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Wavefront-Guided Versus Wavefront-Optimized Photorefractive Keratectomy: Visual and Military Task Performance

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ABSTRACT Purpose: To compare visual performance, marksmanship performance, and threshold target identification following wavefront-guided (WFG) versus wavefront-optimized (WFO) photorefractive keratectomy (PRK). Methods: In this prospective, randomized clinical trial, active duty U.S. military Soldiers, age 21 or over, electing to undergo PRK were randomized to undergo WFG (n = 27) or WFO (n = 27) PRK for myopia or myopic astigmatism. Binocular visual performance was assessed preoperatively and 1, 3, and 6 months postoperatively: Super Vision Test high contrast, Super Vision Test contrast sensitivity (CS), and 25% contrast acuity with night vision goggle filter. CS function was generated testing at five spatial frequencies. Marksmanship performance in low light conditions was evaluated in a firing tunnel. Target detection and identification performance was tested for probability of identification of varying target sets and probability of detection of humans in cluttered environments. Results: Visual performance, CS function, marksmanship, and threshold target identification demonstrated no statistically significant differences over time between the two treatments. Exploratory regression analysis of firing range tasks at 6 months showed no significant differences or correlations between procedures. Regression analysis of vehicle and handheld probability of identification showed a significant association with pretreatment performance. Conclusions: Both WFG and WFO PRK results translate to excellent and comparable visual and military performance.

INTRODUCTION

The visual function of the individual Soldier on the modern battlefield has a direct and critical impact on the decision-making process. Spectacles have considerable disadvantages including degradation in performance due to dust and pitting. Broken or damaged spectacles require replacement, which depending on the tactical situation may not be feasible. Visual demands in the military are unique with operations occurring in adverse, limited visibility environments such as rain, smoke, fog, or darkness. The ability to use ballistic protection, headgear, helmets with front ballistic protection, and more sophisticated weapon systems without additional interface problems of spectacles and inserts, which can obscure viewing conditions, is a significant operational enhancer. To this end and to improve Soldier readiness, the Army instituted the Warfighter Refractive Eye Surgery Program in 2000 as a mission readiness asset, providing refractive surgery to approximately 10,000 Soldiers per year.

Laser refractive surgery has helped reduce Soldiers' dependence on optical corrections such as spectacles and contact lenses.[1–6] Conventional refractive surgery has been associated with reports of various visual disturbances including glare, halos, and starbursts, induction of higher order aberrations (HOAs) as well as reduced contrast sensitivity (CS) following the procedure.[7–9] A loss in visual performance after refractive surgery may potentially impact military task performance in low light conditions.

HOAs have a different impact on vision and can positively or negatively influence visual performance.[10] Elevated HOAs have been related to decreased CS, as well as increases in the symptoms of glare, halos, starbursts, and monocular diplopia.[11–14] However, the relationship between optical quality, characterized by monochromatic aberrations, and visual performance is complex and not perfectly understood. The advent of customization in corneal laser surgery has improved optical and visual outcomes of refractive surgery procedures

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compared to conventional treatment.[15–20] Wavefront-guided (WFG) laser treatments measure and treat not only lower order aberrations, but also HOAs.[17] Treatments are patterned based on the individual ablation profile of each eye. Wavefront-optimized (WFO) laser treatments use adjustments based on population averages to optimize the asphericity of the cornea.[20] WFO ablations also add peripheral treatment aiming to minimize spherical aberration, one of the most visually significant HOAs generated by the surgery.[21]

These technological advances aim to improve postoperative quality of vision. Whether these advances influence visual performance in a military operational environment is yet to be studied. The purpose of this study is to evaluate visual and military task performance following either WFG or WFO photorefractive keratectomy (PRK).

METHODS

The institutional review boards at Walter Reed National Military Medical Center and the U.S. Army Medical Research and Materiel Command granted approval before initiation of this study. Separate written informed consents were obtained for clinical testing and military tasks after counseling on the risks and benefits of participation. Research adhered to the tenets of the Declaration of Helsinki. The trial was registered at www.clinicaltrials.gov identifier: NCT01097525. Health Insurance Portability and Accountability Act compliance was maintained throughout the study. Active duty U.S. military personnel, age 21 or over with myopia ranging from −1.50 diopters (D) to –10.00 D inclusive, with no more than 4.00 D of manifest cylinder and refractive stability for at least 12 months before surgery, electing to undergo PRK were consecutively enrolled in one of two groups: marksmanship performance or target detection and identification. Once assigned to a group, participants were randomized using a computerized randomization program (www.randomization.com) to undergo either WFG or WFO treatment.

Surgical Procedure

WFG treatment was performed using the VISX CustomVue STAR S4 IR Excimer Laser System (Abbott Medical Optics, Santa Ana, California). WFO treatment was performed using the Allegretto Wave Eye-Q 400 Hz Excimer Laser System (Alcon Surgical, Fort Worth, Texas). Treatment plans were calculated using platform-dependent nomograms developed at the surgical center. Epithelium was removed using a rotary brush (Amoils Epithelial Scrubber; Innovative Excimer Inc., Toronto, Ontario). Mitomycin C (MMC) was used on eyes with central ablation depth of greater than 49.5 microns or cylinder >1.25 D. A corneal shield soaked in MMC 0.2 mg/mL (0.02%) was applied to the cornea for 20 seconds and then the ocular surface was irrigated with balanced salt solution. A low oxygen-transmission bandage contact lens (Proclear; CooperVision Inc., Pleasanton, California) was applied until complete re-epithelialization and postoperative medications regimen was the same for both groups as described by Sia et al.[22]

Visual Performance

Uncorrected distance visual acuity (UDVA), corrected distance visual acuity (CDVA), and manifest refraction were assessed for each eye treated preoperatively and at 1, 3, and 6 months postoperatively. Visual acuity was measured using a Snellen chart viewed at a distance equivalent to 20 feet (6 m). Refractive efficacy was determined by UDVA, accuracy with manifest spherical equivalent (MSE), and safety with CDVA.

Contrast testing was performed binocularly using best spectacle correction preoperatively and at 1, 3, and 6 months postoperatively with best correction using the variable contrast 4-m Rabin Super Vision Test (SVT) (Precision Vision, La Salle, Illinois). The Rabin SVT provides both high contrast (SVT HC) visual acuity and CS (SVT CS) on a single chart and is able to detect subtle decreases from normal.[23] Night vision testing was conducted with a retro-illuminated 25% contrast acuity chart (Precision Vision Inc. La Salle, Illinois) with a green night vision goggle (NVG) filter to simulate similar visual challenges of luminance and chromaticity experienced by users of NVG devices.[23] A dark room illuminated by a fluorescent light box was the standard condition for all acuity measurements. The luminance level for the SVT was 112.1 cd/m^2 and the luminance level for the 25% NVG was 42.5 cd/m^2. SVT HC and 25% NVG acuity measurements were recorded as the logarithm of the minimum angle of resolution (logMAR); a credit of −0.02 logMAR units was calculated for each letter correctly identified. For the SVT CS, a credit of 0.05 logarithm of the CS (logCS) units was calculated for each letter correctly identified.

Binocular CS function (CSF) testing was performed using the Metropsis Visual Stimulus Generation Devise (ViSaGe; Cambridge Research Systems LTD, Kent, United Kingdom). CSF was generated preoperatively with correction, as well as at 1, 3, and 6 months postoperatively without correction. Contrast threshold was measured at five different spatial frequencies (SFs): 1.5, 3.0, 6.1, 13.1, and 19.7 cycles per degree (cpd) using a two-alternative forced-choice, linear staircase adaptive procedure with a 90° Gabor stimulus at mean luminance of 50.0 cd/m^2 at a 1.71 m viewing distance. Each test session was preceded by a demonstration. The binocular area under the log CSF (AULCSF) was calculated for each visit.

Marksmanship Performance

Participants in the marksmanship performance group were evaluated preoperatively with correction, at 6 weeks and 6 months postoperatively without correction in the firing tunnel at the Night Vision and Electronic Sensors Directorate (NVESD) at Fort Belvoir, Virginia. Established firing range protocols were adhered to at all times to ensure range safety.

Participants fired an M16-A4 rifle in a supported position under the following three conditions: iron sight (dominant eye); NVG using AN/PVS-7D with AN/PAQ-4C weapon mounted aiming light (biocular); and weapon-mounted forward-looking infrared (FLIR) thermal sight using FLIR-AN/PAS-13 (dominant eye). Low light conditions (simulating dusk approximately 1 cd/m^2) were used for iron sight firing and "starlight" (approximately 0.001 cd/m^2) was used for NVG and FLIR. As visual outcomes are variable in the early postoperative period,[24] the 6-week military performance testing time was selected to gauge military readiness earlier than the current deployment policy of 90 days after uncomplicated PRK.[25] At each visit, the weapon was zeroed before testing and participants adjusted the optics on the NVG and FLIR devices for optimal viewing. A standardized target was used at a distance of 25 m and performance was scored using a standardized grading system as described by Bower et al.[1]

Target Detection and Identification

Participants in the target detection and identification group underwent a series of computer-based tasks with correction preoperatively and at 6 weeks and 6 months postoperatively without correction. The first task was examining the observer's ability to identify vehicles at different ranges using thermal signatures. This experiment evaluated the probability of identification (PID) of eight different military vehicles, imaged at three aspects (front, side, and 45° angle) at five different ranges (approximately 100–2,000 m), with imagery digitally fused together by an algorithm from images captured in multiple wavebands (long wave [LW] and mid wave). There were 24 unique images, at each of the 5 ranges, for a total of 120 images in this experiment. Sample images of vehicles displayed at different ranges in the target set are shown in Figure 1A. Before initial testing, participants trained on the U.S. Army's Recognition of Combat Vehicles (Stevie R. Smith and Ken C. Cook in SimTecT 2011 Conference Proceedings "Recognition of Combatants Training," SimTecT 2011 Conference proceedings; roc@nvl.army.mil) software and achieved a 96% minimum competency level on discrimination of eight combat vehicles in close-range thermal imagery. Each observer was trained on set S and was asked to respond with one of N possible responses $R = (r_1, r_2, r_3, \ldots r_n)$ to stimuli presented. The percentage of correct responses was recorded representing the PID of the ensemble target set.

The second task was similar to the first in that it evaluated the PID of eight different military vehicles, imaged at

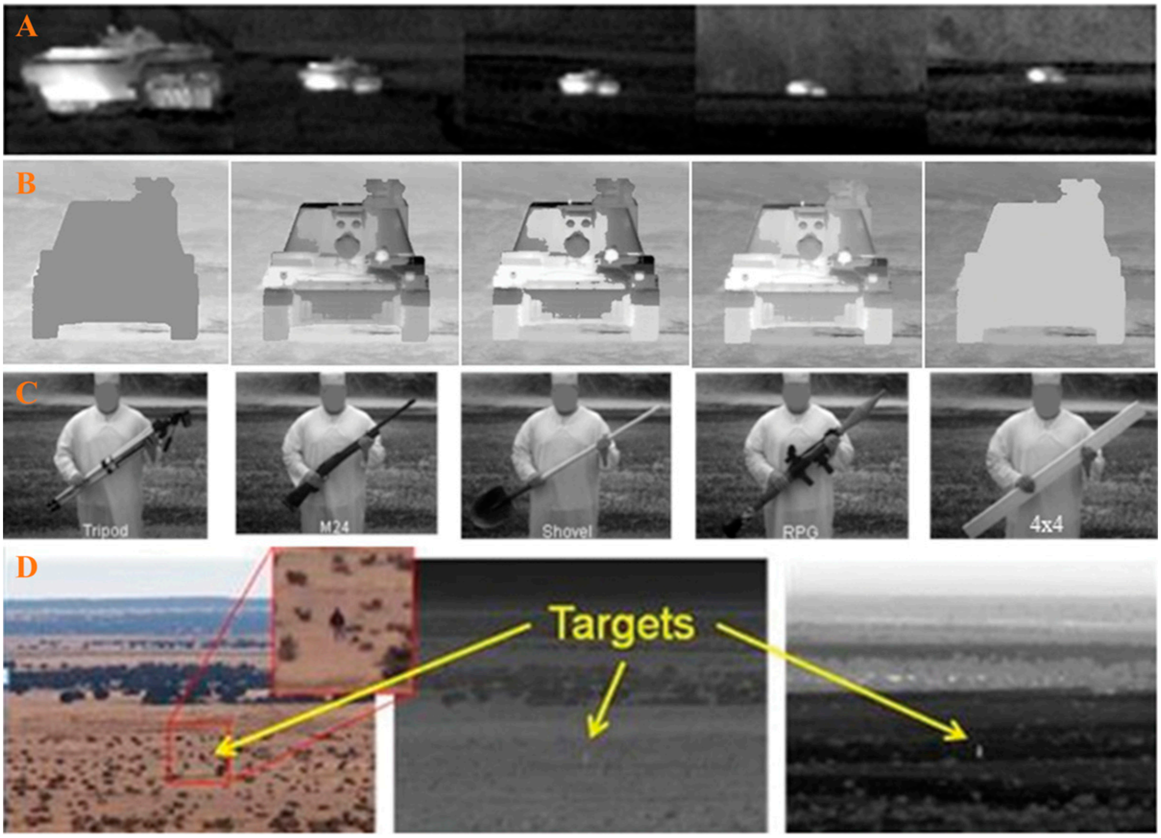

FIGURE 1. Sample imagery of (A) Tasks 1 and 2: vehicles at different ranges and aspects, (B) Task 3: different representations of a fixed contrast value manipulated by varying target and background contrast, (C) Task 4: handheld objects, (D) Task 5: human search in a cluttered environment.

three aspects (front, side, and 45° angle). In this task, only four ranges (approximately 100–2,000 m) were tested and imagery was captured in the LW band.

In the third task, contrast was held constant while three contrast components were manipulated. Five different combinations were formed by manipulating the following components: temperature mean of the target, temperature mean of the background, and temperature standard deviation within the target. The resulting image set included eight different vehicles, captured in the LW band, at three different aspects (front, side, and 45° angle) to be used to determine whether performance varied as a function of SF. Participants were asked to ID a vehicle in each of 120 different images, altered by five different contrast combinations as demonstrated in Figure 1B.

The fourth task was to assess the observer's ability to discriminate handheld objects of military interest in a 10 to 15 second video presented in shortwave infrared.[26] For display, eight military weapons were selected along with eight confounding objects expected in a rural setting (Fig. 1C). Before testing, each participant was given a briefing, which included sample imagery of objects with an overview of distinguishing features. This allowed familiarization before testing. During testing, the participant identified the handheld object in each of 96 videos. PID of the handheld object was recorded.

The final task was to search for a human from a long range in a high clutter, desert environment viewed in infrared (Fig. 1D). Images were presented of day and nighttime conditions, testing a range of target-to-background contrast levels. Participants were presented with 144 images, 10 seconds per image, to search and indicate the area containing the human. In 24 of the images, there was no human and participants could select "No Target" as a response option. To ameliorate with this search task, each participant was briefed using sample imagery before testing. The probability of detection, the number of humans correctly identified divided by 120 (total number of images with humans), was calculated for each participant.[27]

Statistical Analysis

Power calculations for firing performance were based on a previous study by Bower et al.[1] The mean firing score with iron sights was 97.5 ± 3.1 (±SD) in the PRK group. Assuming a common standard deviation as high as 4.7, and controlling the probability of a Type I error at $\alpha = 0.017$ (the α level was reduced to account for three night firing outcome variables using a Bonferroni correction of 0.05/3 = 0.017), 12 subjects per military task performance group would have 80% power to detect a difference of seven in the night firing range scores.

Baseline characteristics were compared using a two-sample t test for continuous data and Fisher's exact test for categorical data. For analysis of categorical visual outcomes and visual performance measures, Fisher's exact test was used to compare treatments at each time point. Changes in AULCSF over time were examined using a repeated measures analysis of variance. For military target performance, firing range scores were compared between treatment groups at each time point using the Wilcoxon rank sum test.

Repeated measures analysis of variance was used to compare WFG versus WFO treatment performance for each target detection and identification task. Exploratory linear regression analysis was used to examine each target detection and identification task at 6 months, controlling for preoperative performance, 6-month AULCSF, and treatment platform. SPSS software version 21.0 (IBM Corporation, Armonk, New York) was used for all statistical analyses. Given that there were a total of eight primary military response variables examined in this study, a Bonferroni corrected $p < 0.006$ was considered statistically significant.

RESULTS

Of the 56 participants enrolled in the study, 54 underwent treatment. Two participants were disenrolled from the study before treatment due to the following reasons: inability to capture a WaveScan analysis and bilateral peripheral retinal tears. Baseline characteristics of 27 WFG participants (54 eyes) and 27 WFO participants (54 eyes) were comparable (Table I).

Visual Performance

At 6 months postoperatively, 26/27 WFG and 25/27 WFO participants were available for clinical examination. There were no significant differences in visual outcomes at 6 months postoperatively: 52 (100%) WFG eyes and 49 (98%) WFO eyes achieved UDVA 20/20 or better (p = 0.49), whereas 42 (80.8%) WFG and 35 (70%) WFO eyes achieved UDVA 20/15 or better (p = 0.25). There was no significant difference between WFG versus WFO-treated eyes in postoperative MSE within ±0.50D of emmetropia: 51 (98.1%) versus 48 (96%), respectively, p = 0.61. No one in either treatment group experienced loss of ≥2 CDVA.

TABLE I. Baseline Characteristics (Mean ± SD)

	WFG (54 Eyes)	WFO (54 Eyes)	p Value[a]
Age (Years)	30.4 ± 6.2	30.4 ± 6.3	0.95
Male/Female	23/4	22/5	0.99[b]
Sphere (Diopter)	−3.29 ± 1.52	−3.23 ± 1.21	0.81
Cylinder (Diopter)	−0.75 ± 0.65	−0.60 ± 0.51	0.19
MSE (Diopter)	−3.67 ± 1.50	−3.53 ± 1.21	0.60
UDVA (logMAR)	1.05 ± 0.40	1.11 ± 0.40	0.45
CDVA (logMAR)	−0.10 ± 0.03	−0.11 ± 0.06	0.51
MMC Use (% of Eyes)	68.5%	55.6%	0.23[b]

[a]t test. [b]Fisher's exact test.

TABLE II. Change in Binocular Visual Performance After WFG and WFO PRK

	(A) Change in SVT HC[a]						(B) Change in SVT CS[c]						(C) Change in 25% Night Vision Acuity[a]					
	1M (n = 54) WFG/WFO		3M (n = 54) WFG/WFO		6M (n = 51) WFG/WFO		1M (n = 54) WFG/WFO		3M (n = 54) WFG/WFO		6M (n = 51) WFG/WFO		1M (n = 54) WFG/WFO		3M (n = 54) WFG/WFO		6M (n = 51) WFG/WFO	
Mean change ± SD	0.04 ± 0.08	0.0 ± 0.06	−0.02 ± 0.06	−0.03 ± 0.05	−0.04 ± 0.05	−0.03 ± 0.03	−0.22 ± 0.26	−0.10 ± 0.22	−0.02 ± 0.19	0.05 ± 0.18	0.05 ± 0.18	0.11 ± 0.17	0.05 ± 0.08	0.2 ± 0.06	−0.04 ± 0.06	−0.02 ± 0.05	−0.05 ± 0.08	−0.04 ± 0.06
Loss ≥ 2 (%)	1 (3.7)	0	0	0	0	0	16 (59.3)	10 (37.0)	6 (22.2)	2 (7.4)	3 (11.5)	1 (4.0)	1 (3.7)	0	0	0	0	0
Loss 1 (%)	8 (29.6)	2 (7.4)	2 (7.4)	0	0	0	2 (7.4)	5 (18.5)	2 (7.4)	4 (14.8)	1 (3.8)	1 (4.0)	9 (33.3)	3 (11.1)	1 (3.7)	0	1 (3.8)	0
No change (%)	17 (63.0)	23 (85.2)	22 (81.5)	23 (85.2)	23 (88.5)	24 (96.0)	5 (18.5)	6 (22.2)	11 (40.7)	12 (44.4)	10 (38.5)	11 (44.0)	14 (51.9)	23 (85.2)	21 (77.8)	23 (85.2)	15 (57.7)	20 (80)
Gain 1 (%)	1 (3.7)	2 (7.4)	3 (11.1)	4 (14.8)	3 (11.5)	1 (4.0)	2 (7.4)	2 (7.4)	4 (14.8)	3 (11.1)	4 (15.4)	5 (20.0)	3 (11.1)	1 (3.7)	5 (18.5)	4 (14.8)	9 (34.7)	4 (16.0)
Gain ≥ 2 (%)	0	0	0 (3.7)	0	0	0	2 (7.4)	4 (14.8)	4 (14.8)	6 (22.2)	8 (30.8)	7 (28.0)	0	0	0	0	1 (3.8)	1 (4.0)
p Value[b]	0.079		0.54		0.61		0.51		0.54		0.94		0.043		0.73		0.22	

[a]Negative shift, improvement. [b]Fisher's exact test; comparison of WFG versus WFO and loss, no change, gain categories. [c]Positive shift, improvement p value <0.006 statistically significant.

There was no significant difference between WFG and WFO in change in binocular SVT HC, SVT CS, and 25% NVG. Results of the SVT HC, SVT CS, and 25% NVG testing are summarized in Table II. Binocular AULCSF was also comparable between treatment groups at all time points ($p > 0.19$ for all comparisons).

Marksmanship Performance

Marksmanship performance performed by all participants preoperatively and at 6 weeks postoperatively (WFG; $n = 13$, WFO; $n = 14$) and 9 WFG and 11 WFO participants 6 months postoperatively is summarized in Figure 2A–C. There were no significant differences in marksmanship performance when comparing WFG versus WFO. Preoperatively, firing performance with correction was comparable between WFG and WFO when using iron sight ($p = 0.20$), NVG ($p = 0.28$) or FLIR ($p = 0.04$). At 6 weeks postoperatively, firing performance without correction was comparable between the treatment groups when using iron sight ($p = 0.43$), NVG ($p = 0.16$), or FLIR ($p = 0.55$). At 6 months postoperatively, firing performance without correction was also comparable between WFG and WFO when using iron sight ($p = 0.44$), NVG ($p = 0.83$) or FLIR ($p = 0.30$).

Target Detection and Identification

PID versus range (Task 1) was measured for military combat vehicles in the fused band. Although 14 WFG and 13 WFO participants underwent threshold target performance, not all WFG subjects participated in all tasks. Preoperatively, 12 WFG and 13 WFO underwent testing for Task 1. At 6 weeks, 14 WFG and 13 WFO underwent testing and at 6 months 12 WFG and 10 WFO underwent testing. Because testing in Task 1 varied, no longitudinal analysis was performed. There was no significant difference in PID over five ranges when comparing WFG versus WFO preoperatively ($p = 0.17$), 6 weeks postoperatively ($p = 0.37$), and 6 months postoperatively ($p = 0.43$).

Participants underwent testing for PID in the LW band (Task 2) including 13 WFG and 13 WFO preoperatively, 13 WFG and 12 WFO at 6 weeks, and 12 WFG and 10 WFO 6 months postoperatively. There was also no significant difference in the LW band (Task 2) when comparing the WFG versus WFO group preoperatively ($p = 0.56$), 6 weeks postoperatively ($p = 0.56$), and 6 months postoperatively ($p = 0.39$).

When identifying vehicles in images of varying vehicle and background contrast component combinations with the overall contrast being held constant, (Task 3), comparing performance of WFG and WFO over time, there was no significant difference ($p = 0.87$). Data analysis included results from 11 WFG and 10 WFO participants. Figure 3A illustrates combat vehicle PID over time in each group.

As seen in Figure 3B, in discriminating handheld objects (Task 4) data analysis from 11 WFG and 10 WFO

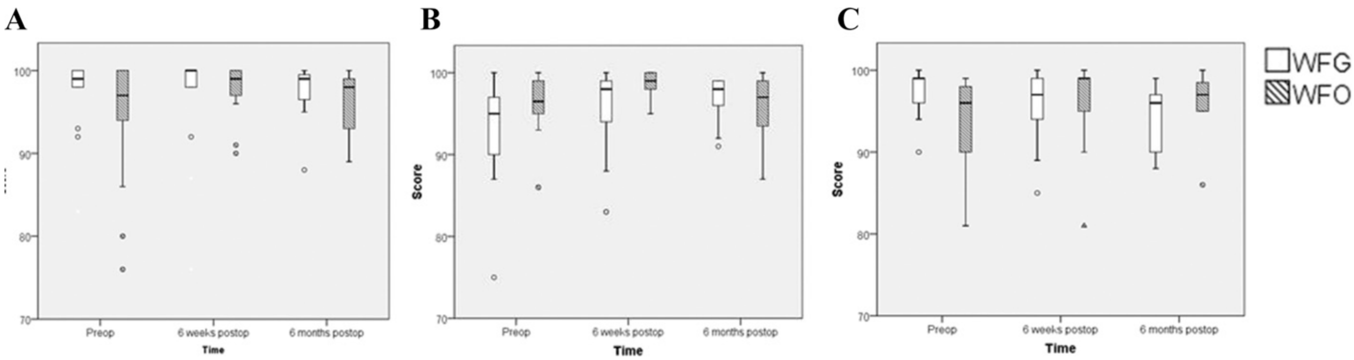

FIGURE 2. Boxplots of firing range performance under each condition (A) Iron sight, (B) Night vision goggle, (C) Forward looking infrared thermal sight showing median and interquartile ranges. °outlier <1.5 × interquartile range. ᐞoutlier >1.5 × interquartile range.

participants demonstrated comparable performance over time ($p = 0.92$). When searching for a human in a high-clutter environment (Task 5), detection by 12 WFG versus 10 WFO participants was comparable over time ($p = 0.76$) (Fig. 3C).

Each threshold target identification and detection task at 6 months was selected as the dependent variable for exploratory regression analysis. Controlling for baseline performance and AULCSF at 6 months, there were no significant differences between treatments in Tasks 1 to 5 ($p > 0.006$). In some tasks, there was a significant association with pretreatment performance results in the following tasks: vehicle PID fused (Task 1; range 4) $p = 0.002$; vehicle PID LW (Task 2; ranges 1 and 2) $p < 0.001$; vehicle contrast (Task 3) $p < 0.001$; Handheld object PID (Task 4) $p < 0.001$.

DISCUSSION

The impairment of visual function resulting from HOA is most recognizable under the intermediate and low light conditions in which many military operations occur. Refractive surgery decreases the second-order aberrations of defocus and astigmatism but it increases the magnitude of HOAs, which can result in decreased CS as well as increased halo, glare, starbursts, and monocular diplopia.[11–14] This has been mitigated by advances in wavefront refractive surgery, resulting in improved nighttime vision in comparison to conventional refractive surgery.[6,28–31] Furthermore, studies have observed an improvement in CS after WFG and WFO surgery.[32–34] As military service members are eligible to deploy 90 days after PRK and may not get minor refractive errors corrected, it was important to evaluate real world performance.[25] This study evaluated visual performance with particular attention to military operation-related tasks following either WFG or WFO PRK.

Efficacy, accuracy, and safety of visual outcomes were comparable between treatments, as seen in previous comparative studies between WFG versus WFO procedures.[22,34,35] In an attempt to detect subtle decreases from normal vision, this study also measured visual performance on the Rabin SVT.[23] The change in contrast from preoperative performance in both treatments showed loss in the early postoperative period with recovery or improvement in a majority of participants by 6 months postoperatively in both SVT HC and CS. This trend was also seen using the NVG filter, a filter used to simulate challenging viewing conditions commonly encountered in night military operations.[23] Results from the SVT and NVG tests were comparable between WFG versus WFO treatments at each time point.

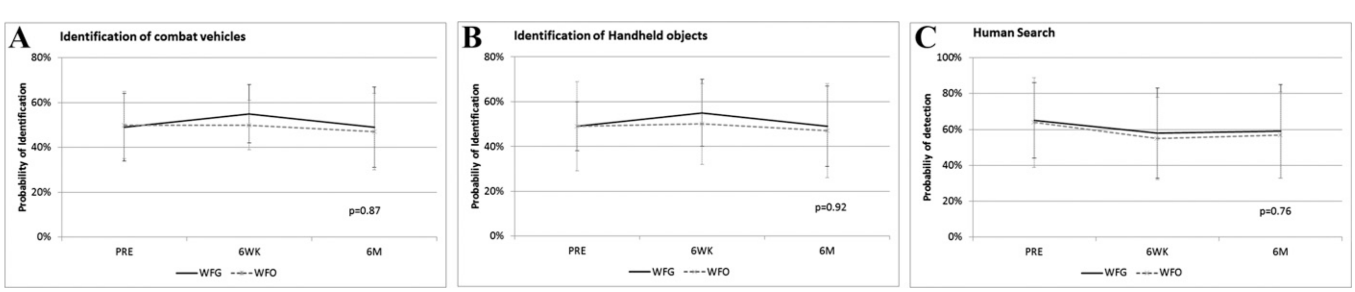

FIGURE 3. (A) Comparison of WFG versus WFO performance in the PID of military vehicles of varying vehicle and background contrast over time (Task 3). (B) Comparison of WFG versus WFO military task performance in the identification of hand held objects (Task 4) over time. (C) Comparison of WFG versus WFO participants searching for humans in a high-clutter environment preoperatively 6 weeks and 6 months postoperatively.

Owsley and Sloane used the CSF to predict real world target performance.[36] CSF in the present study was tested with correction preoperatively and without correction postoperatively to simulate real world refractive surgery experience. This study found participants who underwent either WFG or WFO PRK performed comparably in binocular CSF at each time point.

In a previous study by Bower et al examining iron sight and NVG military firing range performance, conventional laser-assisted in situ keratomileusis and PRK enhanced military performance.[1] Similarly, in the present study, performance was enhanced and comparable after either WFG or WFO PRK using the iron sight and NVG. Firing range performance using FLIR, which intensifies images in the infrared spectrum to allow more precise discrimination in images, was also comparable between treatments. Given the transient nature of our warfighting population, there was a decrease in follow-up at the firing range 6 months postoperatively (4 WFG; 3 WFO). As vision results did not differ significantly over time and firing results 6 weeks postoperatively with 100% follow-up were comparable between procedures, it may be inferred that, although there was a loss in follow-up at the firing range at 6 months, results would be consistent with 6-week firing range findings and visual outcomes.

"Real world" visual function assessment, such as firing range performance, is hampered by costs and limited standardization thereby promoting clinical tests such as visual acuity and CS. These tests, although beneficial for assessing visual function, do not address functional vision performance. A study of occupational psychophysics found that studies usually do not measure how visual performance affects specific job tasks.[37] Although visual acuity is important to establish necessity for job function, the review recommended the use of simulations to recreate work environment conditions as a means of gathering task performance data. As described in previous studies by Hammond et al and Subramanian et al, diminished viewing conditions create difficulties in object detection, discrimination, and recognition.[2,4] The U.S. Army has increased the use of computer-generated imagery for combat readiness training including immersive simulations that may replicate aspects of "real-life" experiences. The NVESD Modeling and Simulation Division develops computer-based perception testing to measure military task performance of the "human-sensor system" and sensor target acquisition models for infrared systems. Validation studies have shown that performance of trained observers in a field environment can accurately be represented with models, which have been developed using laboratory-based human performance.[38–41]

In the present study, computer-based military target acquisition task performance was examined to see if and how it changed after WFG versus WFO PRK. Previous study by the NVESD focused on combining observers to yield a performance measurement representative of the "average" observer, as opposed to this study, in which individual performance variation was examined. When determining the PID of a vehicle as a function of distance, there was no significant difference in PID over ranges when comparing WFG versus WFO PRK at any time point in either the fused imagery, which may produce a more detailed image, or LW band tasks. The tasks in this study are those in which human vision is aided by imaging sensors, which detect electromagnetic radiation outside the spectral response of the human eye. In an operational setting, a user would view the sensor imagery on an external display, the interface between the sensor and the human vision system.[42] Therefore, stereoscopic cues which may assist in close-range detection and identification tasks performed with the unaided eye or direct-view binoculars are not available when using military infrared sensing devices.

In a review by Pelli and Bex, it was noted certain SFs may be affected by clinical conditions such as refractive error and glare sensitivity.[43] Furthermore, a study by Abrahamson and Sjöstrand showed reduced sensitivity at lower SFs in participants complaining of glare with little effect on acuity.[44] Performance in this study did not vary as a function of SF when varying the component contrasts of a target and background, while maintaining a constant overall contrast (p = 0.87). Other task performances were also comparable between treatment groups. Performance was comparable when observing dynamic videos in handheld object discrimination tasks (p = 0.92) and when searching for a human in a high-clutter environment (p = 0.76).

Exploratory regression analysis, controlling for baseline performance and the AULCSF at 6 months, showed a significant association with pretreatment performance results in both handheld object and vehicle PID. Treatment type did not impact performance results. AULCSF was not correlated with task performance, as similarly reported in previous studies of target recognition tasks and in detection of aircraft.[45]

A limitation of the study is that military performance testing includes factors, apart from vision, which may affect a Soldiers' ability to perform tasks. Participants from different uniformed services and varying job specialties were enrolled in this study. This may explain some outliers specifically in the firing range performance group, as greater marksmanship experience can render a better score. This notwithstanding, results of these experiments highlight the independence afforded by either WFG or WFO PRK from spectacles or corrective lenses.

Refractive surgery is a significant military operational enhancer especially when using headgear, helmets with front ballistic protection, and more sophisticated weapon systems without the additional impediment to obscure viewing conditions. Vision enhancement by either WFG or WFO PRK decreases the dependence on glasses and corrective lenses. Although vision difficulties are of critical importance in military operations, they are also a concern in the civilian population, especially related to activity in nighttime conditions. Results from this study show that either surgery leads to comparable performance in military operation-related tasks.

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REFERENCES

1. Bower KS, Burka JM, Subramanian PS, Stutzman RD, Mines MJ, Rabin JC: Night firing range performance following photorefractive keratectomy and laser in situ keratomileusis. Mil Med 2006; 171(6): 468–71.
2. Hammond MD, Madigan WP, Bower KS: Refractive surgery in the United States Army, 2000-2003. Ophthalmology 2005; 112: 184–90.
3. Schallhorn SC, Blanton CL, Kaupp SE, et al: Preliminary results of photorefractive keratectomy in active-duty United States Navy personnel. Ophthalmology 1996; 103(1): 5–22.
4. Subramanian PS, O'Kane B, Stefanik R, et al: Visual performance with night vision goggles after photorefractive keratectomy for myopia. Ophthalmology 2003; 110(3): 525–30.
5. Van de Pol C, Greig JL, Estrada A, Bissette GM, Bower KS: Visual and flight performance recovery after PRK or LASIK in helicopter pilots. Aviat Space Environ Med 2007; 78(6): 547–53.
6. Tanzer DJ, Brunstetter T, Zeber R, et al: Laser in situ keratomileusis in United States Naval aviators. J Cataract Refract Surg 2013; 39(7): 1047–58.
7. Chalita MR, Chavala S, Xu M, Krueger RR: Wavefront analysis in post-LASIK eyes and its correlation with visual symptoms, refraction, and topography. Ophthalmology 2004; 111: 447–53.
8. Sharma M, Wachler BS, Chan CC: Higher order aberrations and relative risk of symptoms after LASIK. J Refract Surg 2007; 23: 252–6.
9. Sakata N, Tokundaga T, Miyata K, Oshika T: Changes in contrast sensitivity function and ocular higher order aberration by conventional myopic photorefractive keratectomy. Jpn J Ophthalmol 2007; 51(5): 347–52.
10. Lombardo M, Lombardo G: Wave aberration of human eyes and new descriptors of image optical quality and visual performance. J Cataract Refract Surg 2010; 36: 313–31.
11. Yamane N, Miyama K, Samejima T, et al: Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis. Invest Ophthalmol Vis Sci 2004; 45(11): 3986–90.
12. Oshika T, Okamoto C, Samejima T, Tokunaga T, Miyata K: Contrast sensitivity function and ocular higher-order wavefront aberrations in normal human eyes. Ophthalmology 2006; 113: 1807–12.
13. Quesnal NM, Lovasik JV, Ferremi C, Boileau M, Ieraci C: Laser in situ keratomileusis for myopia and the contrast sensitivity function. J Cataract Refract Surg 2004; 30: 1209–18.
14. Hiraoka T, Okamoto C, Ishii Y, et al: Contrast sensitivity function and ocular higher-order aberrations following overnight orthokeratology. Invest Ophthalmol Vis Sci 2007; 48: 550–6.
15. Mastropasqua L, Nubile M, Ciancaglini M, Toto L, Ballone E: Prospective randomized comparison of wavefront-guided and conventional photorefractive keratectomy for myopia with the meditec MEL 70 laser. J Refract Surg 2004; 20(5): 422–31.
16. Zhang J, Zhou YH, Li R, Tian L: Visual performance after conventional LASIK and wavefront-guided LASIK with iris-registration: results at 1 year. Int J Ophthalmol 2013; 6(4): 498–504.
17. Mrochen M, Donitzky C, Wüllner C, Löffler J: Wavefront-optimized ablation profiles: theoretical background. J Cataract Refract Surg 2004; 30: 775–85.
18. Cheng AC: Wavefront-guided versus wavefront-optimized treatment. J Cataract Refract Surg 2008; 34(8): 1229–30.
19. Yu J, Chen H, Wang F: Patient satisfaction and visual symptoms after wavefront-guided and wavefront-optimized LASIK with the WaveLight platform. J Refract Surg 2008; 24(5): 477–86.
20. Myrowitz EH, Chuck RS: A comparison of wavefront-optimized and wavefront-guided ablations. Curr Opin Ophthalmol 2009; 20(4): 247–50.
21. Alio JL, Pinero DP, Rosman M: Corneal wavefront guided excimer laser surgery for the correction of ocular aberrations. In: Dr. Agarwal's Textbook on Corneal Topography (Including Pentacam and Anterior Segment OCT). Edited by Agarwal A, Agarwal A, Jacob S. Ed. 2, pp. 201–18. New Delhi, India, Jaypee Brothers Medical Publishers LTD, 2010.
22. Sia RK, Ryan DS, Stutzman RD, et al: Wavefront-guided versus wavefront-optimized photorefractive keratectomy: clinical outcomes and patient satisfaction. J Cataract Refract Surg 2015; 41(10): 2152–64.
23. Rabin J, Gooch J, Douglas I, Harvey R, Aaron M: Beyond 20/20: new clinical methods to quantify vision performance. Mil Med 2011; 176(3): 324–6.
24. Sia RK, Coe CD, Edwards JD, Ryan DS, Bower KS: Visual outcomes after epi-LASIK and PRK for low and -moderate myopia. J Refract Surg 2012; 28(1): 65–7.
25. Office of the Surgeon General/United States Army Medical Command: Deployment Following Refractive Eye Surgery. Policy Memo 07-0 Fort Sam Houston, TX. United States Army Medical Command; 26 Nov 2007. Available at http://www.tamc.amedd.army.mil/offices/Ophthalmology/docs/2010/Army%20-%20deployment%20After%20refractive%20surgery.pdf; accessed February 11, 2016.
26. Self M, Miller B, Dixon D: Acquisition Level Definitions and Observables for Human Targets, Urban Operations, and The Global War on Terror. Ft. Belvoir, VA, U.S. Army Communications and Electronics Command Night Vision and Electronic Sensors Directorate; 2005: US Army AMSRD-CER-NV-TR-235. Available at www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA442798; accessed June 19, 2015.
27. Flug E: Modeling static and dynamic detection of humans in rural terrain. Proceedings of SPIE, infrared imaging systems: design, analysis, modeling, and testing XXV, Vol. 90710. 2014; 1–12.
28. Zhang J, Zhou YH, Li R, Tian L: Visual performance after conventional LASIK and wavefront-guided LASIK with iris-registration: results at 1 year. Int J Ophthalmol 2013; 6(4): 498–504.
29. Schallhorn SC, Tanzer DJ, Kaupp SE, Brown M, Malady SE: Comparison of night driving performance after wavefront-guided and conventional LASIK for moderate myopia. Ophthalmology 2009; 116(4): 702–9.
30. Mastropasqua L, Nubile M, Ciancaglini M, Toto L, Ballone E: Prospective randomized comparison of wavefront-guided and conventional photorefractive keratectomy for myopia with the meditec MEL 70 laser. J Refract Surg 2004; 20(5): 422–31.
31. Villarrubia A, Palacín E, Bains R, Gersol J: Comparison of custom ablation and conventional laser in situ keratomileusis for myopia and myopic astigmatism using the Alcon excimer laser. Cornea 2009; 28(9): 971–5.
32. Moshirfar M, Churgin DS, Betts BS, et al: Prospective, randomized, fellow eye comparison of WaveLight Allegretto Wave Eye-Q versus VISX CustomVueTM STAR S4 IRTM in photorefractive keratectomy: analysis of visual outcomes and higher-order aberrations. Clin Ophthalmol 2011; 5: 1185–93.
33. Tuan KM, Liang J: Improved contrast sensitivity and visual acuity after wavefront-guided laser in situ keratomileusis: in-depth statistical analysis. J Cataract Refract Surg 2006; 32(2): 215–20.
34. Moshirfar M, Betts BS, Churgin DS, et al: A prospective, randomized, fellow eye comparison of WaveLight® Allegretto Wave ® Eye-Q versus VISX CustomVue™ STAR S4 IR™ in laser in situ keratomileusis (LASIK): analysis of visual outcomes and higher order aberrations. Clin Ophthalmol 2011; 5: 1339–47.
35. He L, Liu A, Manche EE: Wavefront-guided versus wavefront-optimized laser in situ keratomileusis for patients with myopia: a prospective randomized contralateral eye study. Am J Ophthalmol 2014; 157(6): 1170–8.
36. Owsley C, Sloane ME: Contrast sensitivity, acuity, and the perception of 'real-world' targets. Br J Ophthalmol 1987; 71: 791–96.
37. Johnson CA: Occupational psychophysics to establish vision requirements. Optom Vis Sci 2008; 85(10): 910–23.

38. James D. Silk: Modeling the observer in target acquisition, Proceedings of SPIE 2743, infrared imaging systems: design, analysis, modeling, and testing VII, 87 (June 10, 1996).
39. O'Kane B L: Validation of models through perception studies. In: Vision Models for Target Detection and Recognition, pp. 192–218. Edited by Peli E. Singapore, World Scientific, 1995.
40. O'Kane BL, Bonzo D, Hoffman JE: Perception studies. Opt. Eng 2001; 40(9): 1768–75.
41. Ratches JA, Vollmerhausen RH, Driggers RG: "Target acquisition performance modeling of infrared imaging systems: past, present and future," IEEE Sensors 2001: 1(1): 31–40.
42. Driggers RG, Cox P, Edwards T: Introduction to Infrared and Electro-Optical Systems, pp. 355–72. Boston, MA, Artech House 1999.
43. Pelli DG, Bex P: Measuring contrast sensitivity. Vision Res 2013; 90: 10–14.
44. Abrahamson M, Sjöstrand J: Impairment of contrast sensitivity function as a measure of disability glare. Invest Ophthalmol Vis Sci 1986; 27: 1131–6.
45. O'Neal MR, Miller II RE: Further Investigation of Contrast Sensitivity and Visual Acuity in Pilot Detection of Aircraft Wright-Patterson AFB, OH, Harry G Armstrong Aerospace Medical Research Lab; 1998:No. AAMRL-TR-88-002. Available at http://www.dtic.mil/dtic/tr/fulltext/u2/a198434.pdf; accessed June 19, 2015.