



Ocular Changes after Simulated Ejection Following Orthokeratology

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Purposes: To determine the stability of subjects' visual acuity, refraction, corneal topography, pachymetry, anterior chamber depth, and intraocular pressure following overnight orthokeratology when subjected to vertical acceleration at six times the force of gravity (+6 Gz) in a simulated ejection system on the ground. **Methods:** The subjects were 10 healthy male flight surgeons, aged 25–26 years (mean 25.3), who had undergone overnight orthokeratology for two weeks before controlled rapid-sequence ejection at +6 Gz. Their visual acuity, refraction, and corneal parameters, including corneal curvature, corneal thickness, anterior chamber depth, and intraocular pressure, were recorded before, immediately after, and 20 min after the +6 Gz ejection. We compared the study group findings with those of a control group of 20 subjects who had not undergone orthokeratology but were exposed to the same ejection procedure. **Results:** The measurements of visual acuity, refraction, and Orbscan topographic parameters, including the anterior and posterior corneal curvatures, central corneal thickness, and intraocular pressure, made before, immediately after, and 20 min after ejection did not differ significantly between the pre- and post ejection values on paired t tests. The only significant difference in the orthokeratology group was in the anterior chamber depth, which was 2.978 mm before ejection and 3.01mm 20 min after ejection ($p < 0.05$). **Conclusion:** The visual acuity, refraction, and corneal topographic changes in patients after orthokeratology are stable under rapid vertical ejection at six times the force of gravity. An increase in anterior chamber depth was the only significant change after ejection in the orthokeratology group.

Key words: corneal topography, simulated ejection, orthokeratology, Orbscan II, G-force

INTRODUCTION

Orthokeratology contact lenses are a specific kind of rigid flat-fitting contact lenses that reduce myopia by flattening corneal curvature.¹ They flatten the apical radius, restructuring the cornea toward an oblate ellipse, which is reflected in the corneal topography.² Holden and Mertz found limiting corneal edema to the levels that occur normally during sleep (i.e., 4% swelling) requires a contact lens to have a minimum oxygen transmissibility of $87 \text{ (cm}^2 \text{ s}^{-1}\text{)(mLO}_2\text{/mL hPa)}$ (ISO/Fatt).³ New-generation materials allow oxygen transmissibility values that minimize hypoxic stress and corneal edema when worn on

an overnight basis. Therefore, patients who wear the lenses only overnight, during sleep, achieve functional vision during waking hours, with no correction required throughout the day.

In 1997, Mountford⁴ conducted a retrospective study of 60 patients who had undergone overnight orthokeratology with reverse-geometry lenses. He found the central corneal topography became spherical and was surrounded by a steep mid-peripheral zone, indicating orthokeratology made the cornea oblate. He also reported more predictable, consistent, and sustained reductions in myopia (mean reduction, 2.19 diopters [D]) with these lenses. The effect of overnight orthokeratology is similar to that of laser refractive surgery, such as photorefractive keratectomy (PRK) or laser-assisted in situ keratomileusis (LASIK), but differs from that of traditional contact lenses.

Nichols and associates⁵ evaluated 10 myopic subjects who had undergone overnight orthokeratology using rigid reverse-geometry contact lenses and concluded overnight orthokeratology is an effective way to temporarily reduce myopia, especially in low-myopia individuals with minimal astigmatism. Therefore, orthokeratology is

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potentially another option for reducing refractive error in aircrew. However, before we undertook this study, it was unclear whether the central flattening and improved visual acuity observed after orthokeratology are altered by an aircraft ejection simulator with high +Gz acceleration.

As far as we know, this is the first study to address this issue. In the study, visual acuity, refraction, and various corneal topography parameters were measured before, immediately after, and 20 min after ejection in an aircraft cockpit ejection simulator.

METHODS

Ten healthy men who were training to be aviation doctors, aged between 25 and 27 years (mean, 25.8 years) and with normal healthy eyes, were enrolled in this experiment, but only the right eye data were analyzed. Informed consent was obtained from all subjects prior to their participation in the experiment. The research followed the tenets of the Declaration of Helsinki. Ethics approval for the study was obtained in advance from the institutional review board of Tri-Service General Hospital Taipei, Taiwan.

The subjects underwent overnight orthokeratology for two weeks, wearing programmed rigid reverse-geometry contact lenses. The orthokeratology lenses were made of Boston Equalens II material (Polymer Technology Corp., Wilmington, MA), which is composed of fluorosilicone acrylate with an oxygen permeability (Dk) of 5×10^{-11} ($\text{cm}^2 \text{s}^{-1}$)(mLO₂/mL hPa) (ISO/Fatt). The posterior surface of each lens consists of four curves: (a) the base curve, which is flatter than the central anterior corneal curvature and exerts a positive pressure on the cornea to induce central flattening; (b) the reverse curve surrounding the optical zone, which has a curvature steeper than that of the optical zone, and forms a tear reservoir displaying a band of mid-peripheral fluorescein pooling, which is considered to be a factor involved in inducing the corneal iron ring;⁶ (c) the alignment curve, which generally parallels the underlying corneal surface to keep the lens centered on the cornea; and (d) the peripheral curve, with a radius selected to create edge lift, which promotes tear flow under the lens. To choose the initial lens, the base curve was determined as the target power plus 0.75 D for each eye. The alignment curve was determined based on the flatter keratometric reading.

The simulated ejection seat system at the Aviation Physiology Research Laboratory, Gangshan Armed Forces Hospital (Kaohsiung, Taiwan) was used to produce an acceleration force set at +6 Gz at ground level. The ejection

seat trainer (EST) in this study included a simulated cockpit equipped with a catapult system, an ejection seat, and a vertical rail. The ejection seat was engaged on the vertical rail track. Safety interlocks were set at the distal end of the vertical rail to ensure the subject's safety.

The EST can simulate a sudden and transitory acceleration stress from 1 G to 7 G. Before ejection, the ejection seat was mounted in the cockpit and fixed to the vertical rail. The subject sat in an upright position and fastened the seatbelt on the ejection seat. He then pulled up the catapult switch in the EST by himself, and the catapult system in the simulated cockpit catapulted the subject up along the vertical rail, simulating an emergent acceleration stress.

In this experiment, the ejection seat was set by aviation physicians to eject with a force of +6 Gz over 0.2 s, calculated according to the body weight of each subject. There was no decelerator or brake system on the vertical rail. The subject was ejected upward about 18 m in about 1.4 s, and was only stopped by gravity. After ejection, the delivery system restored the subject and the seat to the initial position via the vertical rail, without any negative gravitational force.

Before ejection, each subject underwent a series of examinations, including of his bare visual acuity, refraction, corneal topography, and intraocular pressure. Bare visual acuity was tested at a distance of 4 m and was recorded with an Early Treatment of Diabetes Retinopathy (EDTRS) logMAR chart. Autorefractometry was measured with the Topcon RK-3000 autorefractor (Topcon Co., Ltd, Tokyo, Japan). Corneal topography was measured with the Orbscan II Slit Scan Corneal Topography/Pachymetry System Analyzer (Orbtek, Salt Lake City, UT). Corneal thickness values were averaged centrally and peripherally over a circular area of 2 mm diameter with the Orbscan. Because at the instant of ejection, the seat may be automatically restored to its initial position within 5 s, the data were measured immediately after ejection. This series of measurements was then repeated 20 min after ejection. The data were analyzed using IBM SPSS version 10.0. The relationships between the pre- and post-ejection values were assessed with Pearson's correlation. A paired t test was used to compare the physiological parameters before, immediately after, and 20 min after the simulated ejection, with $p < 0.05$ taken to indicate statistical significance. The results are expressed as means $\pm$ SD. We compared the study group findings with those of a control group of 20 subjects who had not undergone orthokeratology but who experienced the same ejection procedure.

Table 1 Refraction and bare visual acuity before and after ejection: Ortho-K and Control group

	Before	Immediately after	After 20 minutes
Ortho-K Group			
Refraction (D)	-1.44±1.16	-1.27±1.61	-1.24±1.33
Bare visual acuity (LogMAR)	-0.060±0.052	-0.050±0.082	-0.045±0.072
Control group			
Refraction (D)	-4.81±2.17	-4.69±1.97	-4.71±1.94
Bare visual acuity (LogMAR)	-0.070±0.072	-0.069±0.07753	-0.080±0.057
N0=10 eyes P=0.677 in refraction and 0.685 in bare visual acuity in Ortho-K group			
N0=20 eyes P=0.335 in refraction and 0.129 in bare visual acuity in Control Group			

Table 2 Central corneal thickness (CCT) before and after ejection: Ortho-K and Control group

	Before	Immediately after	After 20 minutes
Ortho-K Group			
CCT (um)	553.81±16.33	551.34±18.74	547.62±18.12
Control group			
CCT (um)	529.13±32.07	523.34±37.33	525.64±31.45
N0=10 eyes P=0.045 in central corneal thickness in Ortho-K group			
N0=20 eyes P=0.382 in central corneal thickness in Control group			

Two hours after ejection, we checked the anterior chamber through an angle of 360° with three-mirror gonioscopy and the relative position of the lens with a slit-lamp examination through fully dilated pupils.

RESULTS

All patients in the orthokeratology and control groups completed the study. The patients' data are summarized in Tables 1–5. All the data were collected for 30 eyes: the 10 right eyes of the orthokeratology group and the 20 right eyes of the control group. Tables 1 show a slight reduction in refraction after ejection in the orthokeratology group, but there were no statistically significant differences in bare visual acuity or refraction before, immediately after, or 20 min after ejection associated with +6 Gz acceleration. Tables 2 show there was a reduction in the central corneal thickness after ejection in both the orthokeratology and control groups. Although this change was greater in the orthokeratology group, the difference between the groups was not statistically significant. Tables 3 show there were no significant changes in either

Table 3 Corneal curvature before and after ejection: Ortho-K and Control group

	Before	Immediately after	After 20 minutes
Ortho-K Group			
Ant. curvature (D)	41.40±0.63	41.40±0.61	41.36±0.67
Post. curvature (D)	52.19±0.60	52.00±0.76	52.06±0.55
Control group			
Ant. curvature (D)	42.22±1.83	42.12±2.20	41.93±1.62
Post. curvature (D)	52.74±2.30	52.31±2.74	52.13±2.05
N0=10 eyes P=0.880 in ant. curvature and 0.534 in post. curvature in Ortho-K group			
N0=20 eyes P=0.361 in ant. curvature and 0.254 in post. curvature in Control Group			

Table 4 Intraocular pressure(IOP) before and after ejection: Ortho-K and Control group

	Before	Immediately after	After 20 minutes
Ortho-K Group			
IOP (mmHg)	15.80±2.35	15.50±1.51	15.80±1.99
Control group			
IOP (mmHg)	15.28±3.57	15.44±3.53	15.25±3.57
N0=10 eyes P=0.767 in intraocular pressure in Ortho-K group			
N0=20 eyes P=0.869 in intraocular pressure in Control group			

Table 5 Anterior chamber depth (ACD) before and after ejection: Ortho-K and Control group

	Before	Immediately after	After 20 minutes
Ortho-K Group			
ACD (mm)	2.99±0.32	3.03±0.31	3.02±0.31
Control group			
ACD (mm)	3.08±0.23	3.11±0.23	3.11±0.23
N0=10 eyes P=0.004* in anterior chamber depth in Ortho-K group			
*Statistically significant difference (P<0.005).			
N0=20 eyes P=0.022 in anterior chamber depth in Control group			

the anterior or posterior corneal curvature immediately after or 20 min after ejection, in either the orthokeratology or control group. Tables 4 show there was no significant change in intraocular pressure immediately after or 20 min after ejection in either the orthokeratology or control group. Tables 5 show the only significant finding was in the anterior chamber depth, which increased immediately after and 20 min after ejection in both the orthokeratology and control groups. However, this change was only statistically significant in the orthokeratology group, in which the anterior chamber depth was significantly increased immediately after (from 2.99±0.32 to

3.03±0.31, $p < 0.005$) and 20 min after ejection (from 2.99±0.32 to 3.02±0.31, $p < 0.005$). When we compared all the data for the orthokeratology and control groups before, immediately after, and 20 min after ejection, the only significant difference was in their refraction values. This is attributable to the effects of orthokeratology and was not related to the simulated ejection.^{7,8}

Two hours after ejection, no hyphema was found in the anterior chamber or through an angle of 360° with Goldman gonioscopy, and no sublocation or dislocation of the lens or any rupture of the anterior lens surface was observed with a slit-lamp examination.

DISCUSSION

Good visual acuity is important to the military aviator and has been suggested as a possible criterion for personnel selection and retention. Some pilots or aviation students are excluded because of low-level myopia. Various methods have been used to reduce or correct their low refractive error, including laser refractive surgery, contact lenses, and special goggles.

Orthokeratology is another option to improve their visual acuity. Overnight orthokeratology using rigid gas-permeable contact lenses has been effective in temporarily reducing myopia in Taiwan and other countries.^{7,8} The corneal changes accompanying orthokeratology occurred much more rapidly in those studies than in previous studies. This is probably attributable to the new-generation reverse-geometry orthokeratology lens designs and possibly because the lenses were worn overnight.⁸ A 1990 study of more than 6,000 U.S. Air Force (USAF) aircrew⁹ revealed 27.4% of pilots, 51.5% of navigators/weapons system officers, and 40.2% of other aircrew required corrective eyewear. The retention of eyewear and the severity of related injuries is a problem during aircraft ejection. Data on emergencies that involved ejection, occurring between 1956 and 2004, were obtained from the accident records of the Japan Air Self-Defense Force.¹⁰ During Operation Desert Storm, the USAF lost four F-16 aircraft while on combat missions over Iraq and Kuwait, with four pilots ejecting safely.¹¹ Aircraft ejection involves a sequence of events in which the aviator remains belted to a seat that is rocketed out of the aircraft. During the initial discharge, the aircrew member is subjected to a brief but extreme vertical gravitational force (+7 Gz), followed by a windblast as the seat exits the aircraft. When an emergency occurs at high speed, visual performance is important in preventing further catastrophe because the response time is relatively short. In earlier

studies, investigators have reported positive acceleration can cause grayout, blackout, and loss of peripheral vision.¹² Understanding the corneal changes that occur after ejection is important for accurately predicting refractive procedure outcomes, including LASIK and contact lenses, such as those used for orthokeratology.¹³ The ejection seat training system at the Aviation Physiology Research Laboratory, Taiwan, was used to simulate the ejection process at six times the gravitational force in a head-to-toe Z-axis direction (+6 G force). Ejection under high-acceleration force may induce several physiological responses.¹⁴ Our results show visual acuity and refractive indices were well preserved during simulated ejection in both the orthokeratology and control groups. However, there was a slight reduction in refraction after ejection in the orthokeratology group, and corneal thickness decreased in both the orthokeratology and control groups after ejection, but to a greater degree in the orthokeratology group. This may be attributable to the redistribution of the epithelium in patients after orthokeratology,^{15,16} which is exacerbated by high gravitational force, but the change in corneal thickness was not statistically significant between the values for the orthokeratology group before and after ejection. The anterior chamber depth increased in both the orthokeratology and control groups, but only statistically significantly in the orthokeratology group. This may be attributable to the mechanical force of the orthokeratology lens and the gravitational force to replace the lens backward. The same phenomenon has been observed with other acceleration procedures, such as in the human centrifuge in our previous study.¹⁷ Han-Yin Sun and associates¹⁸ have used the same ejection procedure to test pilots who have not undergone the orthokeratology procedure and recorded changes in the biochemical properties of their corneas. They found no statistically significant changes in corneal hysteresis or the corneal resistance factor before or after ejection. Bare visual acuity and refraction were also stable before and after simulated ejection. Cho *et al.*¹⁹ designed a study to determine the extent and duration of contrast sensitivity (CS) loss after high, sustained +Gz acceleration in a centrifuge. They found CS loss was more severe at low and medium frequencies (1.5, 3.0, 6.0 cycles per degree [cpd]) than at a high spatial frequency (18.0 cpd). Recent work by Hiraoka *et al.*²⁰ has provided some insight into the CS loss that occurs during orthokeratology. LogCS decreased significantly at all four spatial frequencies, and the reduction did not worsen further after one month. In our study, visual acuity, refraction, corneal curvature, and intraocular pressure were stable after ejection, even in

patients who had undergone the orthokeratology procedure. Tsai²¹ *et al.* designed a similar ejection procedure to evaluate the ocular responses and visual performance after emergent acceleration stress, finding transient visual acuity decreased immediately after the gravitational stress and returned to baseline 15 min after +6 Gz force exposure. They submitted this transient loss was due to parvocellular dysfunction caused by acute stress acceleration but the exact mechanism is still unknown. On the contrary, in our study, visual acuity remained stable after acceleration. The disparity may be due to the low refraction (under 1D) in their study, and the different definition of just and immediate after the ejection. They may have checked the visual acuity within five minutes and it may recover sooner than they expected. The refraction and macular function is unremarkable before and after acceleration.

Refractive surgery, such as PRK or LASIK, is another way to reduce myopia in pilots. Randall and associates²² evaluated LASIK flap stability during simulated aircraft ejection in a rabbit model, and found the flap was clinically and keratometrically stable at +9 Gz. However, another recent animal study by Laurent *et al.* evaluated the effects of windblast on LASIK flaps,²³ showing the entire globe deformed and suffered extensive injury before any of the LASIK flaps dislocated. Although these preliminary studies suggest LASIK flaps may be tectonically stable during aircraft ejection, other factors such as hypobaric hypoxia may affect LASIK refractive stability. Tanzer *et al.*²⁴ reported the only case of aircraft ejection following refractive corneal surgery by a navy pilot six months after bilateral PRK. In that case, there was no change in refraction or in the results of an ophthalmic examination after ejection. As far as we know, ours is the first report of the effects of previous orthokeratology during simulated ejection. Our results show visual acuity, refraction, corneal curvature, and intraocular pressure remain stable during ejection. Therefore, orthokeratology may be a good alternative to LASIK or PRK for pilots. The statistical analysis of the data presented in this paper was performed using the data from only the right eyes of 10 subjects in the orthokeratology group and the 20 right eyes of the control group to avoid any nonindependence error in the response of each eye of a given subject to orthokeratology lens wear.

The sample of subjects examined in this study was small. A larger-scale study is required to evaluate these effects under +Gz acceleration in subjects who wear orthokeratology lenses. Whether CS deteriorates under high-Gz acceleration in patients after orthokeratology

must also be evaluated. Our experiments were performed on the ground. During real high-altitude ejection, true environmental factors, such as windblast, low temperature, and hypoxia, also challenge the pilots and may affect the parameters reported here. Consequently, further studies are required to examine these factors in the future.

DISCLOSURE

All authors declare that this study has no conflict of interest.

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