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ORIGINAL ARTICLE

Quantification of Stereopsis in Patients with Impaired Binocularity

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ABSTRACT

Purpose. To quantify stereopsis at distance resulting from binocular fusion in patients with impaired binocular vision using a three-dimensional (3-D) display stereotest.

Methods. A total of 68 patients (age range, 6 to 85 years) with strabismus (40 esotropes and 28 exotropes) whose stereoacuity could not be measured with the near and distance Randot stereotests were included. Contour-based circles with a wide range of crossed horizontal disparities (2500 to 20 arcsec) displayed on a 3-D monitor were presented to subjects at 3 m. Between the patients who had stereoacuity of at least 2500 arcsec and those with no measurable stereoacuity, parameters including age, sex, best-corrected visual acuity, spherical equivalent refractive error, Worth 4 dot test results, and type and angle of deviation were compared.

Results. Stereoacuity at distance of 2500 arcsec or better was detected in 25 (63%) of 40 esotropes, and 16 (57%) of 28 exotropes, although stereoacuity of 800 arcsec or better was found only in two (5%) esotropes and one (4%) exotrope. Patients with stereopsis were significantly younger (19.3 ± 16.9 years) than those with no measurable stereopsis (31.5 ± 26.4 years) (p = 0.040). There were no significant differences in best-corrected visual acuity, presence of amblyopia >20/100, spherical equivalent refractive error, type of deviation, deviation angle, sex, and Worth 4 dot test results between these groups.

Conclusions. Stereopsis at distance resulting from binocular fusion that cannot be measured with conventional stereoacuity tests may be preserved in patients with impaired binocular vision. The 3-D display stereotest can be useful for quantifying stereopsis at distance resulting from binocular fusion.
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Key Words: binocular vision, stereoacuity, stereopsis, stereotest, strabismus

Strabismus or amblyopia can cause disruption of normal binocular vision, consequently leading to abnormal stereopsis.[1] In the real world, strabismus or amblyopia subjects use monocular cues to perform depth perception because they may not have fine stereoacuity from foveal fusion as in subjects with normal binocular vision.[2] Monocular depth information may be sufficient for locating a target at near, however, when the target is at a distance within 2 to 3 m, more binocular depth information is required for directing daily activities, including driving and walking.[3,4] There is evidence that strabismus or amblyopia subjects have residual stereoscopic function and mechanisms for binocular summation of contrast.[5–7] Stereopsis can be obtained from larger disparities that produce double vision and can provide reliable depth information that is important for one's orientation in space.[7,8] Thus, quantification of such stereoacuity is important in the evaluation and management of these conditions to estimate their abilities in potential binocular fusion and prognosis after surgery, which can be useful for both clinical and research purposes. Strabismic observers with residual stereopsis are also known to localize a target more accurately than those without any stereoability.[4]

Generally, stereotests are divided into two categories: real depth tests, such as the Frisby test, and dissociative imaging tests, such as the polaroid vectograph, anaglyphs, and Randot stereotests.[9] Real depth and dissociative imaging tests measure different aspects of stereopsis aside from the major differences in the images used that may also account for discrepancies in stereoacuity scores.[9] Real

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depth stereoacuity tests can measure the subject's capacity to perceive depth in the real world. Meanwhile, dissociative imaging stereotests can measure the subject's capacity to perceive depth from two stereo images. Rigorous binocular convergence/divergence for fusion is critical to perform the real depth test, whereas this is not always necessary to obtain a depth sensation from a stereotest with dissociated images.[9] For a strabismic subject, a dissociative test can present each image of the stereotest in alignment with the main visual direction of each eye. Therefore, a dissociative test may be useful to determine the presence or absence of stereopsis as well as quantitative changes in strabismic patients, when a large enough range of disparity is used.

Among the various stereoacuity tests performed to measure stereoacuity, the Lang Stereotest I (LangI) and Lang Stereotest II (LangII) can measure large disparity levels of 400, 550, 600, and 1200 arcsec at near.[10] These tests use a combination of the random dot technique with cylindrical gratings to provide separate images without using polaroid spectacles. However, the Lang Stereotests are subject to monocular cues such as motion parallax and the image should be viewed at a fixed distance from the eye of 40 cm and exactly in the frontoparallel plane to ensure that correct images are visible in each eye. This limits its use for testing at variable distances.[10] The Lang Stereotests also require a rigorous binocular convergence/divergence for fusion in strabismic patients. Polaroid vectograph stereoacuity tests using spectacles are preferred to overcome this limitation with motion cues. However, currently available polaroid vectograph stereoacuity tests performed at near such as the Titmus stereotest and Randot circles stereoacuity tests can only measure fine stereoacuity from 800 to 20 arcsec. The Stereo Fly can assess the presence of stereoacuity at the level of 3000 arcsec, but cannot determine the precise level of stereoacuity threshold.

Regarding stereoacuity tests performed at distance, there have been a number of studies that have evaluated distance stereopsis in both normal and abnormal vision using other systems. The Frisby-Davis distance stereotest (FD2) (Frisby Stereotest, Sheffield, United Kingdom) is a real-depth test that can be performed without dissociation of the eyes at a distance of 3 to 6 m, generating disparities from 200 to 5 arcsec.[11–13] However, real-depth tests are quite subject to monocular cues.[11] Dissociative tests that can reduce monocular cues include the Mentor B-VAT II-SG video acuity tester (Mentor O & O, Norwell, MA), which allows measurement at levels of 15 to 240 arcsec at a distance of 3 to 6 m,[13] and the Distance Randot stereotest (Stereo Optical Co., Inc., Chicago, IL) using random dots measured at a distance of 3 m and testing disparities from 200 to 60 arcsec. However, all of these tests cannot determine the level of stereoacuity that is larger than 240 arcsec. In a previous study, we developed a new stereotest using a three-dimensional (3-D) display and showed its efficacy in measuring stereoacuity at distance.[14] The new 3-D stereotest improved the precision of measurement by increasing the numbers of predefined intervals and has a potential to test stereoacuity thresholds of up to 5000 arcsec, which enables quantification of stereoacuity in patients with low levels of stereopsis. Strabismic subjects may retain sensitivity to large disparities despite the misalignment of the eyes and lack of divergence/convergence and by presenting a stereotest with wide disparity levels would enable the measurement of such kind of stereopsis.

In the present study, we tested the previously developed 3-D display stereotest in strabismic patients with impaired stereo vision not measureable with the conventional random dot–based stereotests. We quantified the level of stereoacuity threshold at distance and compared the clinical characteristics of those who had stereoacuity of at least 2500 arcsec and those without measurable stereoacuity.

METHODS

Ethics Statement

This study was conducted in compliance with the Declaration of Helsinki and was approved by the institutional review board of Seoul National University Bundang Hospital. Written informed consent was obtained from the adult participants and from the parents or guardians of children.

Participants

This study included 68 consecutive patients (male-to-female ratio, 38:30) who visited Seoul National University Bundang Hospital between March 2010 and February 2012. Patients with constant or intermittent horizontal deviation (esotropia or exotropia) at distance and near who failed to answer correctly to any of the dots or animals of the Randot stereotest (Stereo Optical Co., Inc.) and the Distance Randot stereotest (version 2; Stereo Optical Co., Inc.) were included. The mean age of the study participants was 23.5 ± 21.3 years (range, 6 to 85 years). The exclusion criteria were as follows: (1) best-corrected visual acuity (BCVA) of worse than 20/100 in either eye measured with a Snellen chart to exclude severe amblyopia, (2) subjects with vertical deviation (hypotropia or hypertropia) or dissociated vertical deviation with alternate prism cover tests, (3) history of intraocular surgery or strabismus surgery.

All subjects underwent evaluation including BCVA of each eye with the Snellen chart monocularly, cycloplegic refraction, alternate prism cover test with fixation targets at 0.33 and 6 m, the random dot–based Randot stereotest (Stereo Optical Co., Inc.) at 0.4 m and the Distance Randot stereotest (Stereo Optical Co., Inc.) at 3 m, Worth 4 dot (W4D) test at 0.33 and 3 m, and the 3-D stereotest at 3 m. During the Randot and 3-D stereotests, the room illumination was maintained as 250 to 300 lux, measured in front of the eye level of the subject by an illuminance meter (T-10; Konica Minolta, Tokyo, Japan).

3-D Display Stereotest

The distance 3-D stereoacuity test was performed at 3 m as previously described.[14] Briefly, the stereoscopic stimulus was presented on a 1.17-m (46-in) polarized stereoscopic 3-D monitor (G460X; Pavonine Co., Inc., Incheon, Korea) with the background luminance of 250 cd/m^2 (785 lux), resolution of 1920 by 1080 pixels, and Weber contrast ratio of 1800:1. Two images were displayed on the same monitor through different polarizing filters, and the subject wore glasses that also contained a pair of different polarizing filters. Each pair of filters allows light with the same polarization state to penetrate, and it blocks light with an

TABLE 1.
Distribution of stereoacuity according to the type of strabismus

Stereoacuity, arcsec	Esotropia (N = 40)	Exotropia (N = 28)	Total (N = 68)
≤800	2 (5%)	1 (3.6%)	3 (4.4%)
1000–1500	3 (7.5%)	2 (7.1%)	5 (7.4%)
2000–2500	20 (50%)	13 (46.4%)	33 (48.5%)
Nil	15 (37.5%)	12 (42.9%)	27 (39.7%)

orthogonal polarization state, consequently producing different stimuli for each eye.

Four contour-based circles with a diameter of 14 cm placed at the edges of a square with a spacing of 16 cm between each circle and a wide range of crossed horizontal disparities (2500 to 20 arcsec; 19 different disparity levels as follows: 2500, 2000, 1500, 1000, 800, 600, 500, 400, 300, 200, 150, 100, 70, 60, 50, 40, 30, 25, and 20 arcsec) programmed in Visual C^{++} using Visual Studio (version 6.0; Microsoft, Inc., Seattle, WA) were generated on the 3-D monitor. The inside and outside of circles were filled with random dot textures with a pixel dot size of 2 mm at a distance of 3 m.[15] Although the position of the stereoscopic stimulus changed randomly among four possible locations, the subjects were instructed to answer which image they perceived stereoscopically to the instructor and the instructor pressed the correct or incorrect button according to the answer. Testing started with the largest disparity that progressively became smaller from 2500 to 20 arcsec. The testing stopped with one incorrect response, and the *stereoacuity threshold* was defined as the smallest disparity level at which a subject could detect a protruded circle. Each subject underwent three sets of 3-D stereoacuity tests, and if there were any repeated values among the three measurements, those were taken as the result. If there were no repeated values, the median values were taken as the result. Finally, if the test was passed binocularly, each eye was patched alternately and the test was repeated monocularly, restarting at the largest level of disparity.[11] If the same level of stereoacuity passed binocularly was also passed monocularly, the distance stereoacuity was recorded as "nil."

Statistical Analyses

SPSS for Windows (version 18.0; SPSS Inc., Chicago, IL) was used for statistical analyses. Continuous values were expressed as mean ± standard deviation. Between the patients who had stereoacuity of at least 2500 arcsec (group S) and those with no stereoacuity (group N), parameters including age, sex, BCVA, spherical equivalent refractive error (SEQ) in diopters, W4D test results, types of deviation, and deviation angle were compared using χ^2 test, Student t-test, and Mann-Whitney U test, as appropriate.

RESULTS

Of the 68 study subjects, 40 patients had esotropia with a mean deviation of 19.0 ± 9.2 PD (range, 8 to 45 PD) and 28 patients had exotropia with a mean deviation of 28.7 ± 12.9 PD (range, 8 to 60 PD). The angle of deviation was significantly larger in patients with exotropia (p = 0.001). The mean LogMAR BCVA of the better eye was 0.14 ± 0.22 (range, −0.18 to 0.70), and the mean LogMAR BCVA of the worse eye was 0.25 ± 0.24 (range, −0.18 to 0.70). Forty-five patients (66.2%) had mild-to-moderate amblyopia, and the rest had normal visual acuity. The mean SEQ of both eyes was 0.03 ± 2.32D (range, −10.50 to +6.00D).

The distributions of stereoacuity determined with the 3-D stereotest according to the presence of amblyopia and type of strabismus are summarized in Tables 1 and 2, respectively. In patients with esotropia, 25 (62.5%) of 40 patients had stereoacuity of 2500 arcsec or better and 17 (42.5%) of them had stereoacuity of 2000 arcsec or better. In subjects with exotropia, 16 (57.1%) of 28 patients showed stereoacuity of 2500 arcsec or better, and 9 (32.1%) of them had stereoacuity of 2000 arcsec or better. However, only two (5.0%) patients with esotropia and one (3.6%) patient with exotropia showed stereoacuity of 800 arcsec or better. In patients with amblyopia, 24 (53.3%) of 45 patients had stereoacuity of 2500 arcsec or better and 13 (28.9%) of them had stereoacuity of 2000 arcsec or better. In subjects without amblyopia, 17 (73.9%) of 23 patients showed stereoacuity of 2500 arcsec or better and 13 (56.5%) of them had stereoacuity of 2000 arcsec or better. However, only one (2.2%) patient with amblyopia and two (8.7%) patients without amblyopia showed stereoacuity of 800 arcsec or better. Among the 27 patients with nil stereoacuity, six patients (22.2%) achieved the same score with the monocular test and were scored as nil.

Between the patients who had stereoacuity of at least 2500 arcsec (group S) and those with no stereoacuity (group N), there was a significant difference in age between the two groups (19.3 ± 16.9 vs. 31.5 ± 26.4 years old in groups S and N, respectively, p = 0.040). There was no significant difference in BCVA of the better eye, BCVA of the worse eye, presence of amblyopia, SEQ, deviation angle in either esotropia or exotropia, sex, types of deviation, or distance W4D test results (Table 3).

DISCUSSION

We have previously introduced a distance stereotest using 3-D display and contour-based circles constructed by random dots and reported its validity and reliability in normal subjects.[14] However, the efficacy of the stereotest in measuring stereopsis of 250 arcsec or worse was not thoroughly evaluated in the prior study because only normal subjects with good stereopsis were included.[14] Based on the findings that the measurable range of stereoacuity with the 3-D stereotest was between 2500 and 20 arcsec,[14] we attempted to measure stereoacuity in patients with strabismus

TABLE 2.
Distribution of stereoacuity according to the presence of amblyopia

Stereoacuity, arcsec	Amblyopia (N = 45)	No amblyopia (N = 23)	Total (N = 68)
≤800	1 (2.2%)	2 (8.7%)	3 (4.4%)
1000–1500	3 (6.7%)	2 (8.7%)	5 (7.4%)
2000–2500	20 (44.4%)	13 (56.5%)	33 (48.5%)
Nil	21 (46.7%)	6 (26.1%)	27 (39.7%)

TABLE 3.
Comparison of parameters between stereoscopic group (groups S) and nonstereoscopic group (group N)

Parameters	Group S (N = 41)	Group N (N = 27)	p
BCVA of better eye, LogMAR	0.10 ± 0.19	0.19 ± 0.25	0.119†
BCVA of worse eye, LogMAR	0.23 ± 0.24	0.27 ± 0.24	0.453†
Amblyopia	24 (58.5%)	21 (77.7%)	0.101§
Spherical equivalent, D	−0.19 ± 2.10	0.48 ± 2.51	0.257†
Age, yr	19.3 ± 16.9	31.5 ± 26.4	0.040†
Deviation angle, PD			
Esotropia	17.2 ± 7.1 (N = 25)	22.0 ± 11.6 (N = 15)	0.255‡
Exotropia	26.4 ± 11.9 (N = 16)	31.8 ± 14.0 (N = 12)	0.361‡
Sex ratio (male/female)	25:16	13:14	0.297§
Type of deviation (esotropia/exotropia)	25:16	15:12	0.657§
Worth 4 dot test (suppression/fusion/diplopia)	13:9:19	13:4:10	0.384§

*All data are expressed as mean ± SD.
†Student's t-test.
‡Mann-Whitney U test.
§χ^2 test.

whose stereoacuity was not measurable with the near and distance Randot stereotests using a distance random dot test with reduced monocular cues.[16]

In this study, the 3-D stereoacuity test showed that approximately 60% of patients with no measurable stereoacuity with the Randot stereotests had stereoacuity of 2500 arcsec or better and only one exotrope and two estropes had stereoacuity of 800 arcsec or better. The results of this experiment show that some strabismic subjects are characterized by an extremely wide stereoscopic acuity of up to 2500 arcsec with a potential of binocular fusion, although the physiological mechanism that could explain such large stereoscopic acuity is not clear. Our prior study had demonstrated that the results of the 3-D stereoacuity test correspond well with those of the Randot stereotest in normal subjects.[14] These findings suggest that our 3-D stereotest has high efficacy and validity and can be a feasible option in the measurement of stereoacuity in both normal subjects and patients with impaired binocular vision. Meanwhile, although stereoacuity score categories showed a reasonable level of agreement between the Distance Randot stereotest (random dot based) and the 3-D stereotest (random dot plus contour),[14] some degree of stereoacuity score discrepancies are found between the circles tests and the random dot–based tests that may reflect different underlying mechanisms or confounding nonstereoscopic binocular cues in the circles test that should be considered in interpreting the results.[17] In this study, 60% of patients with no measurable stereopsis by the Randot stereotest could discriminate stereopsis of 2500 arcsec or better by the 3-D stereotest. This suggests that the potential for binocular fusion might be preserved, at least in part, in patients with seriously impaired stereoacuity because of strabismus in addition to the monocular cues that are used in the real world. Kitaoji and Toyama[18] showed that position and motion stereopsis can be preserved in patients with strabismus. Hess et al.[6] demonstrated that some patients with strabismic amblyopia retained residual stereoscopic function and had potential for enhanced stereopsis if the degree of interocular suppression is reduced, which they termed "latent stereopsis." Apkarian and Reits[19] showed evidence for sensitivity to large (3000 arcsec) disparities in patients with albinism who also had strabismus. Giaschi et al.[7] also suggested that stereopsis may be spared in children lacking fine stereopsis because of early visual deprivation. Another study revealed that a patient with strabismic amblyopia had intact mechanisms for binocular fusion of contrast.[5] Watanabe et al.[20] also demonstrated that motion-in-depth perception was present in more than 25% of the strabismic patients without fine static stereopsis. Several studies revealed that significant improvement in stereoacuity was found after successful strabismus surgery in adults with long-standing constant strabismus, and even achievement of fine stereopsis of 60 arcsec or better was not uncommon.[21–24] Lal and Holmes[22] showed that 67% of patients with no preoperative fusion regained measurable stereoacuity after strabismus surgery. Fawcett et al.[25] also reported that 95.6% of patients with acquired constant strabismus attained some recovery of stereopsis after successful strabismus surgery, and poor or no measurable preoperative stereopsis did not preclude the development of good postoperative stereopsis. These findings suggest that a potential for binocular fusion and stereoscopic performance might be preserved in patients with severely impaired stereopsis that is unmeasurable with conventional stereotests, which is consistent with our assumption.

Our results suggest that preservation of stereopsis of 2500 arcsec or better may be associated with a younger age. It is possibly because potential binocular fusional ability gradually diminishes with increasing age and longer duration of strabismus. Fawcett et al.[25] reported that a longer duration of strabismus was significantly associated with poorer stereoacuity outcome after strabismus surgery, which supports our assumption. They also suggested that no patient recovered binocular fusion after a period of constant strabismus of 12 months or longer, although the critical interval of susceptibility for restoration of stereopsis in adults may extend past 3 months.[25] However, our statistical analyses did not include a correction for making multiple comparisons within the same data set. Therefore, we believe that further studies with a larger population are needed to evaluate the influence of age on preservation of stereopsis in strabismic patients.

In this study, the deviation angle tended to be smaller in group S in both patients with esotropia and those with exotropia, but the difference was not statistically significant. Although rigorous binocular vergence is critical to perform the real depth test, this is not always necessary to obtain a depth sensation from a stereotest with dissociated images. For a strabismic subject, we could present each image of the stereotest to each eye without compensation for the angle of strabismus. In our study, we compensated the lack of vergence in strabismic subjects by presenting a stereo-imaging test with a wide disparity to induce binocular fusion. Fawcett et al.[25] showed that postsurgical orthotropia supports better stereoacuity than a larger residual deviation of 5 PD or more. Maeda et al.[26] reported that ocular alignment within 10 to 15 PD is an important factor in obtaining binocular motion in depth perception. Watanabe et al.[20] showed that ocular alignment within 20 PD is important to achieve stereo-motion perception. Our results are in disaccord with those studies possibly because (1) most of the patients in our study had horizontal deviation of 20 PD or more, which caused substantial impairment in stereopsis and made the comparison difficult, and the (2) sample sizes in both esotropic and exotropic groups were small. We believe that further studies with a larger study population would be warranted.

The present study has limitations as follows. (1) The test was conducted only at 3 m, and the efficacy of the 3-D stereotest in measuring near stereoacuity was not evaluated.[14] (2) Self-emitting 3-D monitor may influence pupil size, retinal illuminance, and contrast sensitivity, which are factors that can affect the level of stereopsis.[14,27,28] (3) One may argue that monocular cues were not completely excluded conceivably because of contour-based circles and differences in the densities of the random dots inside and outside of the circles.[14] Monocular cues are present in the large disparity levels of the contour-based circle stereotest.[14] Fawcett[17] reported that monocular cues are present in the large disparity level of 140 to 200 arcsec or worse in contour-based stereotests like Titmus or Randot circles tests. However, in our study, the monocular cue test was performed with either eye after wearing polarizing filter glasses to completely eliminate the possibility.[11]

In conclusion, this study suggests that stereoacuity resulting from binocular fusion may be present in strabismic patients who are unmeasurable with conventional stereotests. Our 3-D stereotest can be useful in the determination of such stereoacuity in these patients.

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