The Region of Largest β-Zone Parapapillary Atrophy Area Predicts the Location of Most Rapid Visual Field Progression

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Purpose: To determine if visual field (VF) progression occurs most rapidly in the region of largest β-zone parapapillary atrophy (PPA).

Design: Retrospective cohort.

Participants: One hundred twenty-five patients from the New York Glaucoma Progression Study with both β-zone PPA and VF progression.

Methods: Treated open-angle glaucoma patients with 8 or more Swedish Interactive Threshold Algorithm Standard 24-2 VFs (Humphrey Field Analyzer II; Carl Zeiss Meditec, Inc., Dublin, CA) in either eye were identified. Eyes with optic disc photographs, β-zone PPA, less than 6 diopters myopia, and VF progression were studied. Visual field progression was defined using trend analysis as the presence of at least 2 adjacent progressing points in the same hemifield using standard pointwise linear regression (PLR) criteria.

Main Outcome Measures: The correlation between β-zone PPA and location of most rapid future VF progression.

Results: One hundred twenty-five eyes (125 patients; mean age, 71.9±12.3 years; 58% women; 75% European descent) with β-zone PPA and VF progression were enrolled. The mean follow-up was 6.8±1.7 years and the mean number of VFs was 12.5±3.6. Ninety-three patients (74%) had more β-zone PPA inferiorly and 32 patients (26%) had more β-zone PPA superiorly. The fastest VF progression occurred in the superior hemifield in 77 patients (62%) and in the inferior hemifield in 48 (38%) patients. Patients with superior VF progression had a superior localized mean rate of progression of −1.57±1.7 dB/year, and patients with inferior VF progression had an inferior localized mean rate of −0.94±1.4 dB/year ($P = 0.012$). The mean number of points reaching the predefined PLR end points was 5.6±7.5 for the superior VF hemifield and 3.0±4.9 for the inferior hemifield ($P = 0.006$). The hemifield with more points reaching PLR progression end points, with fastest average velocity of progression, or both was spatially consistent with the location of largest β-zone PPA in 89 (71%) patients ($P = 0.0001$, Fisher exact test; $\kappa = 0.35$; 95% confidence interval, 0.17–0.53).

Conclusions: In treated glaucoma patients with β-zone PPA and VF progression, the location of largest β-zone PPA typically correlates spatially with the region of the most rapid future VF progression.

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β-Zone parapapillary atrophy (PPA) is associated with glaucoma[1–7] and subsequent visual field (VF) progression.[7] Anderson[8] initially reported that the conformation of PPA helps determine the location of disc damage and VF abnormalities, whereas Heijl and Samander[9] found that the location of widest PPA is spatially consistent with the location of the VF defect. Jonas et al[1] and Jonas and Naumann[2] confirmed these findings and divided PPA into α and β zones on the basis of its features. In cross-sectional studies, Park et al[3] demonstrated the spatial relationship between VF defect location and β-zone PPA in normal-tension glaucoma patients, and Kono et al[4] described this relationship for primary open-angle glaucoma.

Although the spatial relationship between the location of VF defects and location of β-zone PPA has been established, the relationship between β-zone PPA and the area of most rapid future VF progression remains unclear. A previous study confirmed that eyes with β-zone PPA progressed more rapidly than eyes without it.[7] The present study sought to determine whether the location of largest β-zone PPA is consistent with the location of the most rapid future VF progression.

Patients and Methods

The New York Glaucoma Progression Study consists of more than 40 000 consecutive subjects (>130 000 VF tests) evaluated in the glaucoma referral practice of the authors (J.M.L., R.R., C.T.) from January 1999 through September 2009. After an initial visit consisting of a complete ophthalmologic examination, perimetry (24–2 Swedish Interactive Threshold Algorithm SAP, Humphrey Field Analyzer II; Carl Zeiss Meditec, Inc., Dublin, CA) and optic disc stereophotographs, patients were re-examined, usually at 3- to 6-month intervals, and the same tests were repeated within 6 to 12 months. The study was approved by the New York Eye and Ear Infirmary Institutional Review Board and followed the tenets of the Declaration of Helsinki.

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The records of all New York Glaucoma Progression Study subjects with established open-angle glaucoma and repeatable VF loss, optic disc photography, and 8 or more Swedish Interactive Threshold Algorithm Standard VF examinations were reviewed for entry into this retrospective study. From this group, eyes with an optic disc photograph, β-zone PPA, less than 6 diopters (D) of myopia, and VF progression (described below) were enrolled. If both eyes of the same patient met the inclusion criteria, the eye with largest number of VF tests was enrolled.

Visual Field Analysis

A glaucomatous VF was defined as glaucoma hemifield test results outside normal limits or a pattern standard deviation of less than 0.5% on at least 2 consecutive baseline VF tests. The 2 baseline tests required reliability indices better than 25% to be included.

Automated pointwise linear regression (PLR) analysis was performed using Progressor software (version 3.3; Medisoft, Ltd., Leeds, UK) providing slopes (decibels [dB]/year) of progression both globally and locally for each point based on threshold maps, as well as its level of significance (P values).[10] Interim VF results were not excluded because of unreliable indices, because Progressor automatically removes outliers from the regression, thus minimizing the effect of unreliable or noisy tests on the slopes.[11]

For patients unfamiliar with automated perimetry (<2 previous VF tests), the first 2 VF examinations were not included in the regression analysis. A test point was defined as progressing if it had a slope of sensitivity over time of more than 1.0 dB loss/year, with $P<0.01$. For edge points, a stricter slope criterion of more than 2.0 dB loss/year (also with $P<0.01$) was used.[10,12,13] A progression end point was defined as the development of at least 2 progressing, adjacent points in the same hemifield meeting the aforementioned criteria. Only eyes reaching these progression criteria were included and analyzed in this cohort.

Clinical Data

β-Zone PPA was defined as the region of chorioretinal atrophy with visible sclera and choroidal vessels adjacent to the optic disc. Using the baseline optic nerve stereophotograph from the visit closest in date to the first VF test entered in the regression analysis, masked β-zone PPA determination was performed by 2 independent investigators (C.C.T., T.S.P.) using the method described by Park et al.[3] This technique superimposes a line on the stereophotograph from the 2:30 to 8:30 clock position to account for the position of the fovea, which is 2° to 6° below the optic disc. The investigators independently reviewed each patients' baseline disc stereophotograph and determined which half of the disc was adjacent to the region of largest β-zone PPA.

The superior or inferior VF hemifield with the fastest rate of progression, determined using PLR, was recorded by an investigator masked to the PPA data (C.G.D.M.). This was determined by choosing the hemifield with the greatest number of points reaching PLR progression end points. In the event that both hemifields had an equal number of progressing points, the hemifield with fastest localized rate of change (mean velocity of the progressing points) was chosen. The hemifield rate of change was defined as the average rate of change of the points in that hemifield reaching a PLR end point.

The mean deviation value of the baseline VF for each enrolled eye was recorded. Mean IOP was obtained by averaging the IOP from every office visit. The IOP fluctuation was defined as the standard deviation of these values, and peak IOP was the highest reported IOP during the follow-up period (excluding measurements within 1 month of any surgery). Central corneal thickness was measured using ultrasonic pachymetry (DGH-550; DGH Technology, Inc., Exton, PA).

Statistical Analysis

The mean rates of superior and inferior localized VF progression (considering only the points reaching the progression criteria), the number of superior and inferior test points reaching a VF progression end point, and the mean of the sum of slopes in the superior and inferior hemifield, respectively, were compared using a paired-samples t test. The relationship between the location of β-zone PPA and location of VF progression was assessed using the Fisher exact test and κ test.

Results

One hundred twenty-five eyes (125 patients; mean age, 71.9±12.3 years; 58% women; 75% European descent) with glaucomatous optic neuropathy, baseline VF damage, β-zone PPA, and VF progression were enrolled. All subjects had been treated with a variety of glaucoma treatments. Mean IOP was 15.5±2.7 mmHg; peak IOP was 20.7±4.3; IOP fluctuation was 2.8±1.4 mmHg; central corneal thickness was 529±37 μm; and VF mean deviation was −7.3±4.9 dB. Mean follow-up was 6.8±1.7 years, and the mean number of VF tests was 12.5±3.6. The mean rate of global VF progression for all subjects was −0.94±0.84 dB/year (Table 1).

Ninety-three patients (74%) had more β-zone PPA adjacent to the inferior half of the optic nerve head and 32 (26%) had more adjacent to the superior half. Visual field progression was more rapid in the superior hemifield in 77 patients (62%) and in the inferior hemifield in 48 patients (38%) (Table 2).

Patients with superior VF progression had a mean rate of superior localized VF progression of −1.57±1.7 dB/year, and patients with inferior VF progression had a mean rate of inferior localized VF progression of −0.94±1.4 dB/year ($P = 0.012$). The mean number of test points reaching a VF progression end point was 5.6±7.5 for the superior VF hemifield and 3.0±4.9 for the inferior VF hemifield ($P = 0.006$). The mean of the sum of slopes for the superior hemifield was −14.5±23.1 dB/year, and the mean of sum of slopes for the inferior hemifield was −7.1±12.4 dB/year ($P = 0.006$; Table 3).

Table 1. Baseline Characteristics of the Studied Population

Variable	(n = 125)
Age (yrs)	71.9±12.3
Gender (female)	73 (58%)
Ethnicity (European descent)	94 (75%)
CCT (μm)	529±37
Total number of VF	12.5±3.6
Follow-up (yrs)	6.8±1.7
Baseline MD (dB)	−7.3±4.9
Mean IOP (mmHg)	15.5±2.7
Peak IOP (mmHg)	20.7±4.3
IOP fluctuation (mmHg)	2.8±1.4
Global rate of VF progression (dB/yr)	−0.94±0.84

CCT = central corneal thickness; dB = decibels; IOP = intraocular pressure; MD = mean deviation; mmHg = millimeters of mercury; VF = visual field.

Table 2. Location of β-Zone Parapapillary Atrophy and Visual Field Progression

Parameter	n (%)	95% Confidence Interval
β-zone PPA greatest superiorly	32 (26)	18.7–33.9
β-zone PPA greatest inferiorly	93 (74)	66.1–81.3
VF progression fastest superiorly	77 (62)	52.8–69.7
VF progression fastest inferiorly	48 (38)	30.3–47.2

PPA = parapapillary atrophy; VF = visual field.

Of the 77 eyes with superior VF progression, the region of greatest β-zone PPA was inferior in 67 eyes and superior in 10 eyes. Of the 48 eyes with inferior VF progression, the region of greatest β-zone PPA was superior in 22 eyes and inferior in 26 eyes. The spatial correlation of the location of β-zone PPA and the location of most rapid VF progression was significant (P = 0.0001, Fisher exact test). There was a moderate agreement between the location of β-zone PPA and VF progression (κ = 0.35; 95% confidence interval, 0.17–0.53; Table 4).

When analyzing only those eyes with spatial consistency between β-zone PPA and future VF progression, there was no significant difference in the number of progressing points between the superior and inferior VFs (9.2±7.8 vs. 7.4±4.9; P = 0.709). Similarly, there was no difference in the mean rate of localized VF progression between these groups (−2.42±1.1 vs. –2.41±0.8 dB/year; P = 0.397; Table 5).

Discussion

The association between PPA and glaucoma was described first by Elschnig[14] and Bücklers.[15] Others recognized the presence of PPA in glaucoma.[16,17] Anderson[8] theorized that PPA location was associated with localized disc and VF damage. Reviewing 108 cases with disc photographs and VFs, he concluded that the appearance of parapapillary tissue helps determine how susceptible a disc is to pressure-induced damage and which portion of the disc and field would be most affected. In 62 consecutive patients with glaucomatous field loss, Heijl and Samander[9] found a significant correlation between the location of widest PPA and the location of the VF defect. They found that 76% of eyes with PPA had a VF defect that was spatially consistent with the location of PPA.

Table 3. Number of Progressing Points, Mean Localized Rate of Visual Field Progression, and Mean of the Sum of Slopes for the Superior and Inferior Visual Field Hemifield

	Superior Visual Field Hemifield	Inferior Visual Field Hemifield	*P* Value*
No. of eyes	77 (62%)	48 (38%)	N/A
No. of progressing points	5.6±7.5	3.0±4.9	0.006
Mean localized rate of VF progression (db/yr)	−1.57±1.7	−0.94±1.4	0.012
Mean sum of slopes (db/yr)	−14.5±23.1	−7.1±12.4	0.006

dB = decibels; VF = visual field.
For eyes that did not reach a progression end point, the localized rates of change were assumed to be 0 dB/yr for comparative purposes.
*Paired-samples t test.

Table 4. β-Zone Parapapillary Atrophy versus Visual Field Progression

β-Zone Parapapillary Atrophy	Visual Field Progression		Total
	More Inferior	*More Superior*	
More superior	22	10	32
More inferior	26	67	93
Total	48	77	125

P = 0.0001, Fisher exact test; κ = 0.35; 95% confidence interval, 0.17–0.53.

These results confirm and expand on the results of Anderson and of Heijl and Samander. By using PLR to analyze VF progression, the present study demonstrated that there is a significant association between the region of largest β-zone PPA and the location of most rapid future VF progression. More eyes had β-zone PPA in the inferior half of the optic nerve complex, and this correlated significantly to more rapid VF progression and a greater number of progressing points in the superior VF hemifield.

Visual field progression was more rapid in the superior hemifield in 77 patients (62%) and in the inferior hemifield in 48 patients (38%). Hart and Becker[18] found the superior VF hemifield to be damaged more often in early to moderate open-angle glaucoma, whereas other studies reported that the superior VF area just above the horizontal meridian is more vulnerable to damage, especially in eyes with normal-tension glaucoma.[19,20]

Park et al[3] reported that PPA and the VF defect was correlated spatially in normal-tension glaucoma patients. Of 51 eyes, 61% had worse VF in the superior hemifield and 39% had worse VF in the inferior hemifield. Of the 31 eyes with worse superior hemifield, 24 had widest total PPA at the corresponding inferior side of the disc, and of the 20 eyes with worse inferior VF hemifield, 12 had widest total PPA at the corresponding superior side of the disc.

Tezel et al[21] reported on the concordance of PPA in ocular hypertension with VF defects and found that progres-

Table 5. Number of Progressing Points and Mean Localized Rate of Visual Field Progression for Patients with Spatially Consistent β-Zone Parapapillary Atrophy and Visual Field Progression

	Inferior β-Zone Parapapillary Atrophy, Superior VF Progression (n = 67)	Superior β-Zone Parapapillary Atrophy, Inferior VF Progression (n = 22)	*P* Value
No. of progressing points	9.2±7.8	7.4±4.9	0.709
Mean localized rate of VF progression (db/yr)	−2.42±1.1	−2.41±0.8	0.397

dB = decibels; VF = visual field.

sive PPA changes in ocular hypertensive patients was correlated with the location of VF abnormalities. The location of progressive PPA change was concordant with the location of VF defects in 78% of quadrants.

Glaucomatous VF progression often follows 1 or a combination of patterns: (1) development of a new scotoma; (2) deepening of a previous scotoma; (3) and expansion of a previous scotoma.[22–24] The latter 2 are the most common patterns[23] and are consistent with the current results. This hypothesis is valid for areas of the VF with mild to moderate loss. As the areas of the VF with defective points start developing very low sensitivities because the VF is already highly damaged, progression is unlikely to be detected using PLR because of floor effect; that is, the sensitivities reach such low values that the slopes become falsely flat (close to 0). This may be one reason that not all patients had spatial consistency between VF progression and location of β-zone PPA.

De Moraes et al[25] demonstrated that eyes with superior hemifield loss at baseline progress more rapidly than eyes in which the inferior hemifield is affected initially. This may be at least in part the result of the structure of the lamina cribrosa, which has attachments to the parapapillary sclera and is an important determinant of the degree of susceptibility to damage by elevated IOP.[26] Ultrastructural features of the lamina cribrosa could result in different superior versus inferior susceptibilities to damage and progression.[27] The inferior temporal lamina cribrosa has the least connective tissue in proportion to the largest pores, which is consistent with greater frequency of superior VF defects.[26,27] Jonas et al[28,29] also reported that a larger single-pore area increased glaucoma susceptibility in the inferior region, followed by the superior disc region, which suggests that lamina cribrosa morphologic features could correspond to clinically observed regional variations in glaucoma susceptibility.

Glaucoma susceptibility may be related to laminar deformation, in which IOP-induced deformation could cause strain on the surrounding tissues, which eventually fail.[30] This transfers the force to the parapapillary sclera and may increase susceptibility to PPA. The choriocapillaris surrounding β-zone PPA may be less densely vascularized and an ultrastructural study demonstrated areas of collapse of choriocapillary vessels in glaucoma eyes with parapapillary atrophy, meaning that the choriocapillaris may be completely closed in the parapapillary region.[31] This was observed in the parapapillary region only, which may indicate that reduced choroidal perfusion resulting from high IOP may cause retinal pigment epithelium degeneration and may cause the formation of β-zone PPA.[31] In addition to decreasing choroidal perfusion, collapse of vessels could reduce nutritional components to the parapapillary area, causing and enlarging PPA and damaging the optic disc.[32]

The parapapillary vasculature was investigated by Hayreh,[33] who described parapapillary choroidal circulation as an open circulation, in contrast to the closed retinal circulation. Increased IOP in glaucoma patients may cause obliteration or closure of the parapapillary choriocapillaris and in turn may lead to degeneration of the retinal pigment epithelium and surrounding cells. β-Zone PPA does not fluoresce in the early angiographic and choroidal filling phases.[34] This likely occurs because β-zone PPA is characterized by atrophy of the retinal pigment epithelium and choriocapillaris, with thinning of chorioretinal tissues.[1,35] The prelaminar portion of the optic nerve head receives its blood flow from the parapapillary choroid via branches of the short posterior ciliary arteries; therefore, closure of the parapapillary choriocapillaris could result in ischemic optic nerve damage and possible formation of β-zone PPA.[3,33]

Alternatively, β-zone PPA may be developmental or acquired during aging and may precede the onset of elevated IOP.[35,36] These regions of β-zone PPA could be a portal of entry for circulating vasoconstrictors that may hamper autoregulatory vasodilation, leaving the optic nerve more vulnerable to pressure-induced ischemia and damage.[35]

These results demonstrate that location of largest β-zone PPA is spatially consistent with the location of most rapid future VF progression. The similarity in the number of progressing points and their localized rates of change between the inferior β-zone PPA–superior VF progression and superior β-zone PPA–inferior VF progression subgroups (Table 5) suggests that the relationship between β-zone PPA and VF progression is an intrinsic feature of the disease process.

It was not the purpose of this study to investigate whether eyes with β-zone PPA progress more rapidly than those without this feature. This already has been confirmed in a different set of patients using trend analysis.[7] Additionally, the location of the central retinal trunk was not investigated, which could have influenced the study because of the association between location of β-zone PPA and longest distance to the central retinal vessel trunk, which has been suggested to stabilize the lamina cribrosa.[37] Although the association between neuroretinal rim thinning and presence of β-zone PPA was not examined, Jonas et al[1] and Jonas and Naumann[2] demonstrated that β-zone PPA is largest adjacent to areas of rim loss. By comparing disc regions and VF hemifields in the same eye, the effect of any systemic or ocular variables that could account for differences in rates of VF progression associated with β-zone PPA were removed.

In conclusion, in treated glaucoma patients with β-zone PPA, the location of largest β-zone PPA correlates with the location of most rapid VF progression. Further investigation to assess the relationships of the structural characteristics of the optic nerve complex and VF progression is warranted.

References

1. Jonas JB, Nguyen XN, Gusek GC, Naumann GO. Parapapillary chorioretinal atrophy in normal and glaucoma eyes. I. Morphometric data. Invest Ophthalmol Vis Sci 1989;30:908–18.
2. Jonas JB, Naumann GO. Parapapillary chorioretinal atrophy in normal and glaucoma eyes. II. Correlations. Invest Ophthalmol Vis Sci 1989;30:919–26.
3. Park KH, Tomita G, Liou SY, Kitazawa Y. Correlation between peripapillary atrophy and optic nerve damage in normal-tension glaucoma. Ophthalmology 1996;103:1899–906.
4. Kono Y, Zangwill L, Sample PA, et al. Relationship between parapapillary atrophy and visual field abnormality in

primary open-angle glaucoma. Am J Ophthalmol 1999;127:674–80.
5. Jonas JB. Clinical implications of peripapillary atrophy in glaucoma. Curr Opin Ophthalmol 2005;16:84–8.
6. Jonas JB, Fernández MC, Naumann GO. Glaucomatous parapapillary atrophy: occurrence and correlations. Arch Ophthalmol 1992;110:214–22.
7. Teng CC, De Moraes CG, Prata TS, et al. Beta-zone parapapillary atrophy and the velocity of glaucoma progression. Ophthalmology 2010;117:909–15.
8. Anderson DR. Correlation of the peripapillary damage with the disc anatomy and field abnormalities in glaucoma. In: Greve EL, Heijl A, eds. Fifth International Visual Field Symposium, Sacramento, CA, October 20-23, 1982. The Hague: W. Junk; 1983:1–10. Doc Ophthalmol Proc Ser 35.
9. Heijl A, Samander C. Peripapillary atrophy and glaucomatous visual field defects. In: Heijl A, Greve EL, eds. Sixth International Visual Field Symposium, Santa Margherita Ligure, Italy, May 27-31, 1984. Dordecht, Netherlands: W. Junk; 1985:403–7. Doc Ophthalmol Proc Ser 42.
10. Viswanathan AC, Fitzke FW, Hitchings RA. Early detection of visual field progression in glaucoma: a comparison of PROGRESSOR and STATPAC 2. Br J Ophthalmol 1997;81:1037–42.
11. Fitzke FW, Hitchings RA, Poinoosawmy D, et al. Analysis of visual field progression in glaucoma. Br J Ophthalmol 1996;80:40–8.
12. Crabb DP, Fitzke FW, McNaught AI, et al. Improving the prediction of visual field progression in glaucoma using spatial processing. Ophthalmology 1997;104:517–24.
13. Strouthidis NG, Scott A, Peter NM, Garway-Heath DF. Optic disc and visual field progression in ocular hypertensive subjects: detection rates, specificity, and agreement. Invest Ophthalmol Vis Sci 2006;47:2904–10.
14. Elschnig A. Der Normale Sehnerveneintritt Des Menschlichen Auges. Denkschr Kais Akad Wiss Math-Naturwiss Cl 1901;70:219–304.
15. Bücklers M. Anatomische Untersuchung über die Beziehungen zwischen der senilen und der myopischen circumpapillären Aderhautatrophie: Unter Beifügung eines Falles von hochgradiger Anisometropie. Albrecht Von Graefes Arch Ophthalmol 1929;121:243–83.
16. Primrose J. The incidence of the peripapillary halo glaucomatosus. Trans Ophthalmol Soc U K 1970;89:585–7.
17. Wilensky JT, Kolker AE. Peripapillary changes in glaucoma. Am J Ophthalmol 1976;81:341–5.
18. Hart WM Jr, Becker B. The onset and evolution of glaucomatous visual field defects. Ophthalmology 1982;89:268–79.
19. Araie M, Yamagami J, Suziki Y. Visual field defects in normal-tension and high-tension glaucoma. Ophthalmology 1993;100:1808–14.
20. Kawano J, Tomidokoro A, Mayama C, et al. Correlation between hemifield visual field damage and corresponding parapapillary atrophy in normal-tension glaucoma. Am J Ophthalmol 2006;142:40–5.
21. Tezel G, Dorr D, Kolker AE, et al. Concordance of parapapillary chorioretinal atrophy in ocular hypertension with visual field defects that accompany glaucoma development. Ophthalmology 2000;107:1194–9.
22. Mikelberg FS, Drance SM. The mode of progression of visual field defects in glaucoma. Am J Ophthalmol 1984;98:443–5.
23. Anderson DR, Patella VM. Automated Static Perimetry. 2nd ed. St. Louis, MO: Mosby; 1999:198–206.
24. Boden C, Blumenthal EZ, Pascual J, et al. Patterns of glaucomatous visual field progression identified by three progression criteria. Am J Ophthalmol 2004;138:1029–36.
25. De Moraes CG, Prata TS, Tello C, et al. Glaucoma with early visual field loss affecting both hemifields and the risk of disease progression. Arch Ophthalmol 2009;127:1129–34.
26. Quigley HA, Addicks EM, Green WR, Maumenee AE. Optic nerve damage in human glaucoma. II. The site of injury and susceptibility to damage. Arch Ophthalmol 1981;99:635–49.
27. Dandona L, Quigley HA, Brown AE, Enger C. Quantitative regional structure of the normal human lamina cribrosa: a racial comparison. Arch Ophthalmol 1990;108:393–8.
28. Jonas JB, Mardin CY, Schlötzer-Schrehardt U, Naumann GO. Morphometry of the human lamina cribrosa surface. Invest Ophthalmol Vis Sci 1991;32:401–5.
29. Jonas JB, Fernández MC, Stürmer J. Pattern of glaucomatous neuroretinal rim loss. Ophthalmology 1993;100:63–8.
30. Burgoyne CF, Downs JC. Premise and prediction-how optic nerve head biomechanics underlies the susceptibility and clinical behavior of the aged optic nerve head. J Glaucoma 2008;17:318–28.
31. Kubota T, Schlötzer-Schrehardt UM, Naumann GO, et al. The ultrastructure of parapapillary chorioretinal atrophy in eyes with secondary angle closure glaucoma. Graefes Arch Clin Exp Ophthalmol 1996;234:351–8.
32. Anderson DR. Introductory comments on blood flow autoregulation in the optic nerve head and vascular risk factors in glaucoma. Surv Ophthalmol 1999;43(suppl):S5–9.
33. Hayreh SS. Blood supply of the optic nerve head and its role in optic atrophy, glaucoma, and oedema of the optic disc. Br J Ophthalmol 1969;53:721–48.
34. Hayreh SS, Walker WM. Fluorescent fundus photography in glaucoma. Am J Ophthalmol 1967;63:982–9.
35. Fantes FE, Anderson DR. Clinical histologic correlation of human peripapillary anatomy. Ophthalmology 1989;96:20–5.
36. Rockwood EJ, Anderson DR. Acquired peripapillary changes and progression in glaucoma. Graefes Arch Clin Exp Ophthalmol 1988;226:510–5.
37. Jonas JB, Budde WM, Németh J, et al. Central retinal vessel trunk exit and location of glaucomatous parapapillary atrophy in glaucoma. Ophthalmology 2001;108:1059–64.

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