CASE REPORT

Visual stability of laser vision correction in an astronaut on a Soyuz mission to the International Space Station

C. Robert Gibson, OD, Thomas H. Mader, MD, Steven C. Schallhorn, MD, Konrad Pesudovs, PhD, William Lipsky, MD, Elias Raid, MD, PhD, Richard T. Jennings, MD, Jennifer A. Fogarty, PhD, Richard A. Garriott, ScD, Owen K. Garriott, PhD, Smith L. Johnston, MD

This report documents the effects of photorefractive keratectomy (PRK) in an astronaut during a 12-day Russian Soyuz mission to the International Space Station in 2008. Changing environmental conditions of launch, microgravity exposure, and reentry create an extremely dynamic ocular environment. Although many normal eyes have repeatedly been subject to such stresses, the effect on an eye with a relatively thin cornea as a result of PRK has not been reported. This report suggests that PRK is a safe, effective, and well-tolerated procedure in astronauts during space flight.

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The utility and validity of photorefractive keratectomy (PRK) is well established in the general aviation community. Since PRK reduces dependence on glasses and contact lenses, it is ideally suited for astronauts who participate in space operations. Additionally, PRK exhibits no significant diurnal fluctuation in visual acuity and has proven stability under hypobaric conditions.[1] Currently, PRK, as well as laser in situ keratomileusis (LASIK), is an approved procedure for aviators in all branches of the military including pilots of high-performance aircraft.

At the inception of the United States space program, all astronauts were military test pilots and were required to meet rigorous vision standards. As the effects of space flight on vision became better understood and as more astronauts were needed in the post-Apollo era, vision standards were relaxed. For many years, National Aeronautics and Space Administration's (NASA) astronaut selection vision standards dictated that uncorrected distance visual acuity (UDVA) could not exceed 20/100 in either eye for pilot astronaut candidates and 20/200 for mission specialist candidates. However, in recent years, NASA has relaxed the vision standards and no longer has a UDVA requirement for astronaut selection. Instead, NASA adopted a cycloplegic refractive error requirement not to exceed ±5.50 diopters (D) in any meridian, with 3.00 D of cylinder for mission specialists and +3.50 to −4.50 D in any meridian, with 2.00 D of cylinder for pilot astronaut candidates. As of September 2007, NASA has approved PRK and LASIK for astronaut selection and retention (preoperative cycloplegic refractive error must be between +4.00 and −8.00 sphere, astigmatism must be 3.00 D or less in minus cylinder format, and

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From the Coastal Eye Associates, Webster and Wyle Integrated Science and Engineering (Gibson, Lipsky), the Space Medicine Division (Fogarty, Johnston), the National Aeronautics and Space Administration, Johnson Space Center, Houston, and the University of Texas Medical Branch (Jennings), Galveston, Texas; the Alaska Native Medical Center (Mader), Department of Ophthalmology, Anchorage, Alaska; the University of California San Francisco, San Francisco and Optical Express (Schallhorn), San Diego, California; and Space Adventures (R.A. Garriott), Vienna, Virginia, USA; the NH&MRC Centre for Clinical Eye Research (Pesudovs), Department of Optometry and Vision Science, Flinders Medical Centre and Flinders University of South Australia, Bedford Park, South Australia; and the European Medical Center (Raid), Moscow, Russia. O.K. Garriott is a retired NASA scientist-astronaut.

Corresponding author: C. Robert Gibson, OD, Coastal Eye Associates, 555 East Medical Center Boulevard, Webster, Texas 77598, USA. E-mail: charles.gibson-1@nasa.gov.

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follow-up must be no less than 6 months [LASIK] and 1 year [PRK] [including enhancements] with no permanent adverse sequelae). Although the successful use of bilateral intraocular lenses in an astronaut during space shuttle operations has been reported,[2] to our knowledge, no case documenting the stability of corneal refractive surgery in an astronaut during spaceflight has been reported.

The end of the U.S. Space Shuttle program marked the beginning of the NASA–Soyuz era for transportation to and from the International Space Station. Environmental conditions of launch, microgravity exposure, and reentry create an extremely dynamic ocular environment in any spacecraft. However, due to its unique flight profile, confined space, and rather poor lighting conditions, this challenging ocular environment is particularly pronounced during a Soyuz mission. Although many Russian cosmonauts with normal eyes have been subjected to such stresses, the effect on an eye with a relatively thin cornea as a result of PRK has not been documented.

On liftoff, gravitational (G)-forces reaching +3 to 4 Gx are produced by a 3-stage sequential rocket thrust lasting 10 minutes. These positive G-forces push the eye backward toward the rear of the bony orbit (eyeballs in) and then dissipate as the astronaut enters space and are replaced by the very different influence of microgravity. Within seconds of reaching microgravity, the human body undergoes changes that alter ocular physiology. Specifically, there is a cephalad shift of about 1.5 to 2.0 liters of blood, initially resulting in altered vascular volume and ultimately in altered interstitial volume of the lower body compared with that in the chest and head.[3] This shift results in a sudden rise in intraocular pressure (IOP) as well as a more gradual onset of facial edema.[4–8] Intraocular pressure has been documented to increase 20% to 58% within 25 seconds of exposure to microgravity.[7] The etiology of the IOP rise has been hypothesized to result from increased episcleral venous pressure, orbital pressure on the globe, choroidal expansion, or a combination of the three.[6–8] Although long-duration studies of IOP in microgravity have not been performed, short duration space shuttle and head-down studies suggest that the eye may rapidly undergo adaptive changes to blunt the initial spike in IOP.[6,8]

During descent, the Soyuz module falls toward Earth, reaching a deceleration of +4.0 to 4.5 Gx (eyeballs in). A series of 4 parachutes are then deployed, slowing the rate of descent until 1 second before touchdown, when 2 engines on the bottom of the descent module ignite to further reduce the force of impact.

This report documents the stability of PRK in an astronaut during a 12-day Russian Soyuz mission to the International Space Station in 2008. The astronaut served as a spaceflight participant during this mission and performed several research projects and medical experiments, which demanded good near and far visual acuity.[9]

CASE REPORT

The astronaut (Richard A. Garriott), a 47-year-old white male, had bilateral PRK for myopia in 1994. A conventional ablation profile and a presumed 6.0 mm optical zone were used. The preoperative refractive errors were −4.00 D and −3.75 D in the right eye and left eye, respectively. The postoperative course was uneventful.

The pre-mission eye examination, performed 10 weeks before flight (Launch-72 days), documented a UDVA logMAR of 0.14 (20/25$^-$) and 0.02 (20/20$^-$) in the right eye and left eye, respectively, which corrected to 20/15 in each eye with cycloplegic refractions of −1.00 +1.25 × 28 (right eye) and −0.75 +0.50 × 155 (left eye). Corneal topography was consistent with a post-PRK shape in both eyes, and keratometry was 41.50/41.87 × 180 (right eye) and 42.00/42.12 × 180 (left eye). Wavefront analysis was also consistent with a refractive surgery optical profile. The IOP measured with Goldmann applanation tonometry was 12 mm Hg in the right eye and 10 mm Hg in the left eye. The right central cornea was clear; there was a faint scar at the 4 o'clock position in the left cornea as a result of ocular trauma approximately 8 years before the mission. The central corneal thickness (CCT) was 508 μm in the right eye and 504 μm in the left eye. The remainder of the ocular examination, including visual fields and dilated fundus examination, was normal. The UDVA and near visual acuity measurements were performed under simulated inflight test conditions 2 days and 1 day before launch (Launch-2 and Launch-1) and were the same as those planned during flight. The median logMAR was 0.08 (20/25$^+$) in the right eye and −0.06 (20/16$^-$) in the left eye for distance and 0.1 (20/25) in the right eye and 0 (20/20) in the left eye for near. The pre-mission questionnaire documented very slight photophobia with slight eye fatigue (Launch-2 days).

The launch took place on October 12, 2008, from the Baikonur Cosmodrome in the Republic of Kazakhstan. The Soyuz capsule docked with the International Space Station 2 days after launch. The atmospheric pressure and O_2 partial pressure throughout the mission were steady at 14.7 PSI and 160 to 170 mm Hg (20% O_2), respectively.

Inflight testing of visual performance was performed (Figure 1) and a questionnaire completed daily. Distance (3 m) and near visual acuity (40 cm) were tested using logMAR charts (Figure 2), and results were recorded by the subject. Ocular and visual symptoms were evaluated using a comprehensive questionnaire. Measurements taken on days 1 and 2 post launch were performed on the Soyuz spacecraft and on days 3 to 11 on the International Space Station.

Compared with preflight visual acuity, both distance and near visual acuity remained stable on-orbit and post-flight, as illustrated in logMAR units in Figure 3. The right eye UDVA remained stable with a mean logMAR of 0.11 (20/25$^-$) and the left eye UDVA remained stable at −0.06 logMAR (20/16$^-$). The subtle daily changes observed were within the retest reliability limits for visual acuity testing (±1 line). The effect of both a +1.00 D and −1.00 D handheld lens on vision was tested throughout flight. The subject consistently reported distance vision was worse with the +1.00 D lens and better with the −1.00 D lens. This suggests that a hyperopic shift in refractive error greater than or equal to 1.00 D did not occur during flight.

Figure 1. Astronaut in position for distance visual acuity testing.

Figure 2. The logMAR visual acuity chart designed for testing at 3 meters.

An assessment of accommodation was performed by measuring the closest distance before blur when viewing small letters on the near vision card. This was measured throughout the flight and remained stable at 4.8 D $\pm$ 0.5 (SD) before, during, and after the flight.

The questionnaire assessed ocular symptoms including eyes feeling dry, irritated, itchy, tired, light sensitive, teary, or painful. The astronaut was also questioned regarding the occurrence of headaches that he thought were related to vision. Specifically, he was asked whether he had experienced any of these symptoms in the past 24 hours using 6 response options: (1) no, not at all; (2) perhaps, very slightly; (3) yes, slightly but not troublesome; (4) yes, and it is a little troublesome; (5) yes, and it is troublesome; (6) yes, and it is extremely troublesome. The responses are graphed in Figure 4. Symptoms increased during spaceflight but were no worse than "a little troublesome" with respect to tired eyes. "Slight but not troublesome" symptoms of irritated and painful eyes were also noted during flight. The severity of other symptoms were in the "perhaps very slightly" category. Dry eyes, visual discomfort, and headaches attributed to vision were not experienced. Headaches were reported but attributed to "fluid shifts" and not to vision.

The questionnaire also addressed visual symptoms such as trouble seeing: blurry, cloudy, or foggy vision; distortion of vision: ghost images, double images, or double outline of images; trouble seeing in dim light; fluctuation of vision; halos around lights, starbursts, difficulty with glare, objects looking different out of one eye versus the other, and difficulty with depth perception. None of these visual symptoms were reported at any time. The astronaut was asked to look out a porthole during the night time to find the brightest star easily visible. Then he evaluated the quality of the image of the star using each eye. The goal was to note any ghosting, doubling, flare, or rays off the star or rings or halos around the star. None of these symptoms were reported at any time. Visual disability

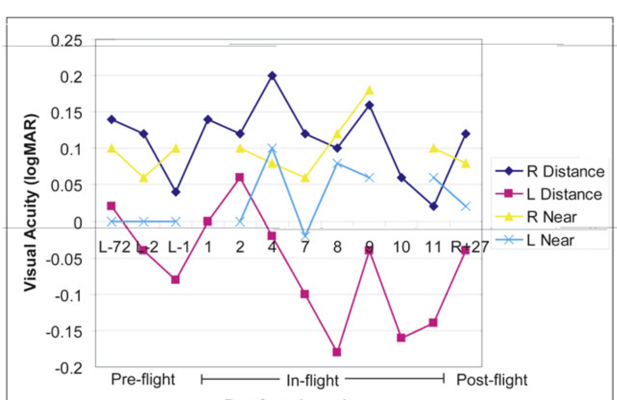

Figure 3. Distance and near visual acuity plotted against day relative to launch. Testing was performed 72 and 2 days prior to launch (L-72 and L-2 days), during the 12 days of the mission, and 27 days after returning to Earth (R+27 days). Visual acuity is given in logMAR form (20/20 = 0) and is fundamentally stable, although there is a suggestion of slight worsening during the first few days in space followed by a gradual improvement.

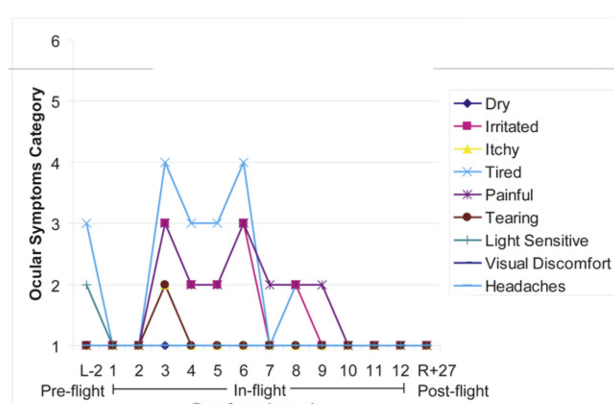

Figure 4. Responses to the ocular symptoms questionnaire, prior to (L-2 days), during (days 1 to 12), and after the flight (R +27 days). The astronaut experienced few symptoms, reporting tired eyes that were "a little troublesome" (category 4) and "slightly" (category 3) irritated or painful eyes during the flight. He reported no dry eyes, visual discomfort, or headaches attributable to vision at any stage.

questions were designed to detect a change in refractive error and included a reduced ability to read up close, read at arm's length, perform any tasks involving near vision (seeing up close), perform any tasks involving seeing at arm's length, and perform any tasks involving distance vision. No reduction in performance was noted during flight.

The return trip from the International Space Station to Earth occurred on day-12 post-launch and took fewer than 3.5 hours. Post-flight testing was performed 2 days and 27 days after landing (Return+2 and Return+27, respectively). At Return+2, ocular parameters were largely unchanged from the pre-flight examination including IOP (13 mm Hg in the right eye, 12.5 mm Hg in the left eye), cycloplegic refraction (−1.00 +1.00 D in the right eye, −0.50 +0.50 D in the left eye), keratometry (41.37/41.75 × 27 in the right eye, 41.75/42.00 × 163 in the left eye), corneal topography, and wavefront aberrations. LogMAR visual acuity and questionnaire data were not collected on this visit. At Return+27, all ocular parameters showed negligible change from the preflight examination including IOP (11 mm Hg in the right eye, 10 mm Hg in the left eye), CCT (510 μm in the right eye, 505 μm in the left eye), and cycloplegic refraction (−0.50 +1.25 × 20 in the right eye, −0.25 +0.75 × 150 in the left eye). LogMAR visual acuity and questionnaire data were collected on this visit (Figures 3 and 4).

DISCUSSION

Since the start of the Russian and American manned space programs, cosmonauts and astronauts have used glasses and contact lenses for the correction of refractive errors and presbyopia during space operations. Since glasses in a 1-G (Earth) environment are secured to the face largely by gravity, they can be difficult to correctly position in microgravity and are prone to fogging, especially during extravehicular activities (spacewalks). Contact lenses are commonly used but can be difficult to clean, store, and insert in the microgravity environment. As on Earth, contact lens use increases the risk for ulcerative keratitis that could prove devastating on a space mission. These mission-related difficulties with traditional methods to correct vision suggest refractive surgery as a practical alternative.

There has been a gradual evolution in the overall safety and effectiveness of laser vision correction using the excimer laser.[10–26] Initial optical zone diameters were relatively small (4.0 to 5.0 mm) and led to frequent reports of glare and halos around lights at night.[27] Larger optical zones reduced, but did not eliminate, the incidence of night-vision disturbances.[28] Wavefront-guided treatment profile further improved quality of vision and contrast sensitivity compared with previous types of surgery.[29,30] Although rare, visual and ocular surface symptoms may occur and, when severe, can cause visual disability[31]

The visual environment in space predisposes even a normal eye to glare and reduced contrast sensitivity. A previous inflight study performed on 23 space shuttle crew members with normal eyes reported evidence of reduced contrast sensitivity.[32] There is at least a 15% reduction of incoming solar radiation at the Earth's surface because of atmospheric absorption.[33] Thus, at an altitude of 220 miles, objects outside the International Space Station are much brighter under solar illumination than on Earth. Lighting conditions inside the International Space Station are suboptimal. During some portions of the International Space Station mission, the astronaut experienced a range in light intensity from the glare of sunlight to the blackness of space. Given that he had PRK in 1994 with a presumed 6.0 mm ablation zone, the astronaut had the potential for visual difficulties with exposure to this broad spectrum of lighting conditions. However, inflight he reported no change in visual ability from what he observed on Earth.

Although the astronaut's eyes were subjected to a wide spectrum of physiologic changes, no measurable changes in distance or near visual acuity, no hyperopic shift in refraction, or change in the amplitude of accommodation were documented during launch, 12 days of microgravity, and reentry. This information suggests that his post-PRK cornea was not significantly affected by these conditions. The astronaut did experience some ocular symptoms, most notably tired eyes reported as "slight but not troublesome" to "a little troublesome" during the first half of the flight. He also noted irritated and painful eyes to a "slight but not troublesome" level, and tearing and itchiness to a "perhaps very slightly" level. He reported no dry eyes, light sensitivity, visual discomfort, or headaches related to vision. These symptoms are probably best interpreted as very low level and possibly more related to sleep deprivation than any space-related ophthalmic changes or any refractive surgery–specific issue. The astronaut reported facial edema and pressure in his face, eyes, and sinuses within minutes of reaching microgravity. These symptoms are commonly reported and are thought to be caused by cephalad microgravity fluid shifts. He also noted several episodes of multiple pixel-like bright light flashes during the mission. The phenomenon of light flashes, thought to be caused by radiation, was observed by Apollo astronauts and has also been reported during space shuttle and International Space Station missions.[34–36] Although short-duration exposure to such radiation appears harmless, some evidence suggests that long-term exposure may lead to cataract formation.[37–39]

In the early days of the space program, potential space-flight candidates were subjected to extremely rigorous physical criteria for selection as an astronaut or cosmonaut. This rigid selection process largely eliminated the need for optical correction. Over time, the selection criteria has become less rigid and more inclusive as scientists, payload specialists, and other spaceflight participants make up a larger proportion of those flying in microgravity. The implementation of more relaxed eye standards has by necessity led to the need for glasses and contact lenses in space travelers. Since these devices have proven suboptimal for use in a microgravity environment, refractive surgery would appear to be a logical alternative. We believe that this case report suggests that PRK is a safe, effective, and well-tolerated procedure for use by astronauts during spaceflight.

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First author:
C. Robert Gibson, OD

Coastal Eye Associates, Webster, Texas, USA