

Automated evaluation of parapapillary choroidal microvasculature in crowded optic discs: a controlled, optical coherence tomography angiography study

Hatice Arda¹, Hidayet Sener¹, Ozge Temizyurek¹, Hatice Kubra Sonmez¹, Duygu Gulmez Sevim¹, Cem Evereklioglu¹, Fatih Horozoglu¹, Ayse Busra Gunay Sener²

¹Department of Ophthalmology, Erciyes University Medical Faculty, Kayseri 38090, Turkey

²Department of Medical Informatics and Biostatistics, Erciyes University Medical Faculty, Kayseri 38090, Turkey

Correspondence to: Hatice Arda. Department of Ophthalmology, Erciyes University Medical Faculty, Kayseri 38090, Turkey. haticearda75@gmail.com

Received: 2023-03-06 Accepted: 2023-11-07

Abstract

• **AIM:** To compare superficial and deep vascular properties of optic discs between crowded discs and controls using optical coherence tomography angiography (OCT-A).

• **METHODS:** Thirty patients with crowded discs, and 47 control subjects were enrolled in the study. One eye of each individual was included and OCT-A scans of optic discs were obtained in a 4.5×4.5 mm² rectangular area. Radial peripapillary capillary (RPC) density, peripapillary retinal nerve fiber layer (pRNFL) thickness, cup volume, rim area, disc area, cup-to-disc (c/d) area ratio, and vertical c/d ratio were obtained automatically using device software. Automated parapapillary choroidal microvasculature (PPCMv) density was calculated using MATLAB software. When the vertical c/d ratio of the optic disc was absent or small cup, it was considered as a crowded disc.

• **RESULTS:** The mean signal strength index of OCT-A images was similar between the crowded discs and control eyes ($P=0.740$). There was no difference in pRNFL between the two groups ($P=0.102$). There were no differences in RPC density in whole image ($P=0.826$) and peripapillary region ($P=0.923$), but inside disc RPC density was higher in crowded optic discs ($P=0.003$). The PPCMv density in the inner-hemisuperior region was also lower in crowded discs ($P=0.026$). The pRNFL thickness was positively correlated with peripapillary RPC density ($r=0.498$, $P<0.001$). The inside disc RPC density was negatively correlated with c/d area ratio ($r=-0.341$, $P=0.002$).

• **CONCLUSION:** The higher inside disc RPC density and

lower inner-hemisuperior PPCMv density are found in eyes with crowded optic discs.

• **KEYWORDS:** crowded optic disc; ischemic optic neuropathy; optical coherence tomography angiography; parapapillary choroidal microvasculature

DOI:10.18240/ijo.2024.01.15

Citation: Arda H, Sener H, Temizyurek O, Sonmez HK, Gulmez Sevim D, Evereklioglu C, Horozoglu F, Gunay Sener AB. Automated evaluation of parapapillary choroidal microvasculature in crowded optic discs: a controlled, optical coherence tomography angiography study. *Int J Ophthalmol* 2024;17(1):113-118

INTRODUCTION

Accurate evaluation of the optic nerve head is essential for the diagnosis of diseases such as congenital optic nerve defects, optic neuropathies, and glaucoma. The optic nerve head is examined by qualitative and quantitative methods^[1]. The morphological properties of the optic disc such as shape, diameter and cup size are important due to their relationship with various optic nerve diseases^[2-3].

Crowded optic disc is a condition in which the small optic disc appears to be overly crowded with blood vessels. Non-arteritic ischemic optic neuropathy (NAION) is a type of optic nerve damage that can cause vision loss. It is sometimes associated with crowded discs, although the relationship between the two is not well understood. While NAION can affect people with or without crowded discs, people with crowded discs have an increased risk of developing the condition^[4]. An optic disc is considered crowded if the cup-to-disc (c/d) ratio is absent or small cup^[5-7].

Optical coherence tomography angiography (OCT-A) is a non-invasive, objective and repeatable method that allows examination of the microvascular architecture of the retina and optic disc by detecting the movement of red blood cells in the retinal vessels and creating angiographic images of the perfused vessels^[8-9]. This study aimed to compare the parapapillary superficial and deep microvascular properties of crowded and normal optic discs by using OCT-A.

SUBJECTS AND METHODS

Ethical Approval All procedures performed with human participants were in accordance with the 2013 Helsinki declaration and its later amendments or comparable ethical standards. The study protocol was approved by the Erciyes University Local Ethics Committee (No: 2022/782). Written informed consent was obtained from all individual participants included in the study.

Baseline Examination All patients underwent biomicroscopic evaluation of the anterior segment and the retina. Demographic data (age and gender) were recorded. OCT-A scans and wide-angle retinal images were performed on all subjects by an experienced retina analysis technician.

Participants, Study Groups, and Eligibility Criteria The participants were selected from patients who applied for routine examination and did not have any ophthalmic pathology other than crowded optic disc images. The eyes of age and gender matched volunteers were included as the control group. Thirty patients with crowded optic discs, and 47 control subjects were enrolled in the study. Only one eye of each participant with the higher signal strength index (SSI) was included. In cases where SSI was equal in both eyes, one of the eyes was selected randomly. Optic discs with absent or small cup (c/d ratio below 0.2) were included in the crowded optic disc group and the others were included in the control group^[5-7,10-11]. The optic disc head appearance of the volunteers included in the control group was completely within normal limits. All optic discs with oblique appearance or suspicious for any ocular disease (ocular hypertension, *etc.*) were excluded from the study. Exclusion criteria were as follows for all participants: diabetes mellitus, hypertension, pregnancy, glaucoma, histories of previous ocular surgery, ischemic optic neuropathy, neurologic disease, high refractive errors (<-3 D or >3 D), and low-quality OCT-A image (SSI<6 or motion artefact).

Wide-Angle Retina Imaging Colored wide-angle retina imaging was performed with an Optomap Panoramic 200Tx scanning laser ophthalmoscope (Optos, Dunfermline, UK). Vertical and horizontal optic disc diameters were evaluated from retinal images with a measure distance tool by two clinicians (Temizyurek O and Sonmez HK).

OCT-A Scan Protocol OCT-A images were obtained using an Avanti RTVue XR instrument (Avanti RTVue XR; Optovue, Fremont, CA, USA), which performs 70 000 A-mode scans per second using an 840 nm light source (bandwidth: 50 nm) and uses the split-spectrum amplitude decorrelation angiography (SSADA) algorithm. Optic disc OCT-A scans were obtained in a 4.5×4.5 mm rectangular area. The device performs 1 horizontal and 1 vertical volumetric scan centered on the optic disc and uses 2- and 4-mm diameter 1 mm wide rings centered

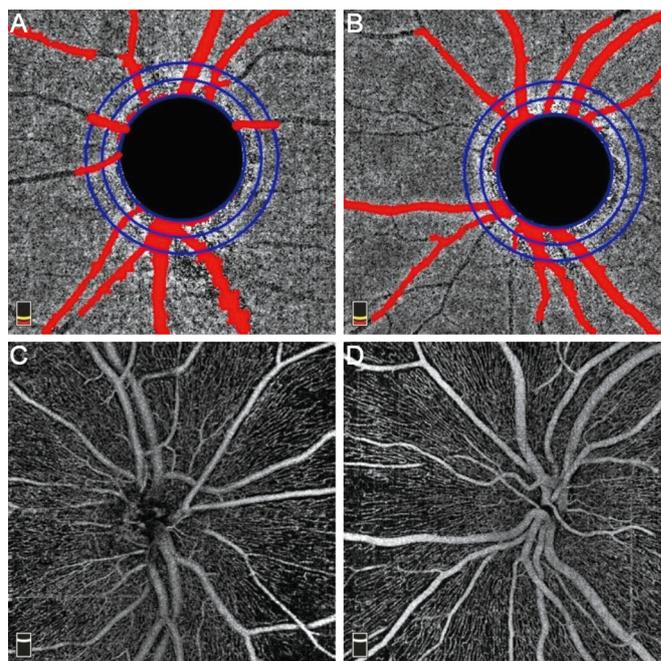


Figure 1 Deep parapapillary microvasculature after removal of retinal vessel shadow (red) Three concentric circles were overlaid on the en face image. Width of rings was 0.5 mm. PPCMv densities of regions of interest were calculated. Image of parapapillary choroidal. Microvasculature in a subject with crowded optic disc (A), and a subject with normal optic disc (B). Image of radial peripapillary capillaries in an eye with a crowded optic disc (C), and with a normal optic disc (D).

on the optic disc. Radial peripapillary capillary (RPC) density (%) was automatically obtained using device software version 2017.1.0.151. The peripapillary and two equal hemispheres (superior and inferior) retinal nerve fiber layer (pRNFL) thickness (μm) were obtained using the same device. Cup volume, rim area, disc area, c/d area ratio and vertical c/d ratio were also obtained with the same device. Images with 6 or more (on a 10-point scale) SSI and without motion artifacts were included in the analysis.

Image Processing for Parapapillary Choroidal Microvasculature A previously developed^[12] and validated^[13] customized MATLAB software (The MathWorks, Inc., Natick, Massachusetts, USA) was used to calculate the parapapillary choroid microvasculature (PPCMv) density (Figure 1). Choriocapillaris en face images with removed shadows of large disc vessels and inside-disc vessels with black mask were used for image processing. The algorithm follows the steps of: creation of the binary position of large retinal vessel shadows; parapapillary capillary segmentation by modified Otsu algorithm; and calculating the PPCMv density with automatic threshold detection. Three concentric circles were overlaid on the en face image. Width of rings was 0.5 mm. PPCMv densities of regions of interest were calculated^[13-14].

Statistical Analysis Statistical analysis was performed

using SPSS version 22 (IBM, Chicago, USA). The Shapiro-Wilk normality test and the Levene variance homogeneity test were performed with the data set. Pearson Chi-square test was performed for nominal data. Student *t*-test was performed for normally distributed data, which was expressed as mean±standard deviation. Mann-Whitney *U* test was performed for non-normally distributed data and expressed as median (quartiles 25%-75%). Linear regression was performed between pRNFL, RPC density, and PPCMv density. Receiver operating characteristics (ROC) analysis was performed on the parameters that were significant. A *P*-value <0.05 was considered statistically significant.

RESULTS

Age and gender of the groups were statistically similar (*P*>0.05). Demographic data of the groups are presented in Table 1. Best corrected visual acuity was 20/20 for all subjects. Anterior segment and retina examinations and intraocular pressures of all subjects were within normal limits. The horizontal disc diameter was lower in crowded optic discs (*P*=0.012) whereas vertical disc diameter was not (*P*=0.127). The vertical c/d ratio was lower in crowded optic discs (*P*<0.001). Comparisons of the optic disc parameters of the groups are presented in Table 2. The correlation between optic disc area and c/d ratio (*r*=0.177, *P*=0.127) and vertical c/d ratio (*r*=0.171, *P*=0.140) is not statistically significant.

The mean SSI of OCT-A images was similar (*P*=0.740) between the crowded optic disc subjects (8.7±0.5) and controls (8.6±0.7). pRNFL thicknesses were similar between the two groups (*P*=0.102). There were no differences in RPC density in whole image (*P*=0.826) and peripapillary region (*P*=0.923), however inside disc RPC density was higher in crowded optic discs (*P*=0.003). Comparison of pRNFL thicknesses and RPC densities of groups are presented in Table 3. Inner and outer annuli and inferior and superior hemifields of PPCMv densities were calculated. PPCMv density in the inner-hemisuperior region was significantly lower in crowded optic discs (*P*=0.026). There was no significant difference in PPCMv density in any other region of interest. Comparison between PPCMv density of crowded optic discs and control eyes is presented in Table 4.

The evaluation of the relationship between PPCMv density and peripapillary RPC density with pRNFL thickness revealed that the pRNFL thickness was positively correlated with RPC density (*R*²=0.248, *P*<0.001). The inside disc RPC density was negatively correlated with c/d area ratio (*R*²=0.116, *P*=0.002). The results for simple linear regression analysis are presented in Table 5.

ROC analysis was performed on inside RPC density and inner-hemisuperior PPCMv density. Area under curve was 0.689 (*P*=0.003) for inside RPC density and 0.651 (*P*=0.017) for

Table 1 Demographic characteristics of eyes with crowded optic discs and controls

Variables	Crowded optic discs (n=30)	Control eyes (n=47)	<i>P</i>
Age	44 (41-50)	43 (41-50)	0.517 ^a
Gender (female/male)	19/11	31/16	0.814 ^b

^aMann-Whitney *U*-test; ^bPearson Chi-square test.

Table 2 Comparisons of optic disc parameters between patients with crowded optic discs and control eyes

Variables	Crowded optic discs (n=30)	Control eyes (n=47)	<i>P</i>
Vertical disc diameter (mm)	1.6 (1.4-1.7)	1.6 (1.5-1.7)	0.127 ^a
Horizontal disc diameter (mm)	1.5±0.1	1.6±0.1	0.012 ^b
Vertical cup-to-disc ratio	0.013±0.034	0.346±0.093	<0.001 ^b
Disc area (mm ²)	1.94±0.29	2.02±0.36	0.324 ^b
Rim area (mm ²)	1.97 (1.65-2.13)	1.72 (1.47-1.95)	0.010 ^a
Cup-to-disc area ratio	0.003±0.010	0.153±0.090	<0.001 ^b
Cup volume (mm ³)	0.0003±0.0011	0.0449±0.0547	<0.001 ^b

^aMann-Whitney *U*-test; ^bStudent *t*-test. *P*-values below 0.05 were accepted as a statistically significant difference.

Table 3 Comparison of parapapillary retinal nerve fiber layer thickness and radial peripapillary capillary density

Variables	Crowded optic discs (n=30)	Control eyes (n=47)	<i>P</i>
pRNFL thickness (μm)			
Parapapillary	117.6±11.8	113.1±11.2	0.102 ^a
Hemi-superior	118.0±13.7	112.1±12.3	0.058 ^a
Hemi-inferior	117.9±12.4	114.6±12.2	0.257 ^a
RPC density (%)			
Whole image	49.6±2.6	49.7±2.6	0.826 ^a
Inside disc	51.9±4.5	48.7±4.2	0.003 ^a
Peripapillary	53.0±3.0	53.1±2.8	0.923 ^a
Hemi-superior	53.1±3.4	53.4±2.9	0.671 ^a
Hemi-inferior	53.0±2.8	52.8±3.0	0.734 ^a

^aStudent *t*-test. pRNFL: Parapapillary retinal nerve fiber layer; RPC: Radial peripapillary capillary. *P*-values below 0.05 were accepted as a statistically significant difference.

Table 4 Comparison between parapapillary choroid microvasculature density of crowded optic discs and control eyes

Variables	Crowded optic discs (n=30)	Control eyes (n=47)	<i>P</i>
Inner ring (%)	54.1 (50.3-55.7)	54.5 (52.0-57.2)	0.155 ^a
Inner-hemisuperior	53.8 (50.6-55.8)	55.2 (52.5-58.4)	0.026 ^a
Inner-hemiinferior	53.8 (50.3-55.7)	53.4 (50.0-55.9)	0.909 ^a
Outer ring (%)	39.8 (38.3-40.8)	40.1 (38.8-41.5)	0.195 ^a
Outer-hemisuperior	40.2±2.5	41.1±3.0	0.164 ^b
Outer-hemiinferior	38.7 (37.3-40.8)	39.3 (37.9-41.4)	0.363 ^a
Whole ring (inner+outer) (%)	21.2±1.7	21.7±1.4	0.229 ^b

^aMann-Whitney *U*-test; ^bStudent *t*-test. *P*-values below 0.05 were accepted as a statistically significant difference.

inner-hemisuperior PPCMv density. ROC curve is presented in Figure 2.

Table 5 The results for simple linear regression analysis

Dependent variable	Predictive variable	Unstandardize coefficient B (Std. Error)	Standardize coefficient β	P	R ²
pRNFL thickness	Constant	7.6 (21.7)		0.727	
	Peripapillary RPC density	2.0 (0.4)	0.498	<0.001	0.248
pRNFL thickness	Constant	98.4 (18.4)		<0.001	
	Whole ring PPCMv density	0.7 (0.8)	0.103	0.374	0.011
Inside disc RPC density	Constant	50.2 (0.6)		<0.001	
	Cup volume	-9.5 (11.0)	-0.099	0.393	0.010
Inside disc RPC density	Constant	51.4 (0.6)		<0.001	
	Cup-to-disc area ratio	-15.4 (4.9)	-0.341	0.002	0.116

pRNFL: Parapapillary retinal nerve fiber layer; RPC: Radial peripapillary capillary. P-values below 0.05 were accepted as a statistically significant difference.

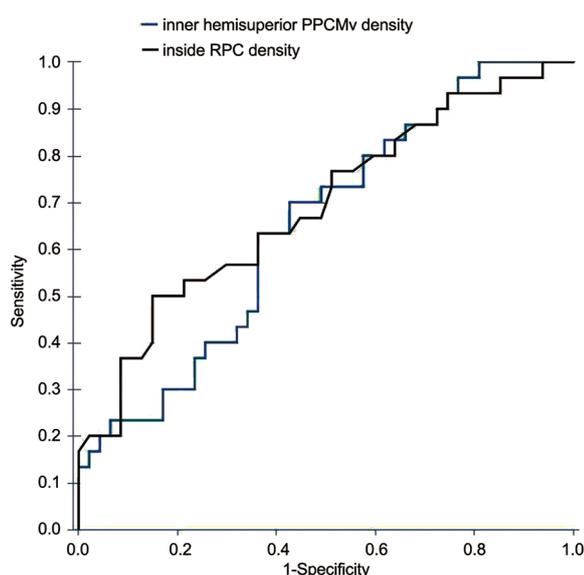


Figure 2 ROC curve of inner hemisuperior PPCMv density (AUC: 0.651, cut-off for crowded disc: ≤ 54.9 , sensitivity: 0.700, specificity: 0.574) and inside RPC density (AUC: 0.689, cut-off for crowded disc: ≥ 52.4 , sensitivity: 0.500, specificity: 0.851) ROC: Receiver operating characteristics; PPCMv: Parapapillary choroidal microvasculature; AUC: Area under curve; RPC: Radial peripapillary capillary.

In our study we worked with groups of at least 30 people each. The significance level or alpha (α) was set at 0.05. Using the data from the RPC inside, we found an effect size of 0.741. We then calculated the statistical power ($1-\beta$), which measures the ability to detect an effect, and found it to be approximately 80.57%.

DISCUSSION

Optic discs with a relatively small, slightly unsharp and slightly elevated disc border without any other pathology can be considered as crowded optic discs, the frequency of which is 3.1% in the Beijing eye study^[11]. The prevalence of NAION has been reported as 1/139 during a 5-year follow-up of a population with crowded optic discs^[15]. Using OCT-A, we reported optic nerve head and deep choroid plexus vessel densities in the peripapillary area of crowded optic discs and compared with controls. We observed a higher inside disc RPC

density and lower inner-hemisuperior PPCMv density in the crowded optic discs.

In the present study, the inside disc RPC density was negatively correlated with the c/d area ratio. The optic cup size is embryologically determined with a small scleral canal being associated with a small cup and optic nerve fibers passing through the small scleral canal becoming crowded^[6]. Besides vascular systemic risk factors, a crowded optic disc is known to be a contributing anatomical variation for the development of NAION^[5-6,16]. Moghimi *et al*^[17] performed peripapillary OCT with NAION patients. They reported that the thick prelaminar tissue and small c/d ratio crowded the optic disc. Their findings showed that smaller c/d ratio was more important than the optic disc size. They suggested that this might cause predisposition to optic disc ischemia. Falavarjani *et al*^[18] evaluated the correlation between optic disc morphometry and optic disc microvasculature in healthy subjects and reported that there was a higher inside disc RPC density in patients with a smaller c/d ratio. Such a result was compatible with the findings of this current study. Increased inside disc RPC density in crowded optic discs revealed by the findings of the present study may be the underlying contributing anatomic risk factor for developing NAION. However, studies by prospective follow-up of crowded optic discs are required in order to evaluate the risk of NAION. We found a significant correlation between pRNFL thickness and peripapillary RPC density but not PPCMv density. Since the RPC network is a unique plexus that feeds pRNFL, this correlation seems reasonable^[19-20].

Ling *et al*^[21] conducted an OCT-A study in patients with NAION and found a negative correlation between the hypoperfused area and BCVA. The high inside disc RPC density leads us to speculate that crowded discs may be more susceptible to ischemia or vascular dysregulation, and this sensitivity to ischemia could potentially affect their visual prognosis. However, demonstrating this requires large-scale controlled studies.

We know that the superficial nerve fibre layer of optic discs is supplied by retinal arterioles. The prelaminar and laminar

region of the optic nerve is supplied by the peripapillary choroid and branches from the choroid and short posterior ciliary arteries (PCAs)^[22]. The choroid is supplied by short PCAs up to the equator^[23]. NAION is due to a non- or hypoperfusion of the ciliary circulation^[24]. Aghsaei Fard *et al*^[13] evaluated the PPCMv density of NAION patients with the same method and found no difference compared to controls. They explained this finding with compression of the choroidal tissue caused by increased neural tissue in NAION. On the other hand, we observed reduced inner-hemisuperior PPCMv density in crowded discs. This impaired parapapillary choroidal perfusion in crowded optic discs did not affect the thickness of the superior nerve fibers. However, pRNFL thickness was also increased in crowded discs in our recent study^[25]. If there is no cup or only a small one, the axons swell and become crowded in a limited area. In this case, the increased axonal volume may expand by compressing the surrounding tissue, *i.e.* the thin blood vessels^[6]. We believe that the reduced PPCMv density in our study may be due to this impingement.

The short PCAs pass forward outside the duramater, pierce the sclera, and supply the choroid^[22]. Therefore, they are not exposed to compression in the scleral canal in the eyes with crowded optic discs. Impaired autoregulation of the disc circulation can play a role in NAION patients^[3]. This deterioration in autoregulatory mechanisms in crowded disc subjects may occur in earlier stages for various reasons and this may be the cause of the decrease in PPCMv density^[26-27].

Our study has some limitations. First, we did not evaluate the impact of peripapillary choroidal thickness on vessel density. Then, we did not evaluate axial length and the impact of Bruch's membrane opening width on vessel density.

In conclusion, the findings of the present research revealed that crowded optic discs were associated with higher inside disc RPC density and lower inner-hemisuperior PPCMv density. There was also a significant positive correlation between pRNFL thickness and peripapillary RPC density and a negative correlation between c/d area ratio and inside disc RPC density. Longitudinal studies of crowded disc subjects are required to determine whether the existing findings have a role in the risk of NAION development. OCT-A provides non-invasive, objective, and reproducible evaluation of optic nerve head vasculature. Therefore, it may have a role in the routine follow-up of individuals with crowded optic discs.

ACKNOWLEDGEMENTS

Gunay Sener AB thanks the "Republic of Turkey Higher Education Council" for the 100-2000 program scholarship for PhD.

Authors' contributions: Conceptualization: Arda H; Data curation: Temizyurek O; Formal analysis: Gunay Sener AB; Investigation: Sener H; Methodology: Sener H, Sonmez HK;

Project administration: Arda H, Evereklioglu C, Horozoglu F; Statistic and Image Processing Software: Gunay Sener AB; Supervision: Evereklioglu C, Gulmez Sevim D; Validation: Arda H, Gunay Sener AB; Visualization: Horozoglu F; Writing-original draft: Arda H, Sener H; Writing-review & editing: Gulmez Sevim D, Evereklioglu C, Horozoglu F, Gunay Sener AB.

Conflicts of Interest: Arda H, None; Sener H, None; Temizyurek O, None; Sonmez HK, None; Gulmez Sevim D, None; Evereklioglu C, None; Horozoglu F, None; Gunay Sener AB, None.

REFERENCES

- 1 Machado LF, Furlanetto RL, Gracitelli CPB. Anatomy and evaluation of the optic nerve head. *Arq Bras Oftalmol* 2022;85(6):636-643.
- 2 Sing NM, Anderson SF, Townsend JC. The normal optic nerve head. *Optom Vis Sci* 2000;77(6):293-301.
- 3 Arnold A. Vascular supply of the optic nerve head: implications for optic disc ischaemia. *Br J Ophthalmol* 2023;107(5):595-599.
- 4 Johannesen RG, Lykkebirk L, Jørgensen M, Malmqvist L, Hamann S. Optic nerve head anatomy and vascular risk factors in patients with optic disc drusen associated anterior ischemic optic neuropathy. *Am J Ophthalmol* 2022;242:156-164.
- 5 Doro S, Lessell S. Cup-disc ratio and ischemic optic neuropathy. *Arch Ophthalmol* 1985;103(8):1143-1144.
- 6 Hayreh SS, Zimmerman MB. Nonarteritic anterior ischemic optic neuropathy: refractive error and its relationship to cup/disc ratio. *Ophthalmology* 2008;115(12):2275-2281.
- 7 Bouffard MA, Cornblath WT, Rizzo JF, Lee MS, DeLott LB, Eggenberger ER, Torun N. Transient monocular vision loss on awakening: a benign amaurotic phenomenon. *J Neuro Ophthalmol* 2017;37(2):122-125.
- 8 Pujari A, Bhaskaran K, Sharma P, Singh P, Phuljhele S, Saxena R, Azad SV. Optical coherence tomography angiography in neuro-ophthalmology: current clinical role and future perspectives. *Surv Ophthalmol* 2021;66(3):471-481.
- 9 Ghasemi Falavarjani K, Tian JJ, Akil H, Garcia GA, Satta SR, Sadun AA. Swept-source optical coherence tomography angiography of the optic disk in optic neuropathy. *Retina* 2016;36(Supplement 1):S168-S177.
- 10 Song A, Sunshine S, Simjanoski E, Zhang YS, Volpe NJ. Optical coherence tomography angiography (OCTA) in unilateral non-arteritic anterior ischemic optic neuropathy (NAION): A comparison with the fellow eyes and with disc-at-risk. *Invest Ophthalmol & Vis Sci* 2019;60:3049.
- 11 You QS, Xu L, Jonas JB. Prevalence of crowded optic discs in adult Chinese. The Beijing Eye Study. *Graefes Arch Clin Exp Ophthalmol* 2008;46(9):1291-1293.
- 12 Hojati S, Kafieh R, Fardafshari P, Fard MA, Fouladi H. A MATLAB package for automatic extraction of flow index in OCT-a images by intelligent vessel manipulation. *SoftwareX* 2020;12:100510.

- 13 Aghsaei Fard M, Salabati M, Mahmoudzadeh R, Kafieh R, Hojati S, Safizadeh M, Moghimi S, Ritch R, Subramanian PS. Automated evaluation of parapapillary choroidal microvasculature in ischemic optic neuropathy and open angle glaucoma. *Invest Ophthalmol Vis Sci* 2020;61(3):35.
- 14 Aghsaei Fard M, Safizadeh M, Shaabani A, *et al.* Automated evaluation of parapapillary choroidal microvasculature in pseudoexfoliation syndrome and pseudoexfoliation glaucoma. *Am J Ophthalmol* 2021;224:178-184.
- 15 You QS, Xu LA, Wang YX, Jonas JB. Frequency of non-arteritic anterior ischaemic optic neuropathy in crowded optic discs: the Beijing Eye Study. *Acta Ophthalmol* 2009;87(3):354-355.
- 16 Beck RW, Servais GE, Hayreh SS. Anterior ischemic optic neuropathy. *Ophthalmology* 1987;94(11):1503-1508.
- 17 Moghimi S, Afzali M, Akbari M, Ebrahimi KB, Khodabande A, Yazdani-Abyaneh AR, Ghafouri SH, Coh P, Okhravi S, Fard MA. Crowded optic nerve head evaluation with optical coherence tomography in anterior ischemic optic neuropathy. *Eye (Lond)* 2017;31(8):1191-1198.
- 18 Falavarjani KG, Shenazandi H, Naseri D, Anvari P, Sedaghat A, Hashemi M, Sadun AA. Correlation of optic disc morphometry and optic disc microvasculature assessed with optical coherence tomography angiography. *Can J Ophthalmol* 2018;53(6):595-599.
- 19 Mase T, Ishibazawa A, Nagaoka T, Yokota H, Yoshida A. Radial peripapillary capillary network visualized using wide-field montage optical coherence tomography angiography. *Invest Ophthalmol Vis Sci* 2016;57(9):OCT504.
- 20 Mansoori T, Sivaswamy J, Gamalapati JS, Balakrishna N. Topography and correlation of radial peripapillary capillary density network with retinal nerve fibre layer thickness. *Int Ophthalmol* 2018;38(3):967-974.
- 21 Ling JW, Yin X, Lu QY, *et al.* Optical coherence tomography angiography of optic disc perfusion in non-arteritic anterior ischemic optic neuropathy. *Int J Ophthalmol* 2017;10(9):1402-1406.
- 22 Hayreh SS. The blood supply of the optic nerve head and the evaluation of it—myth and reality. *Prog Retin Eye Res* 2001;20(5):563-593.
- 23 Hayreh SS. Posterior ciliary artery circulation in health and disease the weissenfeld lecture. *Invest Ophthalmol Vis Sci* 2004;45(3):749.
- 24 Hayreh S. Acute ischemic disorders of the optic nerve: pathogenesis, clinical manifestations and management. *Ophthalmol Clin North Am* 1996;9:407-442.
- 25 Arda H, Sonmez HK, Sevim DG, Temizyurek O, Evereklioglu C. Comparison of optic disc head vascular density status between crowded and normal discs: an optical coherence tomography angiography study. *Photodiagn Photodyn Ther* 2023;41:103293.
- 26 Madill SA. Transient visual loss in young females with crowded optic discs: a proposed aetiology. *Neuro-Ophthalmology* 2021;45(6):372-379.
- 27 Schmidl D, Boltz A, Kaya S, Werkmeister R, Dragostinoff N, Lasta M, Polska E, Garhöfer G, Schmetterer L. Comparison of choroidal and optic nerve head blood flow regulation during changes in ocular perfusion pressure. *Invest Ophthalmol Vis Sci* 2012;53(8):4337.