Acute effects of changes to the gravitational vector on the eye

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Running Head: Acute effects of changes to the gravity vector on the eye

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Abstract

Intraocular pressure (IOP) initially increases upon entering microgravity above seated baseline values. This has been attributed to a headward fluid shift increasing venous pressures in the head. The change in IOP exceeds changes measured immediately after moving from seated to supine postures on Earth, where a similar fluid shift is produced. Further, central venous and cerebrospinal fluid pressures are at or below supine levels when measured initially upon entering microgravity, unlike when moving from seated to supine postures on Earth where these pressures increase. To investigate the effects of altering gravitational forces on the eye, we made ocular measurements on 24 subjects (13 male, 11 female) in the seated, supine, and prone positions in the laboratory, as well as upon entering microgravity during parabolic flight. IOP in microgravity (16.3 ± 2.7 mmHg) was elevated significantly above seated (11.5 ± 2.0 mmHg) and supine values (13.7 ± 3.0 mmHg), and was significantly less than prone pressure (20.3 ± 2.6 mmHg). All p-values are less than 0.001. Choroidal area significantly increased in microgravity (p < 0.007) compared to the seated (increase of 0.09 ± 0.1 mm²) and supine values (increase of 0.06 ± 0.09 mm²). IOP results are consistent with the hypothesis that hydrostatic gradients affect IOP, and may explain how IOP can increase beyond supine values in microgravity when central venous and intracranial pressure do not. Understanding gravitational effects on the eye may help develop hypotheses for how microgravity-induced visual changes develop.

Key Words: Visual impairment and intracranial pressure; Intraocular pressure; Choroidal area; Hydrostatic gradient
Introduction

Understanding the immediate response of the eye to alterations in the gravity vector is important, since it likely initiates the ocular adaptation to prolonged microgravity exposure. Compared to both the upright and supine positions on Earth, intraocular pressure (IOP) is increased initially upon entering microgravity (6, 8-10, 21, 22). IOP increases 50-90% shortly after entering microgravity (11, 21). For example, Draeger et al. showed IOP increased 71% from 14 ± 1 seated to 24 ± 2 mmHg in flight (11) and Mader et al. showed a 58% increase from 12 ± 1 seated to 19 ± 1 mmHg in parabolic flight (21). On Earth, however, going from upright to supine causes IOP to increase initially by only approximately 10-20 % (18, 24). The additional increase in microgravity has been attributed to a cephalad fluid shift caused by removing hydrostatic gradients (10, 22). Underlying the assumption that a fluid shift in microgravity raises IOP above supine levels is the presumption that the fluid shift in microgravity elevates ocular venous pressures (episcleral, vortex, and choroidal) well above supine values (6). Two lines of evidence, however, suggest this is not the case.

Central venous pressure (CVP) is at or below supine values when measured directly during the transition to microgravity during spaceflight (4, 5). Intraocular pressure is determined not only by the balance between the production and outflow facility of aqueous humor, but also by episcleral venous pressure. Since CVP is an important determinant of venous pressures in the head, including ocular venous pressures (24), episcleral venous pressure would also not be expected to exceed supine levels in microgravity unless some major obstruction to venous outflow from the head existed. Also, recently, both CVP and cerebrospinal fluid pressure were measured during short-term parabolic flight microgravity exposure in patients with Ommaya...
reservoirs, and these pressures were not elevated above supine values in weightlessness (19).

These measures of central venous and intracranial pressures in microgravity have been done immediately upon entering microgravity with direct, highly accurate techniques. Little evidence exists to suggest that pressures in the head are elevated above supine values upon entering microgravity. Instead, cranial pressures are likely at or below supine levels during the first few minutes of flight.

These data indicate that the IOP elevations observed in microgravity present a paradox. How can IOP be elevated beyond supine levels in space, when current data suggest that cranial venous pressures are unlikely to be elevated above supine values? To address this question, the effects of gravity on the eye need to be understood. Microgravity results should be compared to both a seated and supine baseline on Earth. Comparing microgravity results to a supine baseline, focuses on gravitational effects on the eye, since both microgravity and the supine posture include a cephalad fluid shift. It has not been possible to evaluate whether the changes in microgravity differ from supine values because previous studies typically used either a seated baseline or didn’t report the posture used for baseline measurements (11, 21). Also, although moving from the upright to supine position and moving from the upright position to microgravity each produce a fluid shift (16), microgravity exposure additionally removes hydrostatic gradients throughout the body, equalizing fluid pressures. In other words, microgravity exposure includes effects due to both removing hydrostatic gradients and shifting fluid to the head.

To assess the effects that changing the direction of hydrostatic gradients might have, a prone baseline for ocular measurements is also important. In the prone position, the direction of the
gravitational field is reversed compared to the supine position. In the prone posture there is not a significant gravitationally-induced fluid shift compared to supine (30). Parameters such as CVP and CSF pressure can be elevated when moving between the supine and prone postures (28, 32). But, the magnitude of these changes when going from supine to prone is significantly less than the increases seen when moving from seated to supine. For example, ICP may change approximately 3 mmHg between supine and prone (23), while ICP may be negative when seated and increase to between 5-15 mmHg supine. The primary change when moving from the supine to prone position is the direction of the force of gravity acting on the fluids and tissues in the head.

With these three baseline measurements (upright, supine, and prone) microgravity results can be put into context. Moving from the upright to supine position changes the direction of gravitational gradients and includes a fluid shift, while moving from the supine to prone position changes the direction of the gravitational gradients, but does not include a significant fluid shift (30). In this study, we made ocular measurements in the seated, supine, prone, and microgravity conditions. We hypothesized that changes in hydrostatic gradients would influence IOP both on Earth and in microgravity. We hypothesized that IOP would be elevated in the prone position compared to supine, and that IOP in microgravity would be in between the supine and prone values. We further hypothesized that these changes would be reflected in changes in ocular geometry and choroidal area. These data are important to understand the acute effects of changes in the gravity vector on the eye, which has implications for Earth based applications, such as ocular and spinal surgery in various body positions (24). Understanding the immediate changes
caused by altering the gravity vector will allow investigation into the subsequent ocular
adaptation to microgravity.

**Methods**

*Subjects:* Data were collected in two sessions corresponding to two parabolic flight campaigns. All human used protocols were approved by the Internal Review Board (IRB) at Dartmouth College and NASA’s IRB and informed written consent was obtained from all subjects. Human subjects ages 18-65 years old were recruited for the study. A total of 24 subjects participated (13 male, 11 female) with a mean age of 38 years (standard deviation = 13 years). Subjects all had an expanded FAA class III physical examination to ensure overall good health and lack of ocular problems prior to data collection.

*Ground-Based Posture Protocol:* Subjects had measurements taken in 3 1G postures – seated upright, supine, and prone. Subjects rotated through each ground-based posture in a randomized order with at least 5 minutes in the upright position between each to allow subjects to return to baseline conditions. A custom-built stand, shown in Figure 1A, allowed all ocular equipment to be mounted horizontally and be rotated to accommodate both supine and prone measurements. The subjects had their measurements recorded while on a medical tilt table with an open-faced headrest for the prone position to maintain a straight neck, Figure 1B. Measurements began approximately 1 minute after each posture was assumed. The ground-based posture measurements occurred within 24 hours of parabolic flight. Due to technical difficulties, however, two subjects had their ground-based measures recorded 2 weeks post-flight. Since the subjects all took scopolamine for the microgravity portion of the study, all the ground-based measurements were also taken after the subjects had taken the same dose of scopolamine to
maintain a consistent protocol across all experimental conditions. Measurement began an hour after subjects were administered scopolamine and were completed within 2.5 hours, the same dose window used for parabolic flight.

**Microgravity Protocol:** Microgravity measures were taken in the seated position aboard a NASA-commissioned aircraft, coordinated with the Reduced Gravity Office at Johnson Space Center, Houston TX. The aircraft flew a parabolic flight pattern, generating ~15-25 seconds of microgravity per parabola. Data were collected within this timeframe on 4 consecutive microgravity exposures per subject per variable. The aircraft cabin was maintained at a normal atmospheric composition at a pressure of 6000 ft., or approximately 11.8 psi. Scopolamine, adjusted for body weight, was given to each subject to combat motion sickness prior to the microgravity flight.

**IOP:** All measures were made using a Perkins tonometer (Mk2, Haag-Streit UK, Essex, United Kingdom) by a trained ophthalmologic technician. Eyes were anaesthetized using fluorescein sodium and benoxinate hydrochloride (0.25%/0.4%). Five repeated IOP measurements in each 1-G posture and 4 repeated measures from the same eye in microgravity were averaged to determine each subject’s IOP in each posture.

**Optical Biometry:** An optical biometer (Lenstar 900, Haag-Streit, Inc., Koeniz, Switzerland) was used to measure axial length, lens thickness, aqueous depth, and corneal thickness (Figure 2) on the right eye. Measures were repeated 5 times in each posture during 1G and as many times as could be completed in microgravity due to the challenging measurement environment.

**Optical Coherence Tomography:** Choroidal area was measured using optical coherence tomography (OCT) (Spectralis OCT, Heidelberg Engineering, Inc., Heidelberg, Germany) on the right eye. Images of the choroid were taken using a single line scan passing through the center of
the optic nerve and center of the fovea, as shown in Figure 3. Choroidal area was determined by outlining the boundaries of the choroid using the Spectralis software. The internal boundary began at the optic nerve and the external boundary was taken as 3000μm from the fovea to ensure the scans were consistent across all posture conditions for a subject. Three independent observers analyzed each image and the correlation coefficient between the observers was calculated to determine variability. If there was agreement between the datasets (R > 0.9) the observations were averaged and analyzed for postural effects.

Statistics: A repeated-measures ANOVA was used to measure the main effect of posture for each of the measures (SPSS, IBM Corporation, Armonk, New York or Matlab 2015a, Mathworks, Natick, MA). When the main effect was significant, a Bonferroni post-hoc test was done to determine any significant differences between postures.

Results

Tonometry: Intraocular Pressure

Intraocular pressure (IOP) was measured on 24 subjects (13 male, 11 female). Fifteen subjects had IOP measured in the right eye (OD), while 9 subjects had IOP measured in their left eye (OS). Figure 4 shows the results of posture and microgravity on IOP in mmHg. The value for each position is as follows (mean ± standard deviation): upright = 11.5 ± 2.0 (OD = 11.4 ± 1.9, OS = 11.7 ± 1.9); supine = 13.7 ± 3.0 (OD = 15.3 ± 2.3, OS = 11.0 ± 1.7); prone = 20.3 ± 2.6 (OD = 21.1 ± 1.9, OS = 18.8 ± 3.0); and microgravity = 16.3 ± 2.7 (OD = 16.3 ± 2.6, OS = 16.1 ± 2.6). There was a significant main effect for posture (F = 77, p = 0.01). All pairwise comparisons were significant (p < 0.001).

Biometry: Ocular Geometric Parameters
Biometry was completed on 12 subjects (5 male, 7 female) in the ground-based postures and in parabolic flight. These measurements were challenging to make in microgravity due to vibration and mechanical issues. Therefore, this measurement was not taken on all subjects and the total number of measurements taken and averaged varied from 1 to 6 times. The mean and standard deviation of axial length, aqueous depth, cornea thickness, and lens thickness are shown in Table 1. A significant main effect on experimental condition was found for aqueous depth \((F = 5.37, p = 0.004)\), with pairwise significant differences between supine and prone \((p = 0.003)\). No main effect was found for axial length \((F = 1.13, p = 0.35)\), lens thickness \((F = 0.83, p = 0.60)\), and cornea thickness \((F = 1.29, p = 0.29)\).

Optical Coherence Tomography: Choroidal Area

OCT was completed on 20 subjects (11 male, 9 female). OCT images were analyzed by three observers with a correlation coefficient \(R > 0.9\). There was a significant main effect for differences across experimental conditions \((F = 8.4, p = 0.0001)\). The average seated choroid area was \(1.82 \pm 0.4 \text{ mm}^2\). Figure 5 shows a single subject as analyzed by a single observer in all test conditions. This subject had one of the largest changes between postures. Due to anatomical individual variability and the small nature of choroidal area changes, data are presented as changes from an individual’s seated baseline. The change in choroidal area from baseline is shown in Figure 6. The average increase from seated to each condition in \(\text{mm}^2\) was \((\text{mean} \pm \text{standard deviation}): \text{supine} = 0.03 \pm 0.06; \text{prone} = 0.05 \pm 0.07; \text{and microgravity} = 0.09 \pm 0.1\).

Choroid area in prone and microgravity were statistically greater than baseline \((p < 0.006)\). Additionally, choroid area in microgravity was statistically greater than supine \((p = 0.007)\). There were no other significant differences between postures.
Discussion

We found IOP in microgravity was significantly greater than supine and significantly less than prone values, confirming our hypothesis that gravity can affect IOP independent of a significant fluid shift. IOP values above seated baseline levels upon entering into microgravity have been reported elsewhere, and have been attributed to a cephalad fluid shift increasing venous pressures in the head (6, 9, 10, 21, 22). Our data are the first to indicate hydrostatic gradients may also influence IOP beyond what might be expected due to fluid shift. Our data also confirm the hypothesis that gravitational effects are reflected in changes to ocular geometry and choroid area. Aqueous depth showed a significantly change with posture. Choroidal area increased significantly in microgravity compared to the seated and supine postures. These are, to the authors’ knowledge, the first published data reporting choroidal area in microgravity.

Hydrostatic Gradients and Intraocular Pressure

We hypothesized that changes in hydrostatic gradients would alter IOP independent from effects due to fluid shifts. Moving from the supine to prone position does not produce the fluid shift seen when moving from upright to supine (30). Also, the fluid shift is time dependent (13) while the changes measured in this study are acute. Thus, a fluid shift cannot explain significant differences between the supine and prone postures. Moving from supine to prone, however, does change the direction of gravitational forces acting on the body, and alters hydrostatic gradients on fluids immediately. At the point of measurement, the hydrostatic column acting on the anterior cornea surface will contribute to IOP measurement. In the supine position the anterior cornea will be at the top of a hydrostatic column of fluid, whereas in prone it will be at the bottom and there will be the pressure from the hydrostatic column.
The changes in hydrostatic gradients in each position are summarized in Table 2. In the seated, upright posture, a hydrostatic column extends from eye level to the point mid-neck where the jugular vein collapses (27). Upon lying down, there is a hydrostatic column in the sagittal plane, extending from the eye to the cavernous sinus. Since fluid columns in the head are in a closed space—the skull—the hydrostatic column is likely to have a point near the center where pressure does not change when the body changes from the supine to prone position (sometimes termed the hydrostatic indifference point). This is the reference point for hydrostatic pressures in the vessels in the supine and prone postures.

The vessels serving the eye experience hydrostatic gradients. Episcleral venous pressure (EVP) (illustrated in Figure 7C) is one of the primary determinants of IOP as described by the Goldman equation:

\[
P_o = \frac{(F-U)}{C} + P_v
\]

where \( P_o \) is intraocular pressure, \( F \) is the rate of aqueous flow through the anterior chamber, \( U \) is the rate of outflow facility leaving the eye through the uveoscleral outflow pathway, \( C \) is trabecular outflow facility, and \( P_v \) is EVP (3). Changes in EVP have a profound effect on IOP (24). While supine, the hydrostatic contribution to venous pressure would be greatest at the back of the head. In the prone position, this situation would be reversed. The highest hydrostatic contribution to venous pressure would be at the anterior part of the head. The magnitude of change based on the hydrostatic column for the average adult head is approximately 5 centimeters from the reference pressure, which is a combined 10 cm hydrostatic column difference going from supine to prone, or 7.5 mmHg. This change is in the same range as the
IOP pressure changes seen in our data, where the difference between supine and prone values is 6.6 mmHg.

In microgravity, hydrostatic gradients on fluids are removed instantaneously. Venous pressures would equalize to the reference pressure throughout the head and EVP may be at an intermediate value between the supine and prone values. The IOP measured in microgravity in this study was significantly greater than supine and significantly less than prone, consistent with this hypothesis. Furthermore, because the eye is a fluid-filled structure, it also has hydrostatic gradients within the aqueous and vitreous humor. In microgravity, pressure becomes uniform across the length of the eye (i.e. IOP at the cornea and retinal surface are the same) due to Pascal’s principle. So, even if fluid flow into and out of the eye were held static, upon entering microgravity IOP measured at the corneal surface would be elevated beyond supine values (i.e. the change in IOP at the corneal surface due to hydrostatic effects would be eliminated). Thus, IOP may be elevated in microgravity compared to seated baselines, despite venous pressures being at or below supine values. The relative change between seated, supine, and prone venous pressure from alterations in hydrostatic gradients affect IOP measurements, even if overall mean venous pressure in the head has not changed or has decreased compared to supine values.

The IOP changes seen in this study are not likely due to the measurement technique. The Perkins tonometer is a hand-held applanation tonometer developed specifically for measuring subjects in any posture (25). It has a spring-counterweight system that compensates for gravity when measurements are made in different orientations (12). The root mean square difference between the Perkins and the gold standard Goldmann applanation tonometer is 1.4 mmHg in the seated
position (12) with a potential negative bias of 1 mmHg in the seated position (33) and 1.8 mmHg in the supine position (1). Since our results focus on the change of IOP with changes in posture, this nulls any bias of absolute IOP values from the Goldmann standard. Changes in altitude do not produce an immediate change in IOP, although IOP has been noted to decrease slightly after 2 hours at a cabin altitude of 8000 feet (2). Our IOP measures were usually taken early in the flight, and even if altitude did cause a slightly decrease in IOP over time, this is opposite to the significant increase in IOP we measured.

Biometry: Ocular Geometric Parameters

Aqueous depth changed significantly between supine and prone postures by shortening in the prone position and lengthening in the supine position. This is consistent with shifting of the lens iris diaphragm and hydrostatic loading in the anterior and posterior chambers. Axial length showed trends anticipated based on gravitational loading, with a change in hydrostatic load in the aqueous and vitreous humor causing compression (supine) or expansion (prone) of the globe respectively. The biometry data collected in microgravity varied by subject due to the challenging environment in which the measures were collected. Overall, axial length shortened the most in the microgravity, but the standard deviation of this measurement was large and the change was not statistically significant. A decrease in axial length may be expected due to tissue offloading causing the eye to return to its most spherical shape. Cornea and lens thickness measurements were not significantly different and were not expected to change acutely under these experimental conditions.

Optical Coherence Tomography: Choroidal Area
Minor changes in choroidal volume can have profound effects on IOP (17). A small increase in choroidal blood volume can dramatically increase IOP. On the other hand, an increase in IOP can compress the choroid, whereas a decrease in IOP can lead to choroidal expansion (in ocular hypotony, for example). Saeedi et al. reported a 1.7% increase in choroid thickness for -1 mmHg change in IOP (29). Usually, the two are closely linked, either in direct or inverse relationship depending on the driving mechanism of change between the two.

Choroidal area was greatest in microgravity compared to all other postures. This increased choroidal area might be expected to be associated with the highest IOP, but in fact IOP was highest in the prone position. These data suggest that other factors may be influencing the relationship between choroidal area and IOP. Loss of tissue weight (Figure 7A), or effects on aqueous humor drainage pathways may affect this relationship. In microgravity, the weight of the tissue is removed, which might allow the choroid to expand at lower venous pressure than in either the prone and supine positions. Also, the hydrostatic pressures in the episcleral vein and in the aqueous drainage pathways may be highest in the prone position, which could impede aqueous outflow and thereby increase IOP.

Potential mechanisms for gravitational effects on IOP and choroidal area

Altering the gravity vector may affect hydrostatic gradients, tissue weight, and aqueous humor dynamics, which could subsequently induce changes in IOP and choroidal area. This is illustrated in Figure 7, which shows an eye in the prone position. Although the relative contribution of these changes cannot be quantified with the data collected in this experiment, these factors are included to provide context to the integrated nature of ocular changes.
Gravitational forces act on tissues giving them weight. On Earth, this effect is seen when the weight of the fetus obstructs venous flow in pregnant women when they are supine (20), or the weight of neck tissues obstructs the airway in patients with sleep apnea (26). In the prone position, for example, the fatty tissue in the ocular orbit may push against the back of the eye (Figure 7A). Similarly, the weight of the aqueous and vitreous humor could push on the lens in the prone position. This may cause the lens-iris diaphragm to shift forward, potentially narrowing the angle where the cornea and iris meet, affecting aqueous outflow through the trabecular mesh (this possibility is suggested in our data with a trend decreased anterior chamber depth in the prone position), shown in Figure 7C. Humor dynamics influence IOP, as shown in the Goldman equation, but limited data exist on the influence of posture on production, and drainage through both the trabecular and uveoscleral pathways. It is known, however, that production and absorption are pressure dependent (15, 24). Therefore, it is possible that the removal of hydrostatic gradients in microgravity may have an effect on aqueous humor dynamics that could be reflected as an increase in IOP. Finally, as shown in Figure 7A, cerebrospinal fluid (CSF) pressure through the optic nerve sheath can cause additional loading at the back of the eye. Although this is hypothesized as the cause of ocular vision changes for astronauts in long duration spaceflight, CSF pressure upon entering microgravity is lower compared to the supine position (19).

Limitations

Although we were able to make a comprehensive set of ocular measures in the eye, we did not measure episcleral venous, ophthalmic vein or intracranial pressures in this study. Accordingly,
our conclusions about venous pressures within the head are derived from other studies. In the absence of direct measures of venous pressures in the eye and head integrated with other ocular measures, it is not possible to determine definitely the mechanism for elevated IOP in microgravity. Also, it is not known what effect parabolic flight that includes the transition between 1.8 and 0 G may have on each of our measures. Nevertheless, these data are important since they show that several potential mechanisms could explain an elevated IOP in space (compared to supine values), without invoking an increase in venous pressures in the head above supine values. Changes due to hydrostatic gradients provide a plausible explanation while remaining consistent with known effects of microgravity exposure on CVP and cerebrospinal fluid pressure (4, 5, 19).

Due to the logistics of the parabolic flight campaign, there is a trade-off between collecting baselines within 24 hours of parabolic flight data to take measures as close to flight as possible, as opposed to collecting data at the same time of day, but a week apart. In this study we chose to collect data within 24 hours to have the baseline measurements made as close to the flight as possible. As a result, diurnal variation could not be accounted for. Average IOP diurnal variation is 5 mmHg in normal eyes (7).

Conclusion

Our results show that upon entering microgravity, IOP is elevated above both seated and supine levels obtained at 1G. Additionally, we show that IOP is not elevated above prone values, consistent with the hypothesis that IOP is driven not only by fluid shifts, but also by changes in hydrostatic gradients produced by changes in the direction of the gravity vector. This provides an
explanation for how IOP may increase beyond supine levels despite evidence indicating that venous pressure and intracranial pressure are not elevated above supine levels upon entering microgravity.

In microgravity, we show an increase in choroidal area despite venous pressures that are likely at or below supine levels. There may be additional factors influencing these measures, such as effects on aqueous humor dynamics and tissue weight. Aqueous depth changes significantly when going from supine to prone, while axial length shows trends consistent with tissue and hydrostatic loading. Due to the integrated nature of the eye’s physiology, further measurements are needed, and a complete understanding may require numerical modeling. Overall, the data suggest that microgravity exposure creates a unique physiological environment, and that microgravity findings cannot be easily extrapolated from terrestrial results. Measuring the immediate changes to the eye by transitioning to microgravity allows us to evaluate the stimulus for ocular adaptation to the space environment. These data have additional implications beyond the field of spaceflight where postural effects on the eye are important to account for, such as during ocular or spinal surgery.

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References


Figure Legends

Figure 1. Custom stand that allows detailed ocular measures to be conducted in any orientation. 
A) Schematic of the stand upon which hardware is mounted. B) Subject in supine position for 
OCT measure.

Figure 2. The geometry of the ocular globe was measured with a laser optical biometer to 
determine axial length (distance from A to E), lens thickness (B to C), aqueous depth (C to E), 
and cornea thickness (D to E).

Figure 3. A single line scan for each subject was taken in each posture through the optic nerve 
and fovea. Choroidal area was bounded by the optic nerve and 3000 μm distance from the fovea. 
Choroidal images are shown for two different subjects in supine (top) and upright (bottom) to 
show methodology and individual variability. Areas were analyzed by three independent 
observers and combined for analysis.

Figure 4. Intraocular pressure in each of the postural conditions and microgravity. For pairwise 
comparisons, ** indicates the condition was significantly different (p<0.001) from each of the 
other conditions.

Figure 5. Choroid area for a single subject in all experimental conditions as analyzed by a single 
observer. Anatomical variability across subjects is large. Although choroid area changes are 
small, minor changes can have a profound effect on the eye.
Figure 6. Difference in choroidal area from seated baseline (mean and standard deviation) of 20 subjects. Prone and microgravity were statistically different from baseline (p<0.006), while microgravity was statistically different from the supine position (p = 0.007).

Figure 7. Ocular globe and orbit in the prone position. Gravity may influence the eye through several different mechanisms. A) Hydrostatic contributions to cerebrospinal fluid pressure in the subarachnoid space of the optic nerve sheath can increase pressure against the back of the eye (14). Similarly, tissue weight may push against the sclera in the prone position. Hydrostatic pressure in the vasculature perfusing the choroid could cause it to become engorged, which in turn may cause a significant increase in IOP (17). B) A hydrostatic gradient in the episcleral veins affects IOP as seen in the Goldman Equation (1). C) IOP measured at the corneal surface is influenced by hydrostatic gradients in the aqueous/vitreous humor. In the prone position, the hydrostatic pressure is greatest at the cornea, in contrast to the supine position where it is lowest at the cornea. Aqueous humor dynamics may also be altered by changes in intraocular pressure both at the production site in the ciliary body and drainage through the trabecular mesh and uveoscleral pathways (15).
Table 1. Average changes from seated baseline of ocular geometry.

<table>
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<tr>
<th></th>
<th>Seated</th>
<th>Δ Supine</th>
<th>Δ Prone</th>
<th>Δ MicroG</th>
<th>p</th>
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<tr>
<td>Axial Length (mm)</td>
<td>24 (1)</td>
<td>-0.002 (0.02)</td>
<td>0.01 (0.03)</td>
<td>-0.01 (0.04)</td>
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<td>Lens Thickness (mm)</td>
<td>3.8 (0.4)</td>
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<td>Aqueous Depth (mm)*</td>
<td>3.2 (0.4)</td>
<td>0.01 (0.04)</td>
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<td>-0.03 (0.03)</td>
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<td>Cornea (μm)</td>
<td>560 (50)</td>
<td>-0.8 (3)</td>
<td>-1.7 (4)</td>
<td>1.8 (8)</td>
<td>0.29</td>
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Values are means ± standard deviation. The p-value is given for repeated measures ANOVA on postural effects. * indicates significance, α < 0.05.
Table 2: Short-Term Effects of Posture and Microgravity.

<table>
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<th>Upright</th>
<th>Supine</th>
<th>Prone</th>
<th>Microgravity</th>
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<td>hydrostatic</td>
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<td>column</td>
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<td>IOP (mmHg)</td>
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<td>13.7 ± 3.0</td>
<td>20.3 ± 2.6</td>
<td>16.3 ± 2.7</td>
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<td>( \Delta ) Choroid (mm(^2))</td>
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<td>(estimated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVP (mmHg)</td>
<td></td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>(from literature)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVP (mmHg)</td>
<td>9</td>
<td>10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(from literature)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid Shift</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tissue Loading</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

The IOP and choroid area change values are data from this experiment. The hydrostatic column length for supine and prone are estimates based on average adult cranial venous anatomy. The hydrostatic column height for upright is from Qvarlander et al. (27) and is based on the vertical distance from the eye to the location of internal jugular collapse. The central venous pressure (CVP) data are from Buckey (4) with the assumption that CVP does not change between supine and prone. Note that CVP is typically measured clinically in the supine position. The episcleral
vein pressure (EVP) data for upright and supine are from Sultan and Blondeau (31). Note that EVP is typically measured upright.
<table>
<thead>
<tr>
<th></th>
<th>Seated</th>
<th>Δ Supine</th>
<th>Δ Prone</th>
<th>Δ MicroG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Length (mm)</td>
<td>24 (1)</td>
<td>-0.002 (0.02)</td>
<td>0.01 (0.03)</td>
<td>-0.01 (0.04)</td>
</tr>
<tr>
<td>Lens Thickness (mm)</td>
<td>3.8 (0.4)</td>
<td>0.001 (0.03)</td>
<td>-0.007 (0.1)</td>
<td>-0.03 (0.1)</td>
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<tr>
<td>Aqueous Depth (mm)*</td>
<td>3.2 (0.4)</td>
<td>0.01 (0.04)</td>
<td>-0.03 (0.4)</td>
<td>-0.03 (0.03)</td>
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<tr>
<td>Cornea Thickness (µm)</td>
<td>560 (50)</td>
<td>-0.8 (3)</td>
<td>-1.7 (4)</td>
<td>1.8 (8)</td>
</tr>
<tr>
<td></td>
<td>Upright</td>
<td>Supine</td>
<td>Prone</td>
<td>Microgravity</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------</td>
<td>--------</td>
<td>-------</td>
<td>--------------</td>
</tr>
<tr>
<td>Arrows indicate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>approximate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydrostatic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>column</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IOP (mmHg)</td>
<td>$11.5 \pm 2.0$</td>
<td>$13.7 \pm 3.0$</td>
<td>$20.3 \pm 2.6$</td>
<td>$16.3 \pm 2.7$</td>
</tr>
<tr>
<td>$\Delta$Choroid (mm$^2$)</td>
<td>Reference</td>
<td>$+0.03 \pm 0.06$</td>
<td>$+0.05 \pm 0.07$</td>
<td>$+0.09 \pm 0.1$</td>
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<tr>
<td>Hydrostatic</td>
<td>-10</td>
<td>-5</td>
<td>+5</td>
<td>0</td>
</tr>
<tr>
<td>Column (cm) (estimated)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CVP (mmHg) (from literature)</td>
<td>-</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
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<td>9</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Seated
2.01 mm²

Supine
2.10 mm²

Prone
2.15 mm²

Microgravity
2.40 mm²