Ocular Responses and Visual Performance after High-Acceleration Force Exposure

Ming-Ling Tsai, Chun-Cheng Liu, Yi-Chang Wu, Chib-Hung Wang, Pochuen Shieb, Da-Wen Lu, Jian-Ming Chen, and Chi-Ting Horng

PURPOSE. To evaluate ocular responses and visual performance after high-acceleration force exposure.

METHODS. Fourteen men were enrolled in the study. A human centrifuge was used to induce nine times the acceleration force in the head-to-toe (z-axis) direction (+9 Gz force). Visual performance was evaluated using the ETDRS (Early Treatment of Diabetic Retinopathy Study) visual chart, and contrast sensitivity (CS) was examined before and after centrifugation. Ocular responses were assessed with biomicroscopy and topographic mapping after gravitational stress.

RESULTS. Transient visual acuity reduction (0.02 ± 0.04 logMar vs. 0.19 ± 0.07 logMar VA; P < 0.05) and temporary ocular anterior segment reactions were observed immediately after centrifugation. These reactions included changes in corneal thickening (553.7 μm vs. 591.2 ± 20.6 μm; P < 0.05), increasing anterior chamber depth (ACD; 3.19 ± 0.26 mm vs. 4.53 ± 0.34 mm; P < 0.05), and pupillary enlargement (3.54 ± 0.73 mm vs. 5.76 ± 0.61 mm; P < 0.05). The increase in ACD continued for 15 minutes after exposure to acceleration (3.19 ± 0.26 mm vs. 4.39 ± 0.27 mm; P < 0.05). Pupillary dilation was noted both 15 (3.54 ± 0.73 mm vs. 5.56 ± 0.67 mm; P < 0.05) and 30 (5.47 ± 0.59 mm, P < 0.05) minutes after the gravitational stress. CS decreased significantly at low and medium spatial frequencies (1.5, 3, and 6 c/deg) and did not return to the baseline level by 30 minutes.

CONCLUSIONS. High-acceleration force may induce transient visual acuity reduction and temporary corneal thickening. Prolonged increase in ACD and pupillary dilation were also observed. The decrease in CS persisted for 30 minutes after centrifugation. The mechanisms underlying these observations are not clear, because there are no previous reports on this topic. Further studies are needed. (Invest Ophthalmol Vis Sci. 2009;50:4836–4839) DOI:10.1167/iovs.09-3500

Vision plays a critical role in humans undergoing high-acceleration movement. With increases in modern vehicle performance, problems associated with acceleration are becoming important.1,2 When an emergency occurs at high speed, visual performance is important to preventing further catastrophe because the response time is relatively short.1,2 Investigators in prior studies have reported that positive acceleration can cause grayout, blackout, and loss of peripheral vision.1,3,4 Many ocular reactions may also occur when the head is suddenly forced to stop or start moving or to turn rapidly. As the eye is forced to follow the movements of the head, this acceleration-deceleration-induced shearing force may induce ocular structure changes and even injuries.5,6 Because previous data are usually based on subjective descriptions and are not quantitative, it is important to clarify the influence of acceleration force on visual performance and ocular reactions. However, this issue has not been explored thoroughly because of the difficulty in designing experiments.

Recent advances in technology allow the human centrifuge to be used to elicit high-acceleration forces.4,7 The centrifuge is designed to improve the trainee’s learning experience during high-G-forces. The desired G-forces recommended for optimal training can be adjusted accurately by the instructor according to the trainee’s weight, which allows each subject to train under the same G-force influence.2,8

A corneal topography system (Orbscan II; Bausch & Lomb, Rochester, NY) can be used to evaluate objectively the ocular reaction after high G-force exposure. The system is a reliable ocular structure analyzer that uses a calibrated and scanning slit beam to access ocular anterior segment-related structures such as the cornea and to measure pupil size and anterior chamber depth (ACD) at the same time. It does not contact the ocular surface and thus avoids touching the corneal surface and disturbing the detected reading.9,10

The goal of this study was to investigate the influence of high-acceleration force on visual performance and ocular reactions. In this study, a human centrifuge was used to elicit an acceleration force set at nine times G-force in the head-to-toe z-axis direction (+9 Gz force). The influence of acceleration force on visual performance was evaluated by measuring visual acuity and contrast sensitivity (CS). The changes in ocular reactions were assessed by biomicroscopy, physical examinations, and corneal topography (Orbscan II; Bausch & Lomb).

MATERIALS AND METHODS

Fifteen men (mean age, 21.1 years) were enrolled in the study. Informed consent was obtained from each subject before participation. All experimental protocols were conducted in accordance with the Declaration of Helsinki. Ethical approval for this study was obtained from the institution review board. Subjects with any his-
Visual and Ocular Changes after High G-Force Exposure

Table 1. The Cornea-Related Parameters before and after Gravitational Stress

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before</th>
<th>Immediately After</th>
<th>After 15 min</th>
<th>After 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>44.52 ± 0.43</td>
<td>45.08 ± 0.63</td>
<td>45.21 ± 1.17</td>
<td>44.89 ± 1.31</td>
</tr>
<tr>
<td>Minimum</td>
<td>43.91 ± 0.67</td>
<td>44.57 ± 0.81</td>
<td>44.32 ± 0.61</td>
<td>44.21 ± 0.87</td>
</tr>
<tr>
<td>Anterior BFS (D)</td>
<td>43.23 ± 1.51</td>
<td>42.94 ± 1.32</td>
<td>42.98 ± 0.94</td>
<td>43.11 ± 1.34</td>
</tr>
<tr>
<td>Posterior BFS (D)</td>
<td>52.37 ± 2.03</td>
<td>52.02 ± 2.21</td>
<td>52.11 ± 0.97</td>
<td>52.29 ± 1.47</td>
</tr>
<tr>
<td>CCT (µm)</td>
<td>553.7 ± 21.7</td>
<td>591.2 ± 20.6*</td>
<td>567.4 ± 21.6</td>
<td>556.2 ± 23.6</td>
</tr>
</tbody>
</table>

n = 14 eyes.  
* Statistically significant difference (P < 0.05).

Results

One subject withdrew from the study because of nausea after the centrifugation. All data were collected from 14 eyes. Most of the ocular-related parameters, such as anterior BFS, posterior BFS, and Sim K, did not change significantly from before to after centrifugation. However, the CCT increased significantly immediately after centrifugation compared with the value before centrifugation (553.7 ± 21.7 vs. 591.2 ± 20.6, P < 0.05), but this was not maintained beyond 15 minutes after high gravitational stress (Table 1).

ACD increased considerably immediately after (3.19 ± 0.26 mm vs. 4.55 ± 0.34 mm, P < 0.05) and 15 minutes after (4.39 ± 0.27 mm, P < 0.05) +9-Gz force stress. ACD returned to the pretest value by 30 minutes after exposure to acceleration (3.24 ± 0.29, P > 0.05; Table 2).

PD enlarged significantly immediately after (3.54 ± 0.73 mm vs. 5.76 ± 0.61 mm, P < 0.05) and 15 minutes (5.56 ± 0.67 mm, P < 0.05) after centrifugation. PD remained enlarged 30 minutes after exposure to acceleration (5.47 ± 0.59 mm, P < 0.05; Table 3).

In the tests of visual performance, transient visual acuity decreased immediately after the gravitational stress (0.02 ± 0.04 vs. 0.19 ± 0.07, P < 0.05; Table 4). CS reduction was also observed at 30 minutes after exposure to acceleration, and significant depression of CS was found at low and medium frequencies. CS in the right eye decreased at 1.5 (P < 0.05), 3.0 (P < 0.05), and 6.0 cyc/deg (P < 0.05; Fig. 1). Refraction remained stable at 30 minutes after gravitational stress (Table 4). The Amsler grid examination revealed no particular finding such as metamorphopsia in any subject.

Throughout the experiment, ocular posterior segment revealed no specific observations. In addition, no particular ocular finding was noted such as hyphema, lens dislocation, or retinal hemorrhage.

Table 2. Anterior Chamber Depth before and after Gravitational Stress

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before</th>
<th>Immediately After</th>
<th>After 15 min</th>
<th>After 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACD (mm)</td>
<td>3.19 ± 0.26</td>
<td>4.53 ± 0.34*</td>
<td>4.39 ± 0.27*</td>
<td>3.24 ± 0.29</td>
</tr>
</tbody>
</table>

n = 14 eyes.  
* Statistically significant difference (P < 0.05).
In this study, we observed a 10% increase in CCT after +9-Gz force exposure. We assume that the transient hydrostatic pressure increase may explain this finding. The ocular anterior chamber in the eye is full of aqueous humor. An exposure to high gravity may increase hydrostatic pressure in the anterior chamber and increase the tendency for fluid to flow across the corneal endothelium into the stroma, which would increase the corneal thickness. The CCT returned to its initial value within 15 minutes, suggesting that the corneal endothelium was not compromised by high gravitational exposure, even at +9-Gz force. An interesting observation was that a 10% increase in CCT occurred without significant concomitant changes in the corneal curvature. Our data are consistent with those of Rom et al., who found no significant correlation between corneal thickness and curvature, even when the corneal thickness increases up to 16%.

PD increased significantly after high G-force exposure in our study. Before the stress, PD was 3.54 ± 0.73 mm, and the marked pupillary dilation persisted for 30 minutes after the stress. The size of the pupil is regulated by the autonomic nervous system, which is influenced by many environmental, physiological, and psychological factors. Previous studies show that gravitational stress can increase sympathetic tone to prevent body fluid shifting downward with gravity. This transient sympathetic tone elevation may account for the early pupil dilation immediately after centrifugation. However, an increase in sympathetic activity cannot clarify completely why the pupil enlargement persisted for 30 minutes. Tran et al. reported that high G-force exposure causes a persistent reduction in parasympathetic activity. This prolonged reduction in parasympathetic activity may also explain the persistent pupil enlargement after gravitational stress. Neurohormonal regulation is another possible explanation for this persistent pupil dilation. Gravitational stress increases the blood somatostatin concentration. Yamaji et al. found that somatostatin may induce mydriasis by attenuating cholinergic neurotransmitter release. Therefore, neurohormonal regulation may also be involved in this prolonged pupil enlargement.

In our experiment, the ACD increased immediately and 15 minutes after +9-Gz force exposure but returned to baseline within 30 minutes after gravitational stress. Pupil enlargement may explain the increase in ACD at 15 minutes after gravitational stress, but it cannot explain why the ACD returned to baseline when mydriasis persisted 30 minutes after centrifugation. We believe that the increase in hydrostatic pressure caused by the +9-Gz force explains this finding. The aqueous humor in the eye may shift toward the gravity direction under gravitational stress. When subjects are under high-gravity stress, the aqueous hydrostatic pressure in the anterior and posterior chambers may increase toward the gravity direction. Because the volume is greater in the anterior chamber than in the posterior chamber, the aqueous humor pressure is also greater in the anterior chamber during high G-force exposure. The greater hydrostatic pressure in the anterior chamber may push the iris toward the posterior chamber and cause the ACD to increase. At the same time, this iris diaphragm may rest on the lens surface and trap fluid in the anterior chamber. When the hydrostatic pressure is relieved, the trapped aqueous humor maintains the ACD, which may explain the prolonged deepening of the anterior chamber. The trapped aqueous humor drains with time, and the ACD returns to baseline. We also observed that the refractive power did not reveal a significant finding at 30 minutes after +9-Gz exposure. This observation suggests that axial length did not change at 30 minutes after gravitational stress. However, further research is necessary to confirm this finding.

In our study, visual acuity showed a transient reduction immediately after centrifugation and returned to baseline at 15 minutes. We assume that temporary corneal edema plays a role, because a study has shown that corneal edema can disturb visual acuity. However, the Amsler grid examination revealed no specific findings in our study, suggesting that the macular structure was not compromised even after the high G-force exposure. For clarification of our supposition, further study may be helpful, such as pinhole, potential acuity testing, and laser interferometry. Visual acuity is usually evaluated with the ETDRS visual chart, a basic method of evaluating visual performance by estimating the visual resolution of our supposition, further study may be helpful, such as pinhole, potential acuity testing, and laser interferometry. Visual acuity is usually evaluated with the ETDRS visual chart, a basic method of evaluating visual performance by estimating the visual resolution of objects and their surroundings. Visual acuity is usually evaluated with the ETDRS visual chart, a basic method of evaluating visual performance by estimating the visual resolution of objects and their surroundings. Visual acuity is usually evaluated with the ETDRS visual chart, a basic method of evaluating visual performance by estimating the visual resolution of objects and their surroundings.

**FIGURE 1. Mean CS before and after +9-Gz force exposure.**

<table>
<thead>
<tr>
<th>Cycle per degree</th>
<th>1.5</th>
<th>3.0</th>
<th>6.0</th>
<th>12.0</th>
<th>18.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast sensitivity</td>
<td>1.0</td>
<td>1.25</td>
<td>2.0</td>
<td>4.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Before centrifugation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 mins after centrifugation</td>
<td></td>
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</table>

**TABLE 4. Visual Acuity and Refraction before and after Gravitational Stress**

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>Immediately After</th>
<th>After 15 min</th>
<th>After 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA (logMAR)</td>
<td>0.02 ± 0.04</td>
<td>0.19 ± 0.07*</td>
<td>0.05 ± 0.06</td>
<td>0.04 ± 0.07</td>
</tr>
<tr>
<td>Refraction (D)</td>
<td>-0.37 ± 0.47</td>
<td>-0.51 ± 0.51</td>
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</table>

**TABLE 3. Pupillary Diameter before and after Gravitational Stress**

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>Immediately After</th>
<th>After 15 min</th>
<th>After 30 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD (mm)</td>
<td>3.54 ± 0.73</td>
<td>5.76 ± 0.61*</td>
<td>5.56 ± 0.67*</td>
<td>5.47 ± 0.59*</td>
</tr>
</tbody>
</table>

n = 14 eyes.

* Statistically significant difference (P < 0.05).
spatial frequency. It thus gives information on visual performance for a range of object scales.\textsuperscript{21}

In this investigation, we observed remarkable CS loss after gravitational stress and that more than 30 minutes was needed for recovery. Several ocular anterior chamber reactions observed in the study may account for this finding, including corneal clarity and pupillary mydriasis. Hess and Garner\textsuperscript{21} reported that corneal edema leads to depression of CS. Other researchers have also demonstrated that pupil mydriasis may compromise CS function.\textsuperscript{22,23} However, the changes of ocular anterior segment reaction cannot fully elucidate why the CS was significantly reduced at low and medium but not at high spatial frequency at 30 minutes after gravitational stress. Factors other than ocular anterior segment response are thought to explain this observation. We assume that the changes in neuroretinal function may play a role in this phenomenon. Ossard et al.\textsuperscript{24} have demonstrated that gravitational stress can cause body fluid to shift toward the lower body, which decreases ocular blood flow and leads to hypoxia. Several studies have reported that hypoxia may compromise neuroretinal function and lead to prolonged CS reduction.\textsuperscript{25–27} Visual acuity was coupled to changes in microcirculation in the retina such as retinal capillary density and the size of the free vascular zone (FAZ). In a past study, Arend et al.\textsuperscript{26} showed that CS is a more sensitive examination for detecting the change of microcirculation in retina. DiLeo et al.\textsuperscript{28} reported that hypoxia may affect magnocellular ganglion cells more severely than parvocellular ganglion cells. Magnocellular ganglion cells are more sensitive to low-contrast stimuli, whereas parvocellular ganglion cells are more sensitive to high-contrast stimuli.\textsuperscript{29} Therefore, they also reported that hypoxia may result in contrast losses, particularly at low and medium spatial frequency.\textsuperscript{28} Because parvocellular ganglion cells were affected less severely than magnocellular ganglion cells, Harris et al.\textsuperscript{30} showed that CS in a patient with minimal diabetic changes in the retina improved significantly, especially at high spatial frequencies, when the patient was subjected to hypoxia. In our study, the CS examination was performed at 30 minutes after gravitational stress. CS still was significantly reduced at low and medium spatial frequency at 30 minutes, perhaps because magnocellular ganglion cells are affected more severely than parvocellular ganglion cells during gravitational stress. Simultaneously, we observed that differences in CS were unremarkable with high special frequency, perhaps because parvocellular ganglion cells are affected less severely than magnocellular ganglion cells during gravitational stress.

In this study, we observed that high-acceleration force induces noteworthy ocular anterior segment reactions and compromises visual performance. There observations may assist individuals on flight or space missions in preparing for such visual phenomenon. However, these phenomena have not been studied thoroughly to date. Moreover, the effect of gravitational stress on neuroretinal structure and function, such as retinal thickness and cone cell function, has not been completely clarified. Further research is necessary.

References


