**Balance Control in Glaucoma**

Aachal Kotecha,1,2 Greg Richardson,1 Reena Chopra,1 Rachel T. A. Faby,1 David F. Garway-Heath,2 and Gary S. Rubin1,2

**PURPOSE.** To examine postural stability in glaucoma patients and subjects with no ocular disease.

**METHODS.** Twenty-four glaucoma (G) and 24 control (C) subjects participated (mean age [SD] G: 65.9 [5.5] years; C: 68.3 [5.2] years). Postural stability was measured using a force-balance platform under four conditions: eyes open/closed standing on a firm surface and eyes open/closed on a foam surface. Average magnitude of center of foot pressure displacement (root mean square [RMS]) was calculated in the anteroposterior (AP) direction. The Romberg Quotient (RQ) was used to evaluate the visual contribution to balance. The difference in sway between firm and foam standing evaluated the relative somatosensory contribution to balance. The binocular mean deviation (BinMD) score was calculated from Humphrey 24-2 SITA strategy tests.

**RESULTS.** Glaucoma patients had a lower visual contribution to sway (AP RQ, G = 1.65 [0.44]; AP RQ, C = 2.25 [0.53], P = 0.0001), and higher relative somatosensory contribution to sway (change in AP RMS eyes open “firm” to “foam” standing: G = 4.12 [1.85] mm, C = 2.22 [2.04] mm, P = 0.002). BinMD was a significant predictor of balance (AP RQ versus BinMD β-coefficient = 0.58, P = 0.0001; change in AP RMS [eyes open “firm” to “foam”] versus BinMD β-coefficient = –0.35, P = 0.02).

**CONCLUSIONS.** Glaucoma patients display differences in their visual and somatosensory contributions to quiet standing balance compared with control subjects, associated with the degree of binocular visual field loss. This suggests that balance control may be compromised in this patient group. ([Invest Ophthalmol Vis Sci. 2012;53:7795–7801] DOI:10.1167/iovs.12-10866)

Postural stability is maintained through a complex interaction of vestibular, somatosensory, and visual inputs. Vision is important not only to detect trip hazards but also to facilitate proprioceptive feedback, providing the brain with continually updated information regarding the position and movements of body in relation to its environment. Studies have shown that elderly people are more dependent on vision for postural stability than their younger counterparts, particularly in more challenging environments. This may be due to an age-related decline in proprioceptive function, musculoskeletal coordination, and neuronal integration of information, disturbing balance control in older individuals. Thus, the risk of falling in older adults is exacerbated in the presence of ophthalmic disease because this will diminish the visual input required to maintain balance.

Glaucoma is the most common cause of irreversible visual impairment worldwide, increasing in prevalence with advancing age. The condition leads to a characteristic reduction in the visual field (VF), with good central visual acuity often maintained until the later stages of the disease. Patients with glaucoma display difficulties in performing tasks of everyday living, even at early stages of the disease. Glaucoma has been shown to be associated with difficulties in mobility and is associated with an increased risk of falling. Recent work has suggested that glaucoma patients with defects in their inferior VF are at a greater risk of falling than those with VF defects elsewhere.

It has been shown that decreased postural stability during upright stance is associated with an increased risk of falling. To date, two studies have evaluated postural stability in patients with glaucoma. Shabana et al. assessed postural stability using a force-balance platform in a group of patients with primary open-angle glaucoma and age-similar controls. They found no significant differences in postural stability between groups. However, their glaucoma patients displayed a reduced visual contribution to postural stability and showed an apparent increase in their somatosensory input to balance compared with the control group. In the second study by Black and colleagues, a cohort of glaucoma subjects was examined using a swaymeter to assess body displacement of the trunk. Their results showed that the worse the visual field defect, the greater the body sway. Their study suggested that older patients with glaucoma have less somatosensory contribution to balance and thus display more sway in more challenging situations. However, there was no control group comparison in the study.

The purpose of this study was to examine the differences in postural stability between glaucoma patients with VF defects and age-similar controls with no eye disease. The secondary aims were to examine whether the severity of binocular VF defect exerted any effect on postural stability and, in view of
the contradictory findings of the previously described studies, whether there were any group differences in the somatosensory contribution to balance.

METHODS

The study had the approval of the local research ethical committee approval and informed consent, according to the tenets of the Declaration of Helsinki, was obtained from each participant prior to examination.

Glaucoma patients from the clinics at Moorfields Eye Hospital, London and control subjects from the local community were invited to participate in the project through “flyer” distribution. Following a telephone interview, participants were excluded if they reported a history of comorbidities affecting their lower limbs, such as arthritis (for which they had a clinical diagnosis and/or were taking medication), hip or knee replacements, diabetes (to exclude peripheral neuropathy), parkinsonian type disorders, or any pathology that affected the vestibular or auditory systems, including the use of a hearing aid. To be eligible for the study, glaucoma patients had to have attended a clinic appointment within 3 months of recruitment, and shown no evidence of disease progression for at least 12 months, as judged by their visual field and optic disc examination. Control subjects had to have had an ocular examination within 6 months of recruitment; the presence of coexisting ocular pathologies (other than glaucoma, if appropriate) constituted an exclusion criterion for the study. Although cataract was not an exclusion criterion, patients had to achieve a vision better than or equal to Snellen acuity 20/40 to be eligible for the study.

Postural Stability Measures

Postural stability was measured using a force-balance platform (Bertec Corporation, Columbus, OH), which measured the coordinates of the center of foot pressure (CoP) during upright stance in both anteroposterior (A-P, “front-to-back”) and mediolateral (M-L, “side-to-side”) directions. The platform was connected to a personal computer and set at a sampling frequency of 1000 Hz.

Participants were asked to remove their shoes and socks and stand still with arms by their side, feet parallel and 15 to 20 cm apart on the center of the platform. Participants were instructed to wear their habitual refractive correction. To estimate the relative contributions of the visual and somatosensory systems to postural stability, participants were asked to close their eyes and/or stand on a 10-cm-thick foam rubber surface that was placed on the platform. Thus, postural stability was examined under four test conditions presented in a randomized order: both eyes open on the firm surface of the platform (EOFi), both eyes closed on the firm surface (ECFi), both eyes open on the foam rubber surface (EOFo), and both eyes closed on the foam rubber surface (ECFo). Under conditions in which eyes were open, the participant was instructed to look steadily at a cross fixation target displayed on a liquid crystal display monitor 90 cm away at eye level. Although it has been shown that target distance influences postural stability,20 there are minimal differences when considering target distances of 90 cm and beyond.21

Stability was measured over a 30-second period under each test condition to minimize intratest variability,22 and repeated three times, generating a total of 12 (4 × 3) postural measures per participant. Participants were instructed to rest between each test condition to minimize fatigue. Each participant had a 20-second familiarization period under each test condition (i.e., EOFi, ECFi, EOFo, ECFo) prior to the start of the test procedure.

The raw CoP data were filtered post hoc with a Butterworth filter to remove any noise from the measurements.23 The CoP displacements in the A-P and M-L directions were calculated and measures of body sway (mm/s) and average magnitude of displacement (root mean square [RMS]) were calculated. The median of the three measures under each test condition was used in subsequent analysis. The visual contribution to sway was determined using the Romberg Quotient (RQ)24: RQ = sway velocity ECFo/sway velocity EOFo. The higher the RQ, the greater the visual contribution to postural stability.

To estimate the relative somatosensory contribution to sway, the difference in sway between foam surface standing and firm surface standing was calculated under eyes open and eyes closed conditions.

Visual Assessments

All participants underwent a visual field test on both eyes using the Humphrey Visual Field Analyzer (HFA; Zeiss Humphrey Systems, Dublin, CA) SITA standard threshold 24-2 strategy. Mean deviation (MD) scores were recorded for each eye and the binocular MD was calculated from the raw sensitivity values from the monocular data using purpose-written software.25 LogMAR (logarithm of the minimum angle of resolution) visual acuity, measured using the ETDRS (Early Treatment Diabetic Retinopathy Study) chart, and Pelli–Robson contrast sensitivity was measured under monocular and binocular viewing conditions with the participant’s habitual refractive correction. Because impaired depth perception has been shown to be associated with an increased risk of falls,26 stereopsis was also measured using the Titmus stereotest.

Supplementary Tests

There is an association between impaired cognitive status and increased risk of falls27; thus, all participants were administered the mini-mental state examination (MMSE) and required a score of better than 25 to be included in the study.28

Physical activity and balance are closely interrelated29; thus, for this study participants also underwent two measures of physical activity. The first was the timed 10-m walk test, a performance-based measure of gait speed that measures the time taken to travel 10 m at the participant’s (1) preferred/comfortable walking speed and (2) fastest walking speed.30 Each participant was also administered the EPIC (European Prospective Investigation into Cancer and Nutrition) Physical Activity Questionnaire (EPQ-2), a validated instrument that requires an individual to report the amount of time spent undertaking activities at work, home, and during recreation over the previous 12 months.31 Energy expenditure was determined by calculating the metabolic equivalent (MET)–hours per week reported for each activity, using the MET scores listed in the Compendium of Physical Activities as reference.32 A MET score of 1 is considered a resting metabolic rate during quiet sitting; thus, the higher the MET score, the greater metabolic energy expenditure for the activity. The combined MET hours per week in all three domains are presented.

A detailed medical history with special reference to systemic and topical medication, specifically beta-blocker usage and number of falls in the preceding year, was taken from each participant.

Data Analysis

The sway data showed a nonnormal distribution and were logarithmically transformed for normalization. A repeated-measures ANOVA was performed with standing conditions (EOFi, ECFi, EOFo, ECFo) as within-subject factors and participant groups (controls, glaucoma) as between-subject factors.

Romberg quotient data and differences in sway between firm and foam surface standing were normally distributed within groups, and were thus analyzed using an independent t-test. Control and glaucoma data were grouped for further analyses to establish the factors most associated with postural stability. A stepwise regression analysis was performed with sway parameters (RMS, sway velocity, RQ, and firm-to-foam sway differences) as dependent variables, nonvisual measures (age, physical activity, sex, topical/ systemic beta blocker usage) as covariates and visual measures as independents, to determine which of the visual factors was most associated with standing balance.
TABLE 1. Demographics for Participant Groups

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Glaucoma (n = 24), Mean (SD)</th>
<th>Control (n = 24), Mean (SD)</th>
<th>Independent t-Test Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>65.9 (5.5)</td>
<td>68.3 (5.2)</td>
<td></td>
<td>0.13</td>
</tr>
<tr>
<td>MMSE score</td>
<td>28.6 (1.2)</td>
<td>28.6 (1.0)</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>10-m walk, m/min</td>
<td>72.9 (15.1)</td>
<td>76.9 (18.3)</td>
<td></td>
<td>0.49</td>
</tr>
<tr>
<td>10-m fast walk, m/min</td>
<td>95.6 (15.1)</td>
<td>105.9 (23.6)</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>Physical activity, MET h/wk</td>
<td>107.9 (44.5)</td>
<td>90.9 (51.7)</td>
<td></td>
<td>0.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Median (IQR)</th>
<th>Median (IQR)</th>
<th>Mann-Whitney P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better eye VA, logMAR</td>
<td>0.02 (0.00–0.10)</td>
<td>0.00 (−0.06 to 0.04)</td>
<td>0.09</td>
</tr>
<tr>
<td>Worse eye VA, logMAR</td>
<td>0.18 (0.03–0.29)</td>
<td>0.04 (−0.02 to 0.16)</td>
<td>0.02</td>
</tr>
<tr>
<td>Binocular VA, logMAR</td>
<td>0.00 (−0.08 to 0.08)</td>
<td>0.00 (−0.1 to 0.04)</td>
<td>0.61</td>
</tr>
<tr>
<td>Better eye CS</td>
<td>1.5 (1.36–1.5)</td>
<td>1.65 (1.60–1.65)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Worse eye CS</td>
<td>1.45 (1.30–1.50)</td>
<td>1.60 (1.50–1.65)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Binocular CS</td>
<td>1.60 (1.39–1.65)</td>
<td>1.65 (1.65–1.75)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Better eye MD, dB</td>
<td>−7.30 (−14.88 to −3.37)</td>
<td>0.42 (−0.41 to 1.12)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Worse eye MD, dB</td>
<td>−15.19 (−19.91 to −9.42)</td>
<td>−0.35 (−0.83 to 0.58)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Binocular MD, dB</td>
<td>−6.1 (−9.49 to −2.81)</td>
<td>0.40 (−0.30 to 1.15)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Stereopsis, sec of arc</td>
<td>80 (50–200)</td>
<td>50 (40–120)</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Independent t-test performed on normally distributed data, Mann-Whitney test on nonnormally distributed data. IQR, interquartile range; CS, contrast sensitivity; dB, decibel.

RESULTS

Twenty-five glaucoma patients and 25 control subjects were recruited for the study. One glaucoma patient was excluded from the final analysis, having reported a history of previous foot cellulitis, which had not been ascertained at the time of recruitment. One control subject was found to have a large interindividual variability in balance control. Inspection

Sway Velocity and RMS

There were no significant differences in postural stability between groups. However, there was a significant effect of standing condition on postural stability and a significant interaction between standing condition and group (Table 2, Figs. 1, 2).

Visual and Somatosensory Contributions to Balance

The RQ for glaucoma subjects was significantly lower than that for control subjects, indicating that glaucoma patients had a reduced visual contribution to balance control (mean [SD] AP RQ glaucoma = 1.65 [0.44], mean [SD] AP RQ control = 2.25 [0.53], test statistic 4.3, P = 0.0001; mean [SD] ML RQ glaucoma = 1.45 [0.64], mean [SD] ML RQ control = 1.84 [0.55], test statistic 2.27, P = 0.03).

The change in balance from firm to foam surface standing was greater in the glaucoma group compared with that in the control group under “eyes open” conditions, indicating that glaucoma patients had an increased relative somatosensory contribution to balance control (Table 3).

Regression Analyses

The stepwise linear regression analysis found no associations between logged sway data and visual factors. After adjusting for covariates age, physical activity, topical or systemic beta blocker usage, and sex, binocular MD remained the only significant visual predictor of AP RQ (binocular MD β-coefficient = 0.58, t = 3.98, P = 0.0001; Fig. 3), but not ML RQ. Binocular MD remained as the only significant visual predictor of change in balance from firm to foam surface standing for AP RMS (binocular MD β-coefficient = −0.35, t = −2.42, P = 0.02; Fig. 4), but not ML RMS, AP, or ML sway velocity.

DISCUSSION

This study suggests that individuals with glaucoma have a lower visual contribution and higher relative somatosensory contribution to balance control during silent standing conditions. This appears to be associated with the degree of binocular visual field defect.

Balance is maintained by a variety of factors and there exists a large interindividual variability in balance control. Inspection
of the “raw” sway data suggests that glaucoma patients had better stability than that of their control counterparts; however, evaluating the change in stability within each participant made it possible to overcome the effects of the interindividual variability in balance control.

The finding that the visual contribution to sway was significantly reduced in the glaucoma group is similar to that found by others evaluating the effects of visual field loss on balance. Shabana and colleagues found that the visual contribution to stability reduced as the visual field mean...
deviation in the weaker eye worsened. In their study of a younger cohort of patients with retinitis pigmentosa (RP), Turano et al.33 found that patients with peripheral VF defects from RP had a reduced visual contribution to balance that was associated with the degree of visual field restriction. In view of the reduced visual contribution to balance, it could be hypothesized that some patients might make better use of the nonvisual inputs to compensate for their loss of visual field.

Foam surface standing under “eyes open” conditions had a greater detrimental effect on glaucoma patients compared with that on control subjects. During foam surface standing, the somatosensory contribution to balance is disrupted; thus, when standing in conditions that challenge the somatosensory input to balance, glaucoma patients have greater instability than that of their control counterparts. The fact that glaucoma patients displayed slightly better firm surface standing than that of their control counterparts makes this finding all the more interesting. When standing eyes open on the firm surface, balance control is maintained from information from the visual, somatosensory, and vestibular systems. Standing on the foam surface reduces the somatosensory contributions to balance; thus, under the “eyes open foam” condition, the visual and vestibular contributions are highlighted. Closing the eyes removes the visual contribution to balance; therefore, standing “eyes closed foam” highlights the vestibular contribution. It has previously been shown that healthy individuals standing on a firm surface are more unstable when they stand with their eyes open in a dark environment compared with when they stand with their eyes closed.54 This phenomenon is thought to be as a result of the brain attempting to process and integrate incongruent visual information with information from the other sensory systems, resulting in an inefficient control of balance; however, when the eyes are closed there is no “dependence” on visual feedback, and thus balance control is better.54

Thus we may hypothesize that, in the present study, the presence of a visual field defect may indeed have compromised the visual feedback for balance control in the glaucoma group, but it was only when the somatosensory system was compromised that this inadequacy of visual input became apparent. This has also been noted by Elliott et al.55 who studied a group of patients with age-related macular degeneration (AMD). They found that under conditions where the somatosensory system was disrupted, AMD patients swayed significantly more than controls. Shabana et al.18 noted that their glaucoma subjects had an increased somatosensory contribution to balance compared with controls, similar to the findings of the current study. Manchester et al.3 also showed that in a group of nonvisually impaired individuals with artificially reduced visual fields, more losses of balance occurred only when somatosensory inputs were compromised. Our data add to the evidence that during silent standing conditions on firm surfaces, patients with visual impairment may make better use of the nonvisual inputs to maintain balance. Reducing the somatosensory contribution by standing on the foam surface elicits a greater instability in glaucoma patients. This finding may suggest a “redundancy” in the

**TABLE 3.** Change in Sway from Firm Surface to Foam Surface Standing in Glaucoma and Control Group

<table>
<thead>
<tr>
<th>Glaucoma Mean Δ (SD)</th>
<th>Control Mean Δ (SD)</th>
<th>t-Statistic (P Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Eyes open” A-P RMS, mm</td>
<td>4.12 (1.85)</td>
<td>2.22 (2.04)</td>
</tr>
<tr>
<td>“Eyes open” M-L RMS, mm</td>
<td>3.65 (1.99)</td>
<td>2.47 (1.34)</td>
</tr>
<tr>
<td>“Eyes open” A-P sway velocity, mm/s</td>
<td>8.16 (+4.46)</td>
<td>6.55 (3.68)</td>
</tr>
<tr>
<td>“Eyes open” M-L sway velocity, mm/s</td>
<td>7.47 (5.84)</td>
<td>4.14 (3.90)</td>
</tr>
<tr>
<td>“Eyes closed” A-P RMS, mm</td>
<td>4.76 (2.89)</td>
<td>6.01 (2.46)</td>
</tr>
<tr>
<td>“Eyes closed” M-L RMS, mm</td>
<td>4.35 (2.36)</td>
<td>4.78 (2.59)</td>
</tr>
<tr>
<td>“Eyes closed” A-P sway velocity, mm/s</td>
<td>19.30 (16.62)</td>
<td>21.45 (10.36)</td>
</tr>
<tr>
<td>“Eyes closed” M-L sway velocity, mm/s</td>
<td>11.27 (8.59)</td>
<td>10.81 (6.37)</td>
</tr>
</tbody>
</table>

Δ = change in sway parameter from firm to foam surface standing.
systems that control postural balance that allow for compensation when one of the systems is functioning inefficiently.

Other studies have found postural control compensatory mechanisms when sensory inputs are altered, and some suggest that younger persons adapt better to short-term perturbations than older individuals. However, studies of older individuals with chronic medical conditions affecting either the vestibular or somatosensory systems have also found increased redundancy in the systems that control posture. This suggests that the central nervous system redistributes its dependence on sensory information when available information is compromised, even in older persons. Although work suggests that peripheral vision is more important for sway stabilization than central vision, and that inducing peripheral field defects in otherwise normally sighted individuals has a detrimental effect on sway, glaucoma is, in most circumstances, a slowly progressive disease. Perhaps this affords patients time to compensate for the loss of peripheral visual information and make better use of their other systems for controlling balance in unchallenging standing situations.

In our stepwise regression analysis, sway parameters (velocity and average magnitude of displacement) were not predicted by any of the visual measures. This is in contrast with the work of Black et al. who found that body sway was associated with the degree of binocular visual field defect, such that those with a worse defect displayed greater body sway. The cohort reported in the study by Black and colleagues was older than that of the present study (median age: 74 years; age range: 65–90 years), and it has been shown that aging has a progressively detrimental effect on balance control. Perhaps this suggests that the mechanisms that compensate for the effects of vision loss on balance control might be age dependent. Authors have shown that over the age of 75 years, both the degree of sway and the visual contribution to balance increase, supporting this idea. It would be interesting to see whether balance control in the current cohort changes with age.

Binocular visual field mean deviation remained a significant predictor of the Romberg quotient and change in RMS between firm and foam surface standing in the A-P directions only. Thus, the worse the binocular field defect, the lower the relative visual contribution and the greater the relative somatosensory contribution to AP sway. The combined vector of AP and ML sway was not used because it has been shown that different visual stimuli have different effects on AP and ML stability. In “side by side” stance, AP stability controlled by the ankles, whereas ML sway is predominantly controlled by the hips. Furthermore, it has been shown that foveola vision contributes significantly to lateral sway, and since all our participants had good binocular visual acuity, it is perhaps unsurprising that there were no associations between ML sway and the extent of visual field loss.

Limitations to our study include the fact that all tests were undertaken in a controlled laboratory setting; thus, it is difficult to ascertain the “real-world” effect of our findings, and the relatively small numbers of participants in each group. The purpose of our study was to evaluate the effects of visual impairment caused by glaucoma on balance control and so it was important to exclude those with comorbidities that might affect balance. Our sample consisted of physically fit volunteers and may not reflect the general population. Indeed, more physically active individuals will have better postural stability. It is clear that there is a complex interaction between the systems that control balance and that there is also a large interindividual variability in postural stability. Our results suggest that some glaucoma patients are better at controlling balance during quiet stance on firm surfaces, and this may reflect the development of adaptation strategies to compensate for their loss of visual input. However, under more challenging situations they display a greater instability compared with those without glaucoma, which may put them at a greater risk of falls. Further work is required to examine how these findings during quiet stance translate to mobility, where the lack of peripheral visual cues may exert a more detrimental effect.

Acknowledgments

The authors thank Nicholas Smith for calculating the binocular mean deviation scores.

References

12. Friedman DS, Freeman E, Munoz B, Jampel HD, West SK. Visual, vestibular and somatosensory contributions to balance during quiet stance on firm surfaces, and this may reflect the development of adaptation strategies to compensate for their loss of visual input. However, under more challenging situations they display a greater instability compared with those without glaucoma, which may put them at a greater risk of falls. Further work is required to examine how these findings during quiet stance translate to mobility, where the lack of peripheral visual cues may exert a more detrimental effect.

Acknowledgments

The authors thank Nicholas Smith for calculating the binocular mean deviation scores.

References

12. Friedman DS, Freeman E, Munoz B, Jampel HD, West SK. Visual, vestibular and somatosensory contributions to balance during quiet stance on firm surfaces, and this may reflect the development of adaptation strategies to compensate for their loss of visual input. However, under more challenging situations they display a greater instability compared with those without glaucoma, which may put them at a greater risk of falls. Further work is required to examine how these findings during quiet stance translate to mobility, where the lack of peripheral visual cues may exert a more detrimental effect.


