# Estimating the Binocular Visual Field of Glaucoma Patients With an Adjustment for Ocular Dominance

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**Purpose.** To investigate whether it is possible to improve estimation of the binocular visual field (VF) using monocular sensitivities on a linear scale adjusted for ocular dominance.

**Methods.** Monocular and binocular VF measurements were evaluated using the Humphrey Field Analyzer (HFA; 24-2 Swedish Interactive Threshold Algorithm standard program) in 60 eyes of 30 patients with open angle glaucoma. Ocular dominance was measured twice in each patient and the average value was used. Measured binocular sensitivity was then predicted based on monocular measurements using the "better sensitivity" integrated visual field (IVF) method, monocular sensitivity summation methods on the dB scale, linear scale (1/Lambert), and finally monocular sensitivity summation methods on the linear scale adjusted for the ocular dominance.

**Results.** The absolute prediction error with the linear scale summation method (mean ± SD: 3.11 ± 4.00) was significantly smaller than the IVF method (3.15 ± 4.09; $P = 0.014$). Further, the absolute prediction error for the ocular dominance adjusted method (3.10 ± 3.99) was significantly smaller than the nonadjusted linear scale summation method ($P = 0.014$). The absolute prediction error associated with the dB scale summation method was significantly larger than any other method (8.15 ± 5.06; $P < 0.0001$).

**Conclusions.** The most accurate estimation of binocular sensitivity was achieved using the linear monocular sensitivity summation model adjusted for ocular dominance.

Keywords: visual field, binocular, dominance

It is of great clinical importance to understand a patient's binocular visual field (VF), in particular to predict the effect of VF impairments on a patient's quality of visual life (QoVL).[1,2] Indeed, previous studies have reported a strong relationship between a patient's QoVL and his or her binocular VF, measured using the binocular Esterman VF test.[2–8] The binocular Esterman VF test can be measured with many automated visual field perimeters, such as the Humphrey Field Analyzer (HFA; Zeiss-Humphrey Systems, Dublin, CA, USA) and the Octopus 900 (Haag-Streit, Koniz, Switzerland); however, in clinical settings, this binocular VF measurement is rarely performed and clinical resources are dedicated to monocular assessment. Consequently, the integrated VF (IVF) has frequently been used to estimate a patient's binocular VF.[9–12] The IVF is calculated by simply taking the better sensitivity value from corresponding VF locations in monocular VF test results of both eyes. It has been reported that the IVF closely agrees with the Esterman test in identifying patients with glaucomatous VF defects[9] and indeed it has also been used to assess fitness to drive in patients with glaucoma in the United Kingdom.[10,12] Furthermore, the IVF has been shown to be more closely related to the deterioration of QoVL in patients with glaucoma than the Esterman test[11] and, hence, a number of studies have used the IVF to analyze the QoVL of glaucoma patients.[2,12–22] In addition, we have previously reported that there is a notable difference between sensitivity measurements of the better eye and the IVF.[23]

Nelson-Quigg et al.[18] previously reported that the IVF gives a reasonable estimate of binocular sensitivity in comparison with the binocular summation model[24]:

$$\sqrt{(S_R)^2 + (S_L)^2},$$

where $S_R$ and $S_L$ represent monocular sensitivities of the right and left eyes on the dB scale, respectively. However, it was not investigated whether monocular sensitivities should be used on a dB or linear scale in the calculation of the binocular summation. Other studies that investigated binocular summation used the Michelson model,[25] in which a linear brightness scale is used.[26–29]

No models have considered ocular dominance. Binocular rivalry is a phenomenon of visual perception; in dichoptic presentation, the image perceived by each eye is not superimposed together, and instead either of the images is seen alternately by suppressing the image from another eye.[30] This phenomenon could manifest in binocular summation, especially if corresponding monocular VF sensitivities are markedly different between eyes. Ocular dominance is a result of a difference of the frequency of suppression of images between eyes.[31] We propose that estimates of binocular sensitivity may be improved by considering ocular dominance.

Glaucomatous VF loss impacts the QoVL of patients,[3,4,32–39] and also, can influence hand-eye coordination,[40] increase the risk of falling,[41] and increase the risk of motor vehicle

accident,[41–45] likely because of an inability to detect peripheral obstacles and hazards.[43,46] People use both eyes together so it is very important to estimate patients' binocular VFs if only monocular VFs are available. The IVF is one of the most frequently used methods, but it may be possible to generate a more accurate estimation of the binocular VF. Thus, the purpose of the current study was to investigate whether it is possible to improve the accuracy of binocular VF sensitivity estimation by using monocular sensitivities on a linear scale, adjusted by ocular dominance.

## Methods

This study was approved by the Research Ethics Committee of the Graduate School of Medicine and Faculty of Medicine at the University of Tokyo. Written consent was given by patients for their information to be stored in the hospital database and used for research. This study was performed according to the tenets of the Declaration of Helsinki.

### Subjects

Thirty patients with glaucoma were included in this investigation (primary open angle glaucoma: 9, normal tension glaucoma: 18, exfoliation glaucoma: 3). All the patients were under treatment in the University of Tokyo Hospital, Tokyo, Japan and informed consent was provided before VF testing. All patients enrolled in this study fulfilled the following criteria: (1) at least 20 years old; (2) glaucoma was the only disease causing VF damage and/or visual impairment; (3) patients had no physical impairments; (4) patients were followed for at least 6 months in which IOP and visual field damage were stable; (5) patients had a glaucomatous VF defect in at least one eye, which was defined with the Anderson and Patella criteria,[47] a pattern deviation probability plot showing a cluster of three or more nonedge contiguous points with a probability of less than 5% and at least one point with a probability less than 1% in an expected hemifield, a pattern SD with a probability of less than 5%, or a glaucoma hemifield test result outside normal limits; (6) visual acuity better than 6/12; and (7) no previous ocular surgery, including trabeculectomy and refractive surgery (except for cataract extraction, intraocular lens implantation and trabeculotomy).

### Visual Field Testing

Each patient's VF was evaluated using the HFA with the 24-2 Swedish Interactive Threshold Algorithm standard program. Reliable results were defined as follows: fixation loss (FL) rate less than 20%, and false-positive error (FP) rate less than 15%; the false-negative error (FN) rate was not used following results in Bengtsson and Heijl.[48] The binocular VF test was performed using soft contact lenses focused on a distance of 30 cm. During binocular testing, patients were aligned to the perimeter by adjusting the vertical head position and then the horizontal position to the bridge of the nose. All patients had undergone at least two previous visual field examinations, and patients with a history of poor fixation were excluded from the study. In the binocular VF test, FLs, FPs, and FNs cannot be measured; hence, fixation was monitored by the examiner (MM) throughout the test and was deemed acceptable for all tests. All of the monocular VFs and the binocular VF were performed on the same visit with a rest period of at least 15 minutes between each test. The order of the tests was randomized. Periodic short rest breaks during a test procedure were provided to patients as required. In the following analyses, only the 48 corresponding test points from the 24-2 VF test in the left eye and right eye were used.

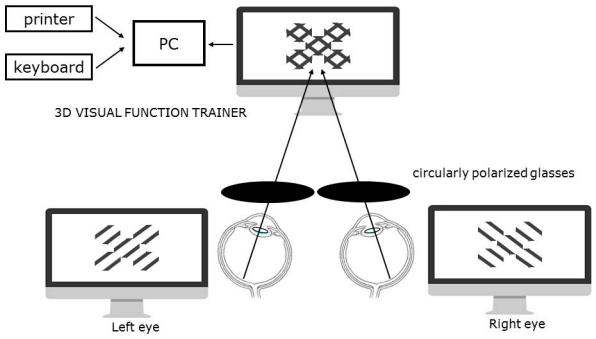


Figure 1. Dominance measuring system. All stimuli were generated on a 24-inch LCD monitor (P240W; Hyundai; pixel solution, 1980 × 1200) using VisageSage (3D Visual Function Trainer; Japan Focus Co., Ltd.).

### Eye Dominance Measurement

For the ocular dominance test, stimuli were generated on a 24-inch liquid crystal display (LCD) monitor (P240W; HYUNDAI, Seoul, Korea; pixel solution, 1980 × 1200) using VisageSage (3D Visual Function Trainer; Japan Focus Co., Ltd., Tokyo, Japan) (Fig. 1). Stimuli were superimposed on a background with luminance equal to 128 RGB (52.3 cd/m$^2$, measured at the center of the monitor). Before starting the study, stimulus luminance was tested at each location using a luminance meter (LS-100; Minolta, Tokyo, Japan). Luminance was measured 10 times from the chin rest, and the mean value was calculated; luminance was found to be uniform at each test location. Ocular dominance was measured following a previous report by Xu et al.[49] In this report, the QUEST algorithm was used to determine thresholds; however, the method of adjustment[50] was used in the current study due to the limitation of the measurement device.

In the dominance measurement, right and left eye viewings were separated using polarized glasses in which right and left eye images were separated using circularly polarized light. Stereoscopic displays create the sense of depth by showing the left eye and right eye different images; the display allocates odd-numbered row pixels to display an image to one eye, and even-numbered row pixels to display a different image to the other eye (Fig. 2). Stimulus lights emitted from the left eye field are in the left-hand (LH) circular polarization, whereas lights emitted from the right eye field are in the right-hand (RH) circular polarization. Accordingly, the left eye lens of the polarized glasses transmits only LH-circularly polarized light, and the right eye lens transmits only RH-circularly polarized light. As a result, a black stripe running from the upper-right corner of the screen to the lower-left corner can be recognized only by the left eye and the right eye can recognize only a stripe running from the upper-left corner of the screen to the lower-right corner. The stripes were rectangular two cycles per degree (cpd) gratings that were 12 degrees in size. The contrast of the target in one eye was varied in 20 grades (20:112 RGB [39.36 cd/m$^2$, measured at the center of the monitor] to 1:12 RGB [0.6 cd/m$^2$, measured at the center of the monitor]) with a regular interval in RGB and the dominance of the tested eye was determined on a 20 scale. The dominance measurement was carried in five zones: central, upper left, upper right, lower left, lower right. Each target was a 12-degree regular tetragon and the exact locations of the targets are

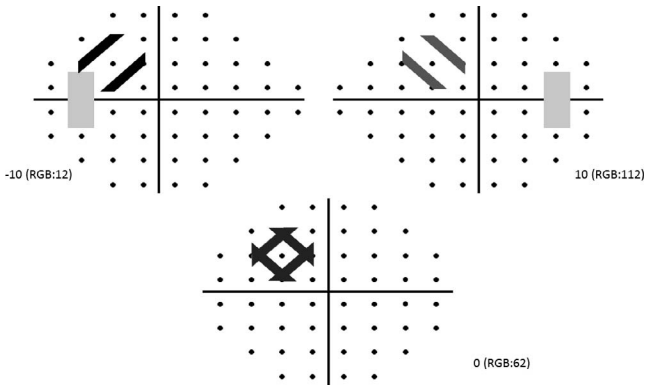


FIGURE 2. Stimulus lights emitted from the left eye field are in the LH circular polarization, whereas lights emitted from the right eye field are in the RH circular polarization. Accordingly, the left eye lens of the polarized glasses transmits only LH-circularly polarized light, and the right eye lens only transmits RH-circularly polarized light. As a result, a black stripe running from the upper-right corner of the screen to the lower-left corner can be recognized only by the left eye and the right eye can recognize only a stripe running from the upper-left corner of the screen to the lower-right corner. The stripes were rectangular two cycles per degree (cpd) gratings that were 12 degrees in size. The contrast of the target in one eye was varied in 20 grades (20:112 RGB [39.36 cd/m$^2$, measured at the center of the monitor] to 1:12 RGB [0.6 cd/m$^2$, measured at the center of the monitor]) with a regular interval in RGB and the dominance of the tested eye was determined on a 0 to 20 scale.

shown in Figure 3. The dominance of all four VF test points in the central area ($x$- and $y$-axis coordinates: [3, 3], [3, −3], [−3, 3], and [−3, −3]) was determined using the single dominance value of the central zone. The dominance value of other VF test points was decided using the dominance value of the quadrant to which each test point belongs. The dominance test at each of the five zones was performed in a random order.

Patients sat 50 cm from the display and were presented with rightward-tilted (45°) and leftward-tilted (135°) square gratings in each eye.

After a sufficient explanation of the dominance measurement was given, followed by demonstration and training sessions, the measurement was carried out twice with a 5-minute interval between each test. Patients can change the RGB of the image viewed by pressing a button and had to decide when both eyes' images looked equivalent where the contrast in the fellow eye was fixed at 10 RGB. The average value of the two measurements was used in subsequent analyses. The refractive power in both eyes was corrected for a focal distance at 50 cm using +2.0-diopter spherical lenses. During the dominance measurement, eye movements were monitored by the observer (MM), and the patient's head was constrained with a chin rest and head rest.

The dominance of the test point with lower VF sensitivity ($k$) was decided using the dominance value of the test point with lower sensitivity (Dominance$_{worse}$):

$$k = \frac{\text{Dominance}_{worse} - 10}{20}.$$

## Statistical Analysis

The reproducibility of dominance values was estimated using the intraclass correlation coefficient (ICC) and the coefficient of variation (CV).

The binocular sensitivity estimation error was calculated for each of the models below:

**Model 1** (IVF method): Better eye VF sensitivity taken[9–12]

**Model 2** (dB scale summation):

$$\sqrt{\left(\text{better sensitivity(dB)}\right)^2 + \left(\text{worse sensitivity(dB)}\right)^2}$$

**Model 3** (linear scale summation):

$$10 \times \log\left(\sqrt{\left(\text{bettersensitivity}\left(\frac{1}{\text{Lambert}}\right)\right)^2 + \left(\text{worse sensitivity}\left(\frac{1}{\text{Lambert}}\right)\right)^2}\right)$$

where sensitivity in (dB) was converted to linear scale ($10^{(\text{sensitivity in dB})/10}$)

**Model 4** (linear scale summation adjusted for ocular dominance):

$$10 \times \log \sqrt{\left\{\left(\left(\text{better sensitivity}\left(\frac{1}{Lambert}\right)\right)^2 + \left(\left(\text{worse sensitivity}\left(\frac{1}{Lambert}\right)\right)^2 + \left(k \times \text{worse sensitivity}\left(\frac{1}{Lambert}\right)\right)^2\right)\right\} \Big/ (2 + k^2)},$$

when $k \geq 0$,

$$10 \times \log \sqrt{\left\{\left(\left(\text{better sensitivity}\left(\frac{1}{Lambert}\right)\right)^2 + \left(\left(\text{worse sensitivity}\left(\frac{1}{Lambert}\right)\right)^2 + \left(k \times \text{worse sensitivity}\left(\frac{1}{Lambert}\right)\right)^2\right)\right\} \Big/ (2 - k^2)},$$

when $k < 0$.

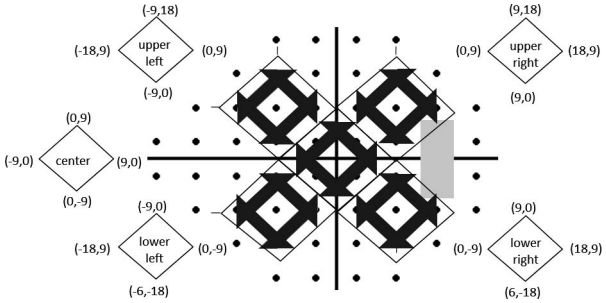


**Figure 3.** Five dominance zones. A dominance measurement was carried out in five zones: central, upper left, upper right, lower left, lower right. The dominance of the 4 VF test points in the central area (*x*- and *y*-axis coordinates: [3, 3], [3, −3], [−3, 3], and [−3, −3]) using the dominance value of the central zone. The dominance of other test points was decided using the dominance values of the quadrant to which each test point belongs.

The absolute prediction errors associated with models 1 to 4 were compared using the linear mixed model where subjects and test locations were treated as a random effect. All analyses were performed using the statistical programming language 'R' (R version 2.15.1; The Foundation for Statistical Computing, Vienna, Austria). The method of Benjamini and Hochberg[51] was used to correct *P* values for the problem of multiple testing.

## Results

Subject demographics are shown in Table 1.

Dominance value of the test point with higher sensitivity ($Dominance_{better}$) (11.4 ± 3.7: mean ± SD) was significantly better than $Dominance_{worse}$ (11.2 ± 3.9, $P = 0.004$, linear mixed model). The dominance of ICC values of $Dominance_{better}$ and $Dominance_{worse}$ were 0.66 and 0.63, respectively. Coefficient of variation values of $Dominance_{better}$ and $Dominance_{worse}$ were 19.6% ± 20.8% and 22.8% ± 21.4%.

The absolute prediction error for estimating binocular sensitivity associated with each model is shown in Table 2. The absolute prediction error with the linear scale summation method (Model 3, 3.11 ± 4.00) was significantly smaller than IVF method (Model 1, 3.15 ± 4.09, $P = 0.014$, linear mixed model adjusted after correction of *P* values for multiple testing). The absolute prediction error with the linear scale summation method adjusted for ocular dominance (Model 4, 3.10 ± 3.99) was significantly smaller than the unadjusted model (Model 3, $P = 0.014$, linear mixed model adjusted after correction of *P* values for multiple testing). The root mean squared errors associated with the dB scale summation method (Model 2: 8.15 ± 5.06) was significantly larger than any other method ($P < 0.0001$, linear mixed model adjusted after correction of *P* values for multiple testing).

## Discussion

In the current study, the binocular VF was estimated from monocular VFs and ocular dominance. Measured binocular VF sensitivity was most accurately predicted using better eye VF sensitivity, worse eye VF sensitivity, and the dominance value of the test location with worse sensitivity.

Estimating the binocular VF is clinically very important because glaucomatous VF damage is closely related to the deterioration of a patient's quality of life (QOL).[4,52] Patients use both eyes in daily life, but only monocular VFs are generally tested in the clinic. Various methods have been proposed to attempt to precisely estimate the binocular VF from a patient's monocular VF. The IVF method is a particularly popular approach and is easy to calculate.[18] The approach has been shown to agree closely with the dB scale summation method[8] (Model 2 in the current study). However, one drawback of this previous report is that the importance of scale (dB or 1/Lambert) in the summation calculation was not evaluated. In two studies,[26,27] monocular and binocular contrast sensitivities were calculated using a linear scale. It should be noted that the linear scale in the previous article is not identical to that in the current study; the Michelson model is given by the following[25]: $C = (L_{max} - L_{min}) / (L_{max} + L_{min})$, where $L_{max}$ and $L_{min}$ represent maximum and minimum luminances in the sinusoidal luminance distribution. This sensitivity is usually converted to a dB scale by taking the log value, such as $-20 \times \log 10C$ in the Humphrey Matrix Perimeter (Carl Zeiss).[53] Thus, the binocular summation model may not be directly applied to retinal sensitivities measured on a dB scale with the HFA. Thus, it was of our interest to investigate retinal sensitivity on a dB scale and (1/Lambert) scale for estimating the binocular summation in the current study.

In the current study, we have shown again that binocular sensitivity is very closely related to better sensitivity, and is more accurately predicted when using the linear scale summation model. Surprisingly, and in contrast to the previous study,[18] we found that the dB scale summation method resulted in a large estimation error. Another possible approach is taking the fourth root summation in which $S_c = (\Sigma S_i \beta)^{1/\beta}$, where $S_c$ is the sensitivity to the compound stimulus, $S_i$ is the sensitivity to its *i*th component alone, and $\beta$ is equal to four.[54] We carried out this calculation using both eyes' sensitivities in both dB and linear scales, but this approach resulted in much larger absolute prediction errors with the dB scale (mean ± SD = 24.04 ± 5.66 dB) and with the linear scale (19.11 ± 4.58 dB; data not shown in Results).

Interestingly, we found that the most accurate prediction of binocular VF sensitivity was given when the linear scale summation was calculated. Further improvement was observed with an adjustment for ocular dominance, although it was statistically significant, the improvement in absolute

**Table 1.** Subject Demographics

| Demographics | Value |
|---|---|
| Age, mean ± SD | 58.2 ± 10.9 |
| Sex, male:female | 16:14 |
| VA, logMAR, mean ± SD | 0.0 ± 0.09 |
| MD in better eye, mean ± SD, dB | −5.6 ± 5.4 |
| MD in worse eye, mean ± SD, dB | −10.3 ± 5.4 |

MD, mean deviation; VA, visual acuity.

**Table 2.** Root Mean Squared Errors Associated With the Four Different Models

| Method | Absolute Prediction Error |
|---|---|
| Model 1 (IVF method), mean ± SD | 3.15 ± 4.09* |
| Model 2 (square root summation in dB scale), mean ± SD | 8.15 ± 5.06† |
| Model 3 (square root summation in linear scale), mean ± SD | 3.11 ± 4.00* |
| Model 4 (linear scale summation with weight for worse sensitivity), mean ± SD | 3.10 ± 3.99 |

* $P < 0.05$ against Model 4 (linear mixed model).
† $P < 0.01$ against Model 4 (linear mixed model).

prediction error was small. The clinical impact of this difference should be investigated in a future study. In particular, recent articles have reported that glaucoma patients' QOL can be better predicted using machine learning methods[19,21]; thus, it should be further investigated whether this significant, but small, improvement in prediction can result in a more accurate estimation of QOL.

One obvious limitation of the current study is that ocular dominance is not usually measured in the clinical setting; hence, a linear scale summation model without adjustment for dominance may be clinically more relevant. Fortunately, the difference in the absolute prediction error was small between the linear models with and without the adjustment for dominance, albeit significant. In addition, the reproducibility of measured dominance values was relatively low, as suggested by the ICC and CV values. Hence, it should be investigated whether "Model 4" can be further improved by increasing the number of dominance measurements in a future study. Furthermore, other variables, such as pupil size, have an influence on binocular summation,[24] and these were not considered in the current study. A further study should be performed to revalidate the current result, ideally using a larger population. Moreover, Tolhurst et al.[55] reported that it is beneficial to use a probability summation model when combining neuronal information, and it is recommended to multiply the input from two neural cells. This approach cannot be investigated in the current study because retinal sensitivity was attained using a bracketing method; therefore, a frequency of seen curve cannot be calculated. A further study should be carried out shedding light on this issue. The sample size in the current study is relatively small compared with an excellent previous study.[18] It would be advisable to investigate binocular summation using a larger sample size in which models are tested on a subset of patients and tested in the remaining patients (whose data were not used to build models).

The results of ocular dominance measurements can vary with different measurement approaches, such as adaptive staircase[56,57] and two alternative forced-choice methods.[29,58] We chose the current approach, because of a previous study by Xu et al.,[49] which suggested good reproducibility with this approach. As suggested by our results, ocular dominance is a possible factor to consider when binocular summation is calculated, hence further efforts should be made to determine which dominance measurement method is most advantageous to accurately estimate the binocular VF.

In conclusion, the binocular VF can be more accurately estimated using the linear scale summation model rather than IVF method or dB scale summation. Furthermore, a significant improvement in the estimation was observed by adjusting for ocular dominance.

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