A Validated Risk Calculator to Assess Risk and Rate of Visual Field Progression in Treated Glaucoma Patients

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PURPOSE. The purpose of our study is to develop and validate a model to predict visual field (VF) outcomes in patients with treated glaucoma.

METHODS. Data from 587 eyes with treated glaucoma evaluated in a cohort were used to develop two equations to predict VF outcomes, one estimating the risk of progression (%) and another estimating the global rate of VF sensitivity change (decibels [dB]/year). These equations, which included variables associated with VF progression in a multivariable model, then were tested in another cohort (n = 62 eyes) for at least 4 years. Agreement, discrimination, and calibration of the model in the validation sample were assessed as main outcome measures.

RESULTS. The mean difference between observed and predicted global rates of sensitivity change was 0.13 dB/year (95% confidence interval [CI] = 0.06 to 0.18 dB/year) and the mean difference between observed and predicted final VF mean deviation (MD) values was 0.37 dB (95% CI = 0.00 to 0.75 dB). The predictive model had moderate discriminative ability to estimate VF progression in the independent sample (c-index of 0.78, 95% CI = 0.59 to 0.97).

CONCLUSIONS. To our knowledge, this is the first attempt to generate and validate a risk model for patients with treated glaucoma. The prediction model showed moderate accuracy in estimating future VF outcomes in an independent glaucoma population, and may be useful for the objective assessment of risk of progressive VF loss. (Invest Ophthalmol Vis Sci. 2012;53:2702-2707) DOI:10.1167 iovs.11-7900

Not only is estimation of the risk and rate of structural and functional optic nerve damage critical to successful management of glaucoma, but validation of methods of estimation is equally important. Major National Institutes of Health (NIH) sponsored clinical trials have enhanced our understanding of factors associated with increased risk of developing glaucoma, and progression of damage in those with established disease.1-5 Nevertheless, risk assessment for eyes with established disc and field damage in clinical practice remains subjective and qualitative. Patients usually are classified as being at “high,” “moderate,” or “low” risk of glaucoma onset or progression on the basis of clinical features and risk factors. Such empirical approaches vary substantially among clinicians, and limit consistent and standardized case management, and the development of practice guidelines to enhance patient care.

There is an increasing need for an objective method to assess the risk of glaucoma onset and progression, particularly in relation to the rate of disease progression.6 This would allow clinicians to personalize individual treatment approaches, and to determine better the risk and benefit of treatment modifications. This challenge has been met partly for patients with ocular hypertension. The Ocular Hypertension Treatment Study (OHTS) Group,1 in collaboration with the European Glaucoma Prevention Study (EGPS)7 developed a 5-year risk calculator that permits objective estimation of the risk of conversion to glaucoma among patients with statistically elevated intraocular pressure (IOP) and normal visual field (VF) tests.8 This type of risk calculator improves clinician assessment regarding treatment versus observation.9-11

The use of the OHTS risk calculator, however, cannot be extrapolated to patients with established glaucoma. Moreover, the OHTS calculator was developed based on the natural history of ocular hypertension by evaluating the untreated arm of the cohort.8 This corresponds to a small proportion of patients in clinical practice, and none of those with established glaucomatous optic neuropathy and/or VF loss. Finally, the OHTS risk calculator uses baseline information to predict the future risk of progression over a 5-year period, but does not provide estimates of the rate of progression, and does not take into consideration the intercurrent variables that interact to increase the risk of progression, such as disc hemorrhage (DH),12 and IOP parameters, such as its peak, mean, and fluctuation.13-15

In a recent review on the importance of risk calculation in glaucoma, Mansberger et al. suggested that the development of a risk calculator for patients with established and treated disease would have profound impact on how clinicians manage their patients, similar to what has been observed with the OHTS calculator.11 Based on clinical information, such as disease severity and life expectancy, calculators for treated glaucoma also would likely increase agreement among clinicians with regard to future management of individual cases. One potential benefit of risk calculation in treated glaucoma is that it would allow clinicians to estimate objectively the risk of VF progression in the mid- and long-
Risk Calculator for Glaucoma Progression

Treatment modalities were chosen at the discretion of the attending glaucoma specialists in both cohorts. These could include topical medications (prostaglandin analogs, beta-blockers, carbonic anhydrase inhibitors, alpha-agonists, and cholinergic agents), laser therapy (selective laser trabeculoplasty, argon laser trabeculoplasty, peripheral iridotomy, and iridoplasty), and filtration surgery (trabeculectomy or shunt implants). This approach was chosen to resemble the current repertoire of glaucoma management, as opposed to standard protocols that may fail to consider individual patient needs.

Definition of Visual Field Progression

Both populations had their SAP sequences analyzed using trend analysis. Computerized point-wise linear regression (PLR) analysis was used to calculate global and localized rates of threshold sensitivity changes (PROGRESSOR software; Medisoft Ltd., Leeds, UK).17 We used the default definition of progressing VF locations provided by the manufacturer, that is a test point was deemed progressing if the rate of sensitivity decline was >1.0 dB/year at \( P < 0.01 \). For an eye to be considered progressing, at least two adjacent points in the same hemifield had to meet the above criteria. This definition likely improves specificity to define progression, as it takes into consideration the topographic orientation of the nerve fiber layer bundles that are damaged in glaucoma.

Development of the Model

Details on how the regression model was built have been described in detail previously.15 First, a logistic regression was used to evaluate the role of each IOP parameter on VF progression. All analyses were adjusted for the length of follow-up, which consisted of the time interval between the first and last VF tests entered in the analysis. Each variable was tested first in a univariable model. Those with \( P < 0.25 \) then were entered in the multivariable analysis. Since glaucoma filtering procedures lead to more substantial IOP lowering than medical therapy, which has been shown to slow the rates of VF progression,18,19 we included the occurrence of any type of incisional glaucoma surgery during follow-up in the multivariable model. Given that IOP variability during follow-up differs between filtered and non-filtered eyes,18,19 we also added the interaction term “glaucoma surgery*mean IOP” to the model. A backwards elimination procedure then was used to derive the final model (alpha-level = 0.05). The aforementioned variables were used to generate two equations: A) an equation in which the dependent variable is the risk of progression (%) in a given number of years based on the independent variables derived from our reference population, and B) an equation in which the dependent variable is the global rate of VF change, or rate of VF progression (dB/year).

A) Risk equation:

\[
\logit(p) = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \ldots + b_kx_k
\]

Where \( p \) is the probability of the outcome of interest, or dependent variable (VF progression); \( \logit(p) \) is the natural log of the odds ratio for progression; \( b_0, b_1, b_2 \ldots b_k \) are the regression coefficients of the multivariable regression equation; and \( x_1, x_2, x_3 \ldots x_k \) are the independent variables (age, CCT, IOP, etc.).

\[
\logit(p) \text{ can be back-transformed to } p \text{ by the following formula:}
\]

\[
p = 1 / \left[ 1 + e^{-\logit(p)} \right]
\]

B) Rate of progression equation:

\[
y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_3 + \ldots + \beta_kx_k
\]

Where \( y \) is a dependent, continuous variable (global rate of VF change (dB/year)); \( \beta_0, \beta_1, \beta_2 \ldots \beta_k \) are the regression coefficients of the
multivariable regression equation; and $X_1$, $X_2$, $X_3$ ... $X_k$ are the independent variables (age, CCT, IOP etc.).

Following the selection of variables from the univariable models and generating the multivariable models, the following final equations were produced:

A) \[
\text{Logit}(\rho) = -0.1862 + (\text{Age}) + 0.015596 + (\text{CCT}) + -0.0094176 \\
+ (\text{DH}) + 1.00135 + (\text{Peak IOP}) + 0.079432 \\
+ (\text{mean IOP}) + 0.0051659 + (\beta_{\text{PPA}}) + 0.81466 + (\text{Exfoliation}) \\
+ 0.41452 + (\text{Time}) + 0.10754 + (\text{Glaucoma surgery}) \\
+ -1.44953 + (\text{Glaucoma surgery} + \text{mean IOP}) \\
+ -0.13982
\]

Where $\rho$ can be obtained from the formula:

\[
\rho = 1 / \left[ 1 + e^{-\text{Logit}(\rho)} \right]
\]

B) \[
\text{Rate of VF change (dB/year)} \\
= -0.5343 + (\text{Age}) + -0.005227 + (\text{CCT}) + 0.002212 + (\text{DH}) \\
+ (\text{Peak IOP}) + -0.0259 + (\text{mean IOP}) + -0.008372 \\
+ (\beta_{\text{PPA}}) + -0.04003 + (\text{Exfoliation}) + -0.07813 \\
+ (\text{Glaucoma surgery}) + 0.4521 \\
+ (\text{Glaucoma surgery} + \text{mean IOP}) + -0.04704
\]

Assuming linearity of VF progression in glaucoma,\textsuperscript{20} one can estimate the final VF mean deviation (MD) after a given number of years applying the following equation:

\[
\text{MD}_T = \text{MD}_b + \delta \times (\Delta T)
\]

Where $\text{MD}_T$ is the final MD, $\text{MD}_b$ is the baseline MD, $\delta$ is the global rate of change (dB/year) obtained from equation B, and $\Delta T$ is the future time interval one wishes to predict the VF outcomes.

**Main Outcome Measures**

The equations for risk (%) and rate of progression (dB/year), which were developed based on the reference population, were tested in the validation population. We compared the performance of predicted and observed outcomes using the following methods:

- Hosmer-Lemeshow test (test of goodness of the fit for the predictive model).
- Bland-Altman plots comparing predicted versus observed rates of VF change as a continuous variable (dB/year).
- Bland-Altman plots comparing predicted versus observed final VF MD values (dB).

- Linear regression coefficients ($R^2$) comparing predicted and observed final VF MD values,
- Calibration of predicted and observed risks (%) of progression,
- Calibration of global rates using categorical separation of subgroups based on quartiles of predicted rates of progression: very fast, fast, moderate, and slow progressors,
- Performance of the model to discriminate risk (%) of progression and observed outcomes (c-statistic).

We used similar statistical approaches described in the reports validating the OHTS- and Diagnostics Innovation Glaucoma Study (DIGS)-derived risk models.\textsuperscript{8,21} Categorical variables were compared between the reference and validation samples using the chi-square test. Independent samples $t$-tests were used for comparisons of continuous variables. Discrimination was defined as the ability of a predictive model to separate glaucomatous eyes with and without progression. In other words, discrimination is an estimate of the probability that the model assigns a higher risk for those with progression compared with those who remained stable based on our predefined progression criteria.\textsuperscript{22} Discrimination was assessed by calculating the c-statistic as proposed by Harrell et al.,\textsuperscript{23} which is analogous to the area under the receiver operating characteristic curve. A c-index value of 0.5 indicates random predictions, whereas a value of 1.0 indicates perfect prediction.

Calibration measures how closely predicted outcomes agree with actual outcomes. To assess calibration, the predictive risks calculated for the validation population using the reference population-derived model were used to divide eyes into quartiles of predicted risk of progression.\textsuperscript{8,21} In each of the quartiles, the average predicted risk was compared with the average outcome during the follow-up time. Since a greater number of visual fields improves the performance of trend analysis to measure rates of progression minimizing the effect of VF variability,\textsuperscript{24} we tested the hypothesis that our model would predict the VF outcomes more accurately in eyes with longer sequences of tests. For that purpose, we performed a secondary analysis only on eyes with 10 or more VF tests. Computerized statistical analyses were performed using MedCalc (MedCalc software v.3.3; MedCalc, Inc., Mariakerke, Belgium) and SPSS version 16.0 (SPSS Inc., Chicago, IL).

**Results**

The equations describing the linear and logistic regression models were tested in the validation sample, and the results between predicted and observed outcomes were compared. The Hosmer-Lemeshow test showed that the final logistic model was able to fit the data correctly ($P = 0.67$). For the linear regression model, which used global rates of progression (dB/year) as a dependent variable, the coefficient of determination was $R^2 = 0.14$, the adjusted-$R^2$ was 0.13, and the multiple correlation coefficient was 0.37 at $P < 0.001$. The

<table>
<thead>
<tr>
<th>Table</th>
<th>Demographic and Ocular Characteristics of the Study Populations</th>
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<tbody>
<tr>
<td></td>
<td><strong>BPEI (n = 62)</strong></td>
</tr>
<tr>
<td>Age at baseline (years)</td>
<td>67.4 ± 8.3</td>
</tr>
<tr>
<td>Baseline MD (dB)</td>
<td>-3.7 ± 4.4</td>
</tr>
<tr>
<td>Vertical cup-disc ratio</td>
<td>0.64 ± 0.1</td>
</tr>
<tr>
<td>Mean CCT (µm)</td>
<td>539.4 ± 38.4</td>
</tr>
<tr>
<td>Peak IOP (mm Hg)</td>
<td>17.3 ± 4.5</td>
</tr>
<tr>
<td>Mean IOP (mm Hg)</td>
<td>13.4 ± 3.3</td>
</tr>
<tr>
<td>N of eyes with DH (%)</td>
<td>8 (13)</td>
</tr>
<tr>
<td>N of eyes with βPPA (%)</td>
<td>42 (67)</td>
</tr>
<tr>
<td>Exfoliation syndrome (%)</td>
<td>3 (4.8)</td>
</tr>
<tr>
<td>N of eyes undergoing glaucoma surgery (%)</td>
<td>6 (9.6)</td>
</tr>
<tr>
<td>Follow-up time (years)</td>
<td>4.0 ± 0.9</td>
</tr>
</tbody>
</table>

Values are shown as mean ± SD. BPEI, Bascom Palmer Eyes Institute; NYGAPS, New York Glaucoma Progression Study.
Table compares clinical characteristics between the reference and validation populations. The reference population had worse mean baseline VF MD, higher peak and mean IOP, greater prevalence of exfoliation syndrome and PPA, and were followed longer.

The mean difference between observed and predicted global rates of sensitivity change was 0.13 dB/year (95% CI = 0.06 to 0.18 dB). The red dashed line corresponds to the 95% limits of agreement (mean ± 1.96 SD, –0.35 to 0.61 dB). The orange dotted line in the middle represents the zero difference. (B) The Bland-Altman plot illustrates the difference between the observed and the predicted final MD values (y-axis) and their average (x-axis). The green dashed line corresponds to the 95% CI of the mean difference (0.00–0.75 dB). The red dashed line corresponds to the 95% limits of agreement (mean ± 1.96 SD, –2.56 to 3.31 dB). The orange dotted line in the middle represents the zero difference.

A secondary analysis was performed in a subgroup of eyes from the validation sample with 10 or more VF tests (n = 28 eyes). There was a discretely more uniform distribution of differences between predicted and observed values with more values ranging close to zero (Figs. 2A, 2B).

Figure 3 shows the calibration plots with predicted versus observed probabilities of glaucoma progression for the reference population-derived model when applied to the validation sample. Overall, there was good agreement between predicted and observed probabilities. The c-index for the entire sample was 0.78 (95% CI = 0.59 to 0.97). However, our model tended to overestimate progression, that is, tended to predict more progressing eyes than actually observed.

When comparing subgroups based on quartiles of predicted rates of progression (very fast, fast, moderate, and slow) the model tended to predict faster rates of progression in all groups. This overestimation was more pronounced among those with very fast rates of progression, and minimal among those with slow rates (Fig. 4).
Among the first and most important is progression. The model tended to overestimate rates and risk of progression, evidently taking into account a margin of error and the fact that the model was robust in prediction VF outcomes. Therefore, the calculator was robust despite the significant differences in the reference and validation populations illustrated in the Table. This observation supports the generalizability of our model to other populations with similar characteristics. Two equations were generated: one that provides the risk of glaucoma progression (%) based on pre-defined PLR criteria in a given number of years, and another that estimates future rates of VF change based on clinical characteristics. Assuming linearity of glaucoma VF progression, the latter equation allowed estimating the VF MD value for an individual eye in a given number of years. Despite differences between the two populations and inherent challenges related to populations seen in clinical practice, our model revealed a moderate performance in predicting VF outcomes. Therefore, the calculator was robust despite the significant differences in the reference and validation populations illustrated in the Table. This observation supports the generalizability of our model to other populations, evidently taking into account a margin of error and the fact that the model tended to overestimate rates and risk of progression.

Risk models to predict future outcomes long have been used in medicine. Among the first and most important is the Framingham Risk Score, derived from the Framingham Heart Study to estimate the 10-year risk for coronary heart disease outcomes (myocardial infarction and coronary obstruction). This model has proven useful as a means of stratifying patients based on their risk profiles, which allows customized, individualized intervention. In ophthalmology, the OHTS and the DIGS developed risk models to assess the 5-year risk of conversion to primary open-angle glaucoma among patients with ocular hypertension and have proven clinically useful in clinical practice, our model revealed a moderate performance in predicting VF outcomes. Therefore, the calculator was robust despite the significant differences in the reference and validation populations illustrated in the Table. This observation supports the generalizability of our model to other populations, evidently taking into account a margin of error and the fact that the model tended to overestimate rates and risk of progression.

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measurement error, biological variation, variables not entered in the model or sometimes entered as indirect estimates, and due to a non-linear relationship between outcome and predictor variables. These all are inherent limitations of using a mathematical model to explain a biological phenomenon that still is poorly understood, such as glaucoma progression. We are unable to compare our results directly with the OHTS/EGPS or DIGS calculators, since their publications do not report measures of goodness of the fit of their model, which was based on Cox proportional hazards modeling using an event-based approach. However, this observation underscores the importance of interpreting the results of the calculator with caution, not using its results to tailor glaucoma therapy, but rather providing an objective, numerical variable to measure risk and that could be added to the clinician repertoire of factors used to monitor glaucoma.

In conclusion, to our knowledge our report represents the first attempt to generate and validate a risk model for patients with treated glaucoma. Our prediction model demonstrated moderate accuracy in estimating future VF outcomes in an independent glaucoma population, and may be useful for assessment of risk and rate of progressive VF loss.

References