66.7)	1 (16.7)	1 (16.7)
45°	3	1 (33.3)	2 (66.7)	3 (100)	3 (100)	3 (100)
90°	3	1 (33.3)	2 (66.7)	3 (100)	0	2 (66.7)
135°	3	1 (33.3)	2 (66.7)	3 (100)	0	1 (33.3)
180°	3	0	2 (66.7)	2 (66.7)	0	1 (33.3)
Totals	18	6 (33.3)	9 (50)	15 (83.3)	4 (22.2)	8 (44.4)
Pearson's Chi-Squared		$p = 0.690$	$p = 0.406$	$p = 0.463$	$p = 0.010$	$p = 0.163$

Appendix B



Figure 1. The headform mounted to the ARA shock tube testing platform. The splitter plate sensor is the disc-shaped object located above and ahead of the headform, which is oriented to 45°.

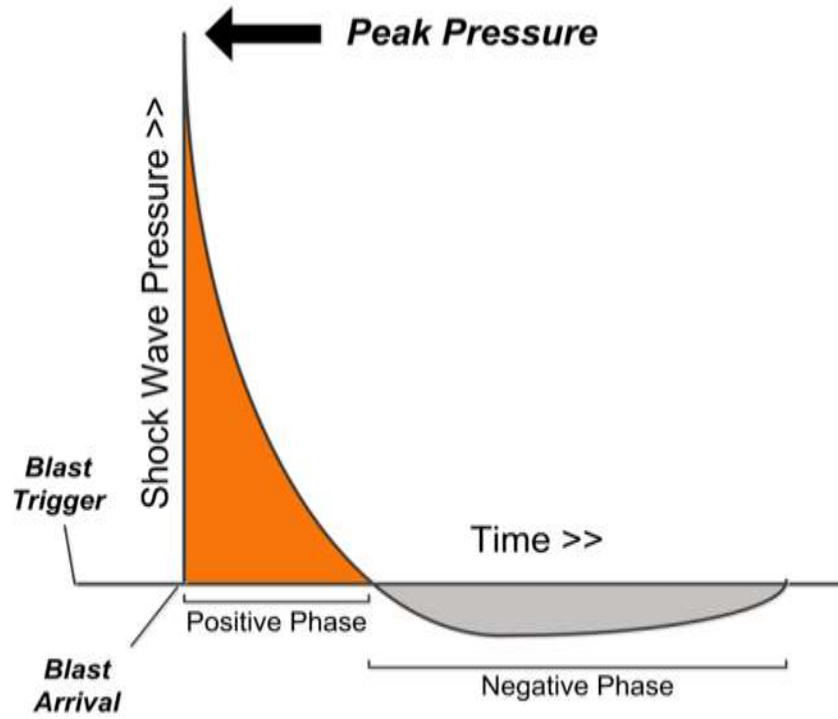


Figure 2. Illustration of a Friedlander waveform for a primary blast shock wave. Positive pressure of the shock wave is shown in orange with the peak pressure indicated at the leading edge of the platform.

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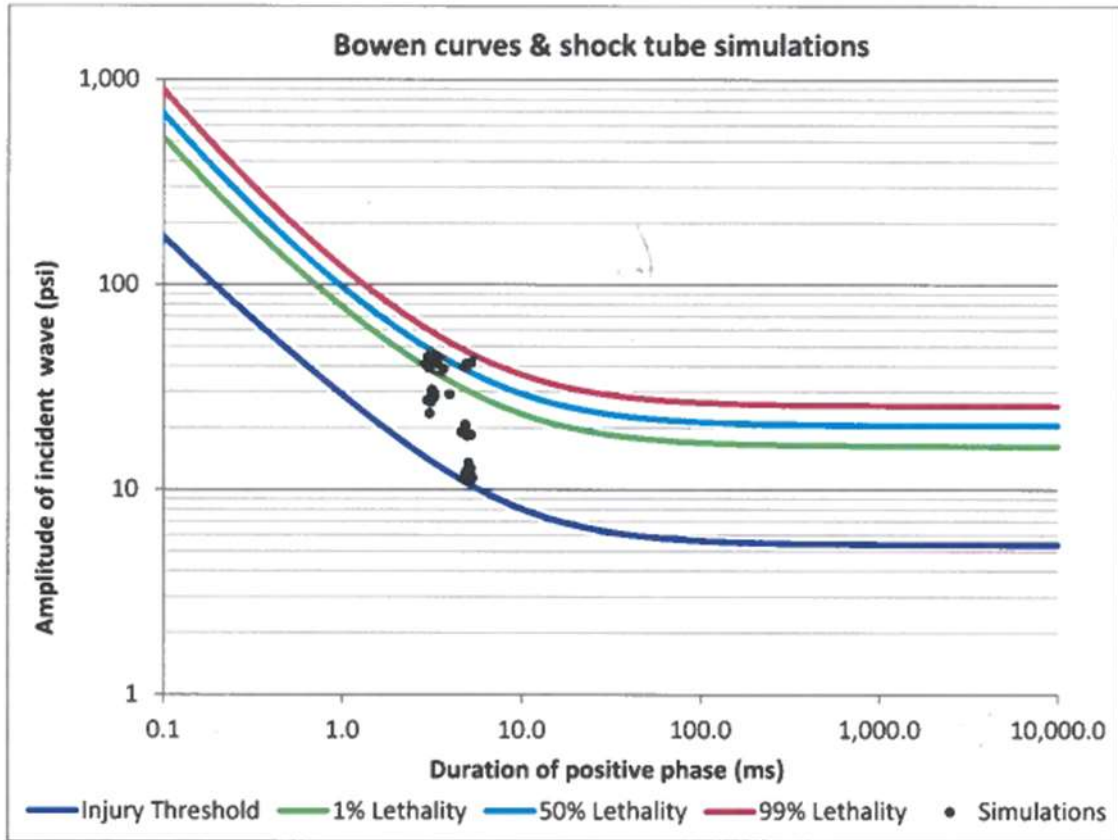


Figure 3. Bowen Risk-Injury Survival Curves with data from the current study plotted.

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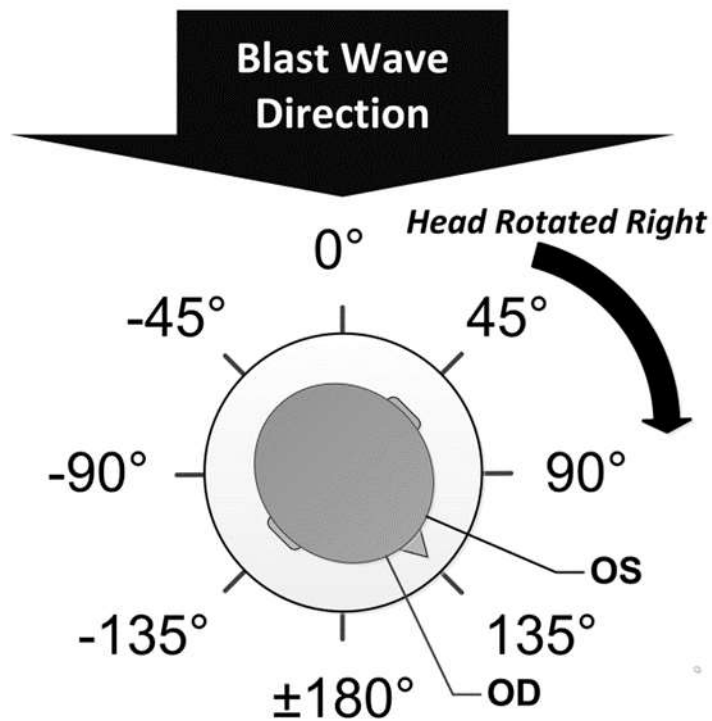


Figure 4. Illustration of the orientation angles of the headform with respect to the blast wave direction. This example shows the head rotated to the right 135°. This orientation would allow blast energy to enter behind the spectacles on the left eye.

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Figure 5. Protective eyewear tested during the study. The Revision Sawfly® ballistic armor spectacles (top) and the Arena Flakjak® ballistic armor tactical goggles (bottom).

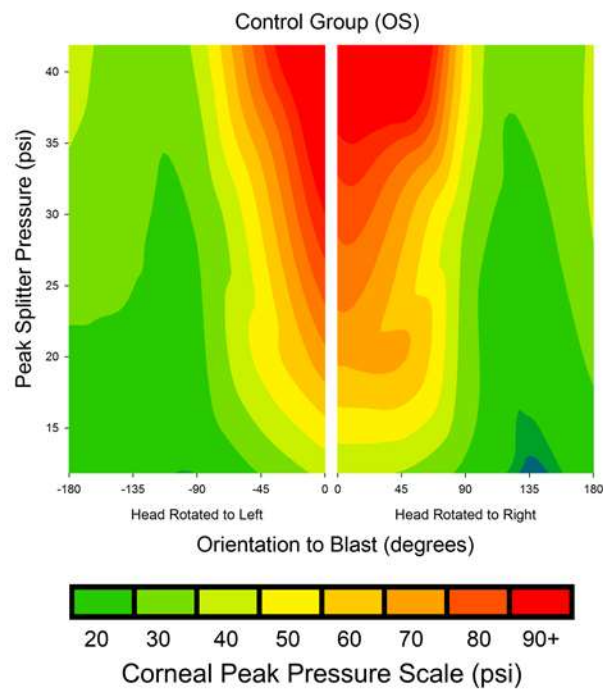


Figure 6. Peak corneal pressure contour plot for the unprotected left eye control group.

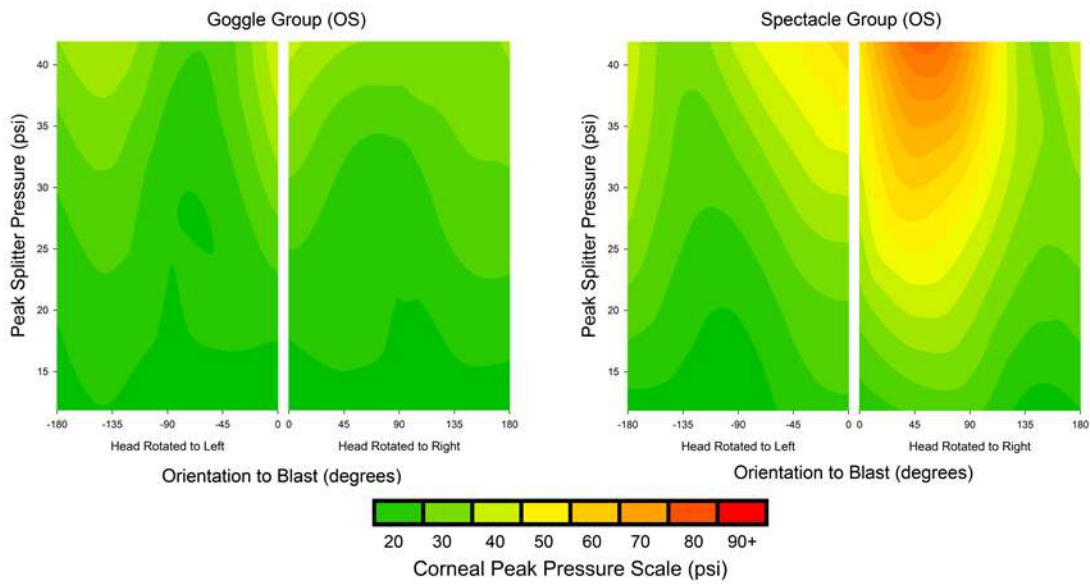


Figure 7. Peak corneal pressure contour plots for the goggle protected left eye(left) and the spectacle protected left eye (right).

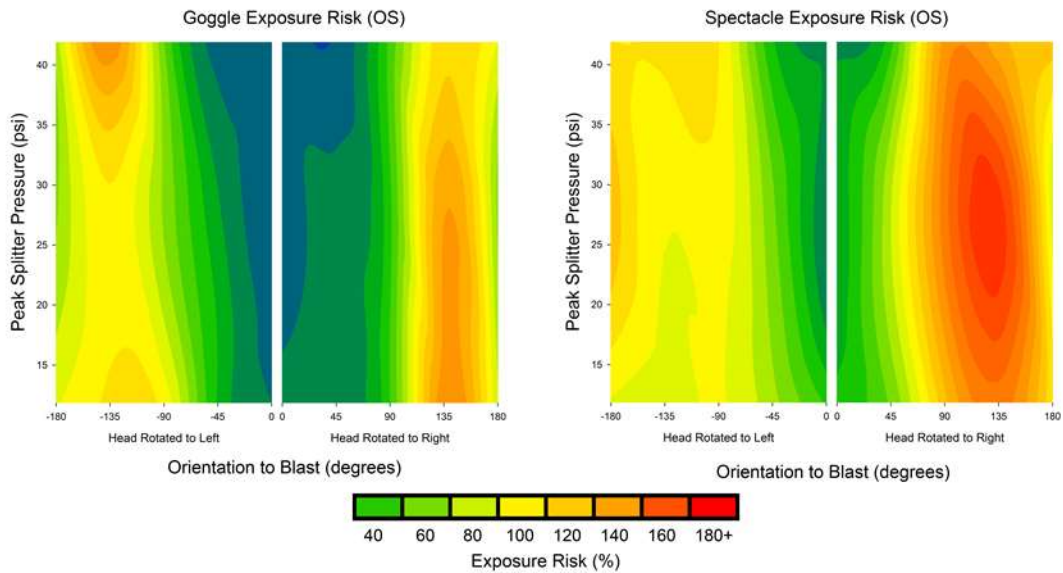


Figure 8. Exposure risk contour plots for the goggle protected left eye (left) and the spectacle protected left eye (right). Note the larger range of protection for orientation that is obtained with goggles. Also note the region of greater exposure risk to blast energy with spectacles when the head is oriented toward 135°.



Figure 9. Example of chin strap damage and loss of helmet. Top: Ripping of chin strap seams was considered a significant event because it permits helmet movement and potentially leads to a complete loss of the helmet. Bottom: Example of a complete failure of the chin strap occurring 11.4 ms after the arrival of the shock wave.



Figure 10. Example of helmet displacement without chin strap ripping. Blast wave helmet displacement was considered a significant event when it was sufficient to adversely affect eyewear retention.

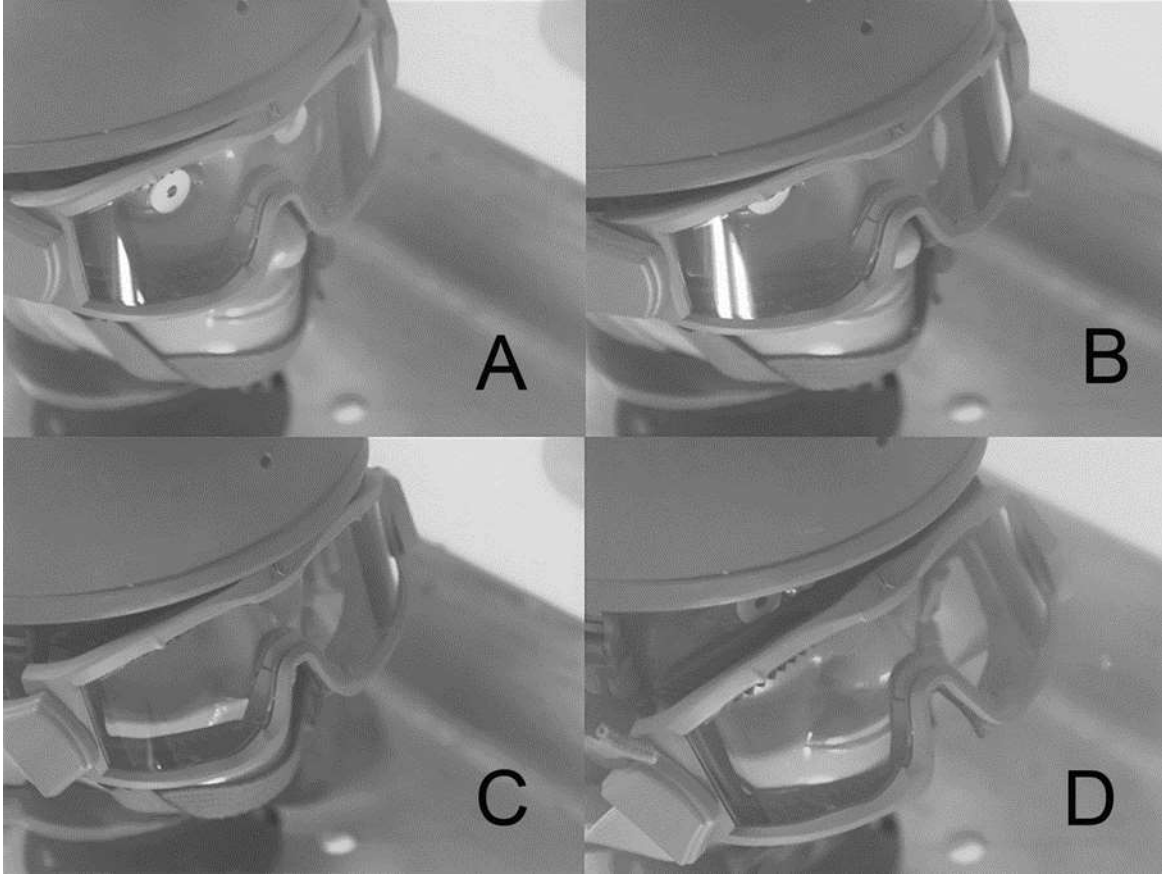


Figure 11. High-speed video sequence showing goggle displacement. A, 10.94 ms; B, 25.94 ms; C, 52.94 ms; D, 76.94 ms. All times were relative to the arrival of the shock wave.

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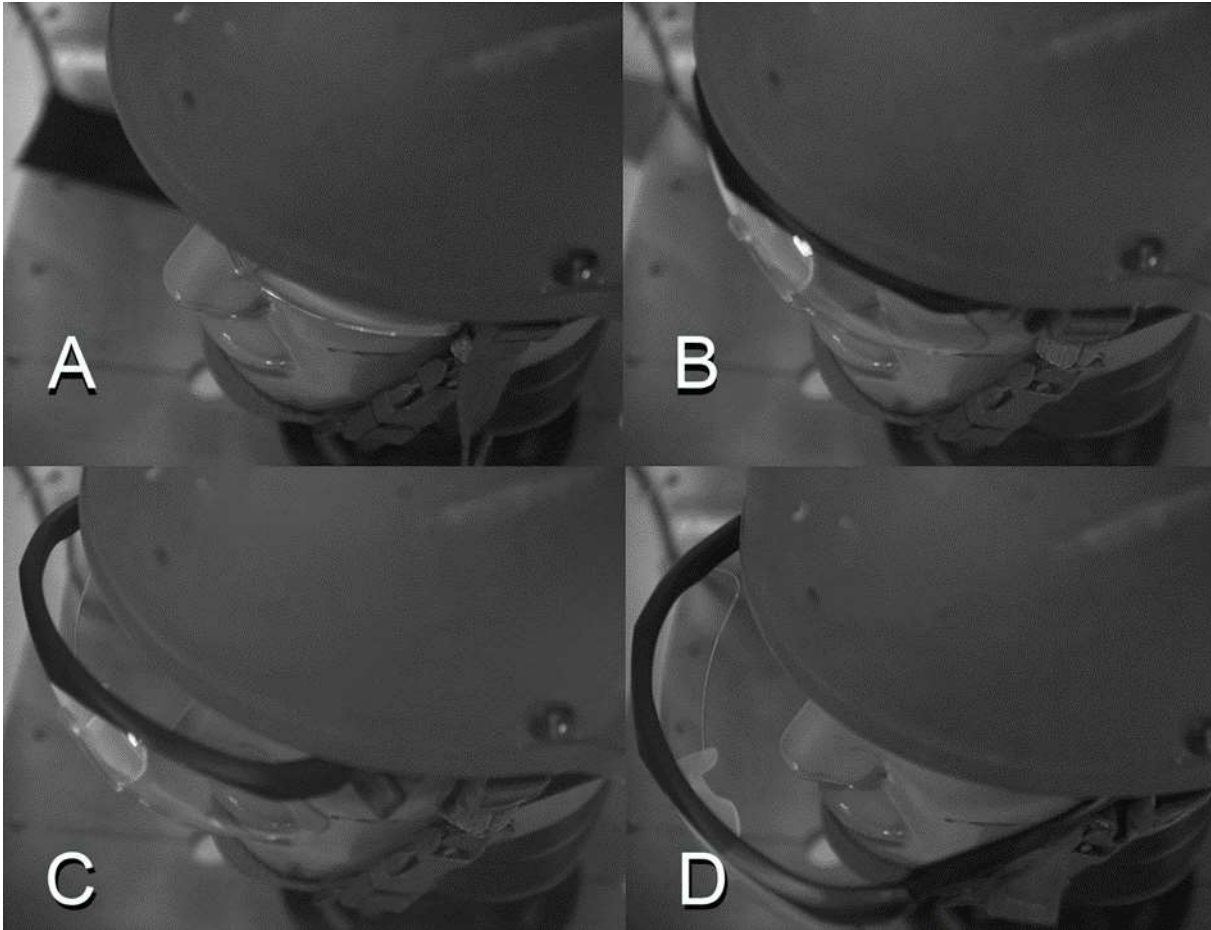


Figure 12. High-speed video sequence showing spectacle displacement. A, Pre-blast; B. 9.68 ms; C. 15.68 ms; D. 28.68 ms. All times relative to the arrival of the shock wave.

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