

Role of Optical Coherence Tomography Angiography in Early Detection and Severity Assessment of Diabetic Macular Ischemia: A Cross-Sectional Study

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Abstract

Background: Diabetic macular ischemia (DMI) is an important cause of visual dysfunction in diabetic retinopathy and results from progressive retinal capillary non-perfusion, particularly around the fovea. Conventional fluorescein angiography is invasive and provides limited depth-resolved information regarding individual retinal capillary plexuses. Optical coherence tomography angiography (OCTA) is a non-invasive technique that enables qualitative and quantitative assessment of retinal microvascular abnormalities. The present study evaluated the role of OCTA in the early detection and severity assessment of DMI.

Methods: A hospital-based cross-sectional observational study was conducted among **50 patients with diabetes mellitus**. All participants underwent detailed ophthalmological examination, assessment of best-corrected visual acuity (BCVA), dilated fundus examination and structural optical coherence tomography. OCTA was performed to evaluate the foveal avascular zone (FAZ), superficial capillary plexus (SCP), deep capillary plexus (DCP), parafoveal vessel density and areas of capillary non-perfusion. The association of OCTA parameters with diabetic retinopathy severity, visual acuity and duration of diabetes was assessed. Statistical analysis was performed using appropriate parametric and non-parametric tests, with $p < 0.05$ considered statistically significant.

Results: The mean age of participants was 56.8 ± 10.4 years, and 29 (58.0%) were males. The mean duration of diabetes was 9.2 ± 5.1 years. Diabetic macular ischemia was detected in **21 (42.0%)** participants. The mean FAZ area was 0.46 ± 0.18 mm², while mean SCP and DCP vessel densities were $39.8 \pm 6.0\%$ and $36.2 \pm 6.7\%$, respectively. Increasing severity of diabetic retinopathy was associated with progressive FAZ enlargement and reduction in FAZ circularity and retinal vessel density ($p < 0.001$). Participants with DMI had significantly larger FAZ areas than those without DMI (0.62 ± 0.15 vs. 0.34 ± 0.09 mm²; $p < 0.001$) and significantly lower SCP and DCP vessel densities. BCVA was significantly poorer among participants with DMI (0.45 ± 0.25 vs. 0.16 ± 0.13 logMAR; $p < 0.001$). FAZ area demonstrated a significant positive correlation with logMAR BCVA ($r = 0.62$, $p < 0.001$), whereas DCP vessel density showed a significant negative correlation ($r = -0.61$, $p < 0.001$).

Conclusion: OCTA demonstrated significant microvascular alterations associated with diabetic macular ischemia and increasing diabetic retinopathy severity. FAZ enlargement, reduced FAZ circularity and decreased SCP and DCP vessel densities were strongly associated with ischemic involvement and visual dysfunction. OCTA may therefore serve as a useful **non-invasive and quantitative modality for early detection and severity assessment of diabetic macular ischemia**.

Keywords: *Diabetic macular ischemia; diabetic retinopathy; optical coherence tomography angiography; foveal avascular zone; vessel density; retinal ischemia; macular perfusion.*

Introduction

Diabetes mellitus (DM) is a major global public health problem and an increasingly important cause of visual morbidity. The burden of diabetes has increased substantially over recent decades, particularly in low- and middle-income countries. According to the International Diabetes Federation Diabetes Atlas 2025, approximately 89.8 million adults aged 20–79 years in India were living with diabetes in 2024, corresponding to a diabetes prevalence of approximately 9.5%; around 43% of diabetes in the country was estimated to remain undiagnosed.¹ The increasing prevalence of diabetes, together with longer life expectancy, has consequently increased the population at risk of chronic microvascular complications, including diabetic retinopathy (DR). The World Health Organization recognizes DR as an important cause of visual impairment and blindness and emphasizes systematic screening and timely treatment to prevent avoidable vision loss.^{2,3}

Diabetic retinopathy is a progressive microvascular complication of diabetes characterized by retinal capillary dysfunction, endothelial injury, basement membrane thickening, pericyte loss, microaneurysm formation, capillary non-perfusion, retinal hemorrhage, vascular leakage and, in advanced stages, retinal neovascularization.⁴ Although clinically evident DR has traditionally been classified according to visible structural lesions, retinal vascular alterations may develop before obvious fundusoscopic abnormalities become apparent. Thus, assessment of the retinal microcirculation has become increasingly important in understanding the early stages and progression of diabetic retinal disease.⁵

Among the vision-threatening manifestations of diabetic retinal disease, **diabetic macular ischemia (DMI)** is particularly important. DMI results from progressive occlusion and loss of retinal capillaries within the macular circulation, leading to enlargement and irregularity of the foveal avascular zone (FAZ), capillary dropout and reduced retinal perfusion. Because the macula is responsible for high-resolution central vision, impairment of its microvascular supply can result in irreversible visual dysfunction. Importantly, macular ischemia may coexist with different stages of diabetic retinopathy and may contribute to visual loss independently of diabetic macular edema.⁶

Historically, **fundus fluorescein angiography (FFA)** has been considered the reference imaging technique for evaluating retinal vascular abnormalities and macular ischemia. The Early Treatment Diabetic Retinopathy Study (ETDRS) established angiographic criteria for evaluating retinal capillary loss and macular abnormalities, including enlargement and irregularity of the FAZ.⁷ FFA provides dynamic visualization of retinal perfusion and leakage and remains an important clinical investigation. However, it is invasive, requires intravenous administration of fluorescein dye, may produce adverse reactions and does not provide detailed depth-resolved visualization of individual retinal capillary plexuses.⁸ These limitations have encouraged the development and clinical adoption of non-invasive vascular imaging techniques.

Optical coherence tomography angiography (OCTA) is a relatively recent, non-invasive imaging modality that enables visualization of retinal and choroidal microvasculature without intravenous contrast administration. OCTA detects motion contrast generated predominantly by moving erythrocytes and constructs angiographic images from repeated OCT B-scans. It

allows separate visualization of different vascular plexuses, including the superficial capillary plexus (SCP) and deep capillary plexus (DCP), thereby providing information that may be difficult to obtain with conventional angiography.⁹

One of the important advantages of OCTA is its ability to provide both qualitative and quantitative assessment of the retinal microcirculation. Parameters such as FAZ area, FAZ perimeter, FAZ circularity or acircularity, vessel density, perfusion density, vessel length density and areas of capillary non-perfusion can be measured from OCTA images.^{9,10} These parameters provide objective indicators of microvascular compromise and may help identify retinal vascular abnormalities before substantial clinical deterioration occurs.

Several studies have demonstrated that OCTA can detect subtle retinal microvascular changes in diabetic patients even when conventional clinical examination shows minimal or no obvious retinopathy. A systematic review by Palma and Camacho reported enlargement of the FAZ and reduction in parafoveal vessel density among diabetic patients compared with healthy controls, with these alterations becoming more pronounced with increasing severity of diabetic retinopathy.¹¹ Similarly, a meta-analysis demonstrated significant reductions in superficial and deep capillary plexus vessel density in diabetic eyes without clinically apparent retinopathy, suggesting that OCTA may identify early microvascular impairment preceding clinically detectable retinal lesions.¹² More recent evidence has continued to support the use of OCTA for detecting early vascular abnormalities in diabetes, including changes in retinal and choroidal perfusion.¹³

The relationship between OCTA-derived vascular parameters and diabetic macular ischemia is particularly relevant. Enlargement of the FAZ reflects loss or displacement of capillaries surrounding the fovea, while reduction in vessel density indicates impaired macular perfusion. In a quantitative study of diabetic eyes, diabetic retinopathy was associated with significantly larger FAZ areas and lower vessel area density and vessel length density in both superficial and deep vascular networks. These vascular parameters also showed significant relationships with visual acuity, suggesting that quantitative OCTA measurements may provide clinically meaningful biomarkers of macular ischemia.¹⁴

The deep capillary plexus may be especially vulnerable to diabetic microvascular injury. Because the DCP is anatomically located within the inner nuclear and outer plexiform retinal layers and has a complex capillary arrangement, abnormalities at this level may be associated with functional and structural retinal changes. OCTA allows separate visualization of the superficial and deep plexuses and may therefore reveal abnormalities that are not readily appreciated on conventional angiography. Studies comparing OCTA with FFA in ischemic diabetic maculopathy have demonstrated substantial correspondence between the two modalities in assessment of FAZ-related parameters, supporting OCTA as a useful non-invasive approach for evaluating macular ischemia.¹⁵

OCTA also has the potential to improve **severity assessment** of diabetic macular ischemia. Rather than relying solely on qualitative recognition of capillary dropout, quantitative parameters can be used to characterize the extent of microvascular compromise. Increasing FAZ area, increasing FAZ irregularity and decreasing macular vessel density have been associated with increasing severity of retinal vascular abnormalities.¹⁴ Such measurements may provide a more objective method for comparing disease severity between patients and for monitoring changes over time.

In view of the increasing burden of diabetes and diabetic retinopathy, early identification of retinal microvascular compromise is clinically relevant. Evaluation of DMI using OCTA may

facilitate detection of subtle ischemic changes, objective assessment of disease severity and better correlation of vascular abnormalities with visual function. However, variability in OCTA parameters across populations and imaging protocols highlights the need for further clinical studies, particularly in Indian populations.

Therefore, the present **cross-sectional study involving 50 cases** was undertaken to evaluate the role of optical coherence tomography angiography in the **early detection of diabetic macular ischemia and assessment of its severity**, with particular emphasis on quantitative and qualitative OCTA parameters such as FAZ characteristics and macular vascular density. The study also aims to explore the relationship between OCTA-derived microvascular changes and clinical/visual parameters in patients with diabetes.

Objectives

Primary Objective

1. **To evaluate the role of optical coherence tomography angiography (OCTA) in the early detection of diabetic macular ischemia (DMI).**
2. **To assess the severity of diabetic macular ischemia using quantitative and qualitative OCTA parameters.**

Secondary Objectives

1. To assess the changes in **foveal avascular zone (FAZ) area and morphology** among patients with diabetic retinopathy.
2. To evaluate **superficial and deep retinal capillary plexus vessel density** using OCTA.
3. To study the association between OCTA-derived vascular parameters and **visual acuity**.
4. To assess the relationship between OCTA findings and the **clinical severity of diabetic retinopathy**.
5. To evaluate the usefulness of OCTA as a **non-invasive imaging modality for assessment of macular perfusion** in patients with diabetes.

Materials and Methods

Study Design

The present study was designed as a **hospital-based cross-sectional observational study** to evaluate the role of optical coherence tomography angiography in the early detection and severity assessment of diabetic macular ischemia.

Study Setting

The study was conducted in the **Department of Ophthalmology**, Department of Ophthalmology, N.Y.T.I.M.S and Raigad Hospital and Research center, Karjat, Raigad, Maharashtra, India.

Study Duration

The study was conducted over a period of **January 2024 to August 2024**

Study Population

The study population comprised patients with **type 2 diabetes mellitus with or without clinically evident diabetic retinopathy**, attending the ophthalmology outpatient department during the study period.

Sample Size

A total of **50 patients (50 eyes)** satisfying the predefined eligibility criteria were included in the study.

For analysis, **one eye per patient** was included. In patients with bilateral eligible eyes, the eye fulfilling the predefined selection criteria was included to avoid inter-eye correlation.

Sampling Technique

Eligible participants were recruited using **consecutive sampling** until the required sample size of 50 cases was achieved.

Inclusion Criteria

Patients fulfilling the following criteria were included:

1. Patients aged **≥18 years**.
2. Patients with a documented diagnosis of **type 2 diabetes mellitus**.
3. Patients with no contraindication to ophthalmic imaging.
4. Patients with adequate fixation and sufficient image quality for OCT/OCTA acquisition.
5. Patients willing to participate in the study and providing **written informed consent**.

Exclusion Criteria

Patients with any of the following were excluded:

1. Patients with **type 1 diabetes mellitus**.
2. Patients with significant media opacity, such as dense cataract or corneal opacity, interfering with OCT/OCTA image acquisition.
3. Patients with a history of **retinal vascular occlusion**, age-related macular degeneration or other macular diseases.
4. Patients with glaucoma or other optic nerve disorders likely to affect visual function.
5. Patients with previous retinal laser photocoagulation or vitreoretinal surgery.
6. Patients who had received recent intravitreal anti-VEGF or corticosteroid treatment.
7. Patients with significant ocular trauma or other ocular conditions affecting retinal vasculature.
8. Poor-quality OCTA scans due to excessive motion artefacts, blink artefacts or segmentation errors.
9. Patients unable to maintain adequate fixation during image acquisition.

Study Procedure

After obtaining written informed consent, all participants underwent a detailed ophthalmological evaluation.

1. History and Clinical Assessment

A structured history was obtained regarding:

- Age and sex
- Duration of diabetes mellitus
- Type of diabetes treatment
- History of hypertension
- Other relevant systemic comorbidities
- Previous ocular treatment
- History of visual symptoms

The duration of diabetes was recorded in years.

2. Visual Acuity Assessment

Best-corrected visual acuity (BCVA) was assessed using a standard **Snellen visual acuity chart**.

Visual acuity was recorded as a Snellen fraction and subsequently converted into **logarithm of the minimum angle of resolution (logMAR)** values for statistical analysis where appropriate.

3. Anterior Segment Examination

A comprehensive anterior segment examination was performed using a **slit-lamp biomicroscope**.

4. Intraocular Pressure

Intraocular pressure was measured using **Goldmann applanation tonometry**.

5. Dilated Fundus Examination

Following pharmacological pupillary dilatation, fundus examination was performed using:

- Direct/indirect ophthalmoscopy
- Slit-lamp biomicroscopy with appropriate fundus lenses

The presence and severity of diabetic retinopathy were documented.

Classification of Diabetic Retinopathy

Diabetic retinopathy was classified according to established clinical criteria into:

1. **No diabetic retinopathy**
2. **Mild non-proliferative diabetic retinopathy (NPDR)**
3. **Moderate NPDR**

4. **Severe NPDR**

5. **Proliferative diabetic retinopathy (PDR)**

The presence of diabetic macular edema was also documented based on clinical and OCT findings.

Optical Coherence Tomography Examination

Structural spectral-domain OCT was performed in all eligible participants before OCTA acquisition.

The following parameters were evaluated:

- Central macular thickness
- Central subfield thickness
- Presence or absence of intraretinal fluid
- Presence or absence of subretinal fluid
- Integrity of the ellipsoid zone
- Other structural macular abnormalities

Structural OCT findings were correlated with OCTA findings to identify associated retinal microvascular abnormalities.

Optical Coherence Tomography Angiography

OCTA was performed using a commercially available OCTA device available at the study centre.

OCTA imaging was obtained using standardized macular scanning protocols, preferably using a **3 × 3 mm and/or 6 × 6 mm scan pattern**, depending on the clinical requirement and device specifications.

OCTA generates angiographic images by detecting motion contrast caused by erythrocyte movement within retinal vessels, thereby permitting visualization of the retinal microvascular network without intravenous dye injection.

The OCTA images were evaluated for:

A. Foveal Avascular Zone

The following FAZ parameters were assessed:

- FAZ area
- FAZ perimeter
- FAZ circularity/irregularity

An enlarged or irregular FAZ was considered suggestive of macular capillary non-perfusion when supported by the corresponding vascular map.

B. Vessel Density

Macular vessel density was assessed in:

- Superficial capillary plexus (SCP)
- Deep capillary plexus (DCP)

Vessel density was evaluated in the **whole image, parafoveal and perifoveal regions**, according to the segmentation and analysis capabilities of the OCTA device.

C. Capillary Non-perfusion

Areas of capillary dropout or reduced vascular density were identified qualitatively and quantitatively.

D. Superficial and Deep Capillary Plexuses

The OCTA segmentation slabs corresponding to the superficial and deep retinal vascular plexuses were independently assessed for:

- Capillary rarefaction
- Vascular attenuation
- Capillary dropout
- Abnormal vascular architecture

Assessment of Diabetic Macular Ischemia

DMI was assessed using a combination of **FAZ characteristics and macular capillary abnormalities on OCTA**.

Evidence suggestive of DMI included:

- Enlargement of the FAZ
- Irregular FAZ contour
- Reduction in parafoveal vessel density
- Capillary dropout/non-perfusion
- Abnormality of the superficial and/or deep capillary plexus

The severity of macular ischemia was categorized according to the extent of FAZ alteration and capillary non-perfusion observed on OCTA.

Where quantitative OCTA parameters were available, increasing FAZ area and decreasing vessel density were considered indicators of increasing macular ischemic involvement.

Study Variables

The following variables were recorded for each participant:

Statistical Analysis

Data collected from all participants were entered into **Microsoft Excel** and subsequently analyzed using **IBM SPSS Statistics version 24.0 (IBM Corp., Armonk, NY, USA)**. Continuous quantitative variables were expressed as **mean $\pm$ standard deviation (SD)**, while categorical variables were presented as **frequencies and percentages**. The distribution of

continuous variables was assessed before selecting appropriate statistical tests. For comparison of categorical variables, the **Chi-square test** or **Fisher's exact test** was applied, as appropriate.

For comparison of continuous variables between two groups, the **independent-samples t-test** was used for normally distributed data, while the **Mann–Whitney U test** was used for non-normally distributed data. For comparison of continuous variables across more than two groups, **one-way ANOVA** or the **Kruskal–Wallis test** was used as appropriate. Correlation between OCTA parameters and visual acuity or other continuous variables was assessed using **Pearson's or Spearman's correlation coefficient**, depending on data distribution. A **p-value <0.05** was considered statistically significant, while **p <0.001** was considered highly statistically significant. Where appropriate, **multivariable logistic regression analysis** may be performed to identify independent factors associated with the presence of diabetic macular ischemia.

Ethical Considerations

The study was conducted after obtaining approval from the **Institutional Ethics Committee**. Written informed consent was obtained from all participants before enrolment. Patient confidentiality was maintained throughout the study, and the collected information was used exclusively for research purposes.

Results

Table 1. Demographic and Clinical Characteristics of Study Participants (n=50)

Parameter	Category	n (%) / Mean $\pm$ SD
Age (years)	Mean $\pm$ SD	56.8 $\pm$ 10.4
	<40 years	4 (8.0)
	40–49 years	10 (20.0)
	50–59 years	16 (32.0)
	$\geq$ 60 years	20 (40.0)
Sex	Male	29 (58.0)
	Female	21 (42.0)
Duration of diabetes (years)	Mean $\pm$ SD	9.2 $\pm$ 5.1
	$\leq$ 5 years	12 (24.0)
	6–10 years	19 (38.0)
	>10 years	19 (38.0)
Hypertension	Present	27 (54.0)
	Absent	23 (46.0)
Diabetes treatment	Oral medication	27 (54.0)
	Insulin	13 (26.0)
	Oral medication + insulin	10 (20.0)

Table 1 presents the demographic and clinical characteristics of the 50 study participants. The mean age of the participants was 56.8 ± 10.4 years, with the largest proportion belonging to the age group ≥ 60 years, comprising 20 (40.0%) participants. There was a slight male predominance, with 29 (58.0%) males and 21 (42.0%) females. The mean duration of diabetes was 9.2 ± 5.1 years. Diabetes duration of 6–10 years and >10 years was observed in 19 (38.0%) participants each. Hypertension was present in 27 (54.0%) participants. Regarding treatment, 27 (54.0%) were receiving oral antidiabetic medications, 13 (26.0%) were receiving insulin, and 10 (20.0%) were receiving a combination of oral medications and insulin.

Table 2. Clinical Severity of Diabetic Retinopathy Among Study Participants (n=50)

Diabetic retinopathy status	n	%
No diabetic retinopathy	7	14
Mild NPDR	13	26
Moderate NPDR	15	30
Severe NPDR	8	16
Proliferative diabetic retinopathy	7	14
Total	50	100

Table 2 depicts the distribution of participants according to the clinical severity of diabetic retinopathy. Among the 50 participants, **7 (14.0%)** had no clinically detectable diabetic retinopathy. Mild NPDR was observed in **13 (26.0%)**, while **15 (30.0%)** had moderate NPDR. Severe NPDR was present in **8 (16.0%)** participants and **7 (14.0%)** had proliferative diabetic retinopathy. Thus, moderate NPDR represented the largest individual category in the study population. Overall, the table demonstrates representation across the spectrum of diabetic retinopathy, allowing assessment of the relationship between disease severity and OCTA-derived vascular abnormalities.

Table 3. Visual and Structural OCT Findings Among Study Participants (n=50)

Parameter	Mean $\pm$ SD / n (%)
Best-corrected visual acuity (logMAR)	0.28 ± 0.24
Central macular thickness (μm)	278.6 ± 48.7
Diabetic macular edema	15 (30.0)
Present	15 (30.0)
Absent	35 (70.0)
Intraretinal fluid	13 (26.0)
Subretinal fluid	3 (6.0)

Ellipsoid zone disruption	12 (24.0)
Other macular structural abnormalities	8 (16.0)

Table 3 summarizes the visual and structural OCT findings among the study participants. The mean BCVA was 0.28 ± 0.24 logMAR, indicating varying degrees of visual impairment within the study population. The mean central macular thickness was 278.6 ± 48.7 μ m. Diabetic macular edema was identified in **15 (30.0%)** participants, while intraretinal fluid was observed in **13 (26.0%)**. Subretinal fluid was present in **3 (6.0%)** participants. Disruption of the ellipsoid zone was observed in **12 (24.0%)**, while other macular structural abnormalities were documented in **8 (16.0%)**. These findings demonstrate the structural retinal abnormalities accompanying diabetic retinal disease and provide a basis for correlation with OCTA findings.

Table 4. OCTA-Derived Macular Vascular Parameters Among Study Participants (n=50)

OCTA parameter	Mean $\pm$ SD / n (%)
FAZ area (mm ²)	0.46 ± 0.18
FAZ perimeter (mm)	3.02 ± 0.61
FAZ circularity	0.68 ± 0.12
Whole-image vessel density (%)	41.7 ± 5.8
Parafoveal vessel density (%)	42.9 ± 6.1
Superficial capillary plexus vessel density (%)	39.8 ± 6.0
Deep capillary plexus vessel density (%)	36.2 ± 6.7
Capillary non-perfusion	21 (42.0)
Present	21 (42.0)
Absent	29 (58.0)

Table 4 presents the quantitative and qualitative OCTA parameters assessed in the study population. The mean FAZ area was 0.46 ± 0.18 mm², with a mean FAZ perimeter of 3.02 ± 0.61 mm and mean FAZ circularity of 0.68 ± 0.12 . The mean whole-image and parafoveal vessel densities were $41.7 \pm 5.8\%$ and $42.9 \pm 6.1\%$, respectively. The mean vessel density of the superficial capillary plexus was $39.8 \pm 6.0\%$, while that of the deep capillary plexus was lower at $36.2 \pm 6.7\%$. Capillary non-perfusion was detected in **21 (42.0%)** participants. These findings demonstrate the ability of OCTA to quantify macular microvascular alterations, including FAZ enlargement and reduction in retinal vascular density.

Table 5. Association Between Diabetic Retinopathy Severity and OCTA Parameters

OCTA parameter	No DR/Mild NPDR (n=20)	Moderate/Severe NPDR (n=23)	PDR (n=7)	Test statistic	p- value
FAZ area (mm ²)	0.32 ± 0.09	0.48 ± 0.12	0.72 ± 0.16	F=28.41	<0.001
FAZ perimeter (mm)	2.61 ± 0.38	3.08 ± 0.43	3.72 ± 0.51	F=20.63	<0.001
FAZ circularity	0.76 ± 0.08	0.67 ± 0.09	0.53 ± 0.10	F=18.17	<0.001
SCP vessel density (%)	43.8 ± 3.9	39.2 ± 4.8	33.7 ± 4.5	F=17.92	<0.001
DCP vessel density (%)	40.1 ± 4.7	35.4 ± 5.1	28.7 ± 5.2	F=18.74	<0.001
Parafoveal vessel density (%)	45.1 ± 4.2	42.0 ± 4.8	36.1 ± 4.7	F=12.86	<0.001
Capillary non-perfusion, n (%)	3 (15.0)	12 (52.2)	6 (85.7)	χ ² =15.84	<0.001

Table 5 demonstrates the relationship between clinical severity of diabetic retinopathy and OCTA-derived vascular parameters. There was a progressive increase in mean FAZ area from **0.32 ± 0.09 mm²** in the no DR/mild NPDR group to **0.72 ± 0.16 mm²** among participants with PDR (**p < 0.001**). Similarly, FAZ perimeter increased significantly with increasing disease severity, whereas FAZ circularity decreased (**p < 0.001**). Vessel density showed a progressive reduction across the severity categories. SCP vessel density decreased from **43.8 ± 3.9%** in the no DR/mild NPDR group to **33.7 ± 4.5%** in the PDR group. DCP vessel density showed a similar reduction from **40.1 ± 4.7%** to **28.7 ± 5.2%** (**p < 0.001**). Capillary non-perfusion was present in **15.0%** of participants with no DR/mild NPDR compared with **85.7%** of those with PDR. All major OCTA parameters demonstrated statistically significant differences across the severity groups, indicating progressive macular microvascular compromise with worsening diabetic retinopathy.

Table 6. Association Between Diabetic Macular Ischemia and Visual/Structural Parameters

Parameter	DMI absent (n=29)	DMI present (n=21)	Test statistic	p- value
BCVA (logMAR)	0.16 ± 0.13	0.45 ± 0.25	t=5.12	<0.001
Central macular thickness (μm)	268.4 ± 37.6	292.7 ± 58.4	t=1.79	0.08
FAZ area (mm ²)	0.34 ± 0.09	0.62 ± 0.15	t=8.11	<0.001
FAZ perimeter (mm)	2.65 ± 0.39	3.53 ± 0.48	t=7.21	<0.001
FAZ circularity	0.75 ± 0.08	0.59 ± 0.09	t=6.65	<0.001
SCP vessel density (%)	43.0 ± 4.0	35.4 ± 5.0	t=5.90	<0.001
DCP vessel density (%)	39.8 ± 4.8	31.2 ± 5.2	t=5.96	<0.001
Parafoveal vessel density (%)	44.6 ± 4.1	40.5 ± 6.0	t=2.83	0.007

Table 6 compares visual and structural OCT parameters between participants with and without diabetic macular ischemia. DMI was identified in **21 (42.0%)** participants, while 29 (58.0%) did not demonstrate ischemic changes. Participants with DMI had significantly poorer mean BCVA (**0.45 ± 0.25 logMAR**) compared with those without DMI (**0.16 ± 0.13 logMAR; $p < 0.001$**). The mean FAZ area was significantly larger among participants with DMI (**0.62 ± 0.15 mm²**) than among those without DMI (**0.34 ± 0.09 mm²; $p < 0.001$**). Similarly, FAZ perimeter was significantly greater and FAZ circularity significantly lower in the DMI group. SCP and DCP vessel densities were also significantly reduced among participants with DMI. Parafoveal vessel density was lower in the DMI group (**$40.5 \pm 6.0\%$**) compared with the non-DMI group (**$44.6 \pm 4.1\%$; $p = 0.007$**). Central macular thickness did not differ significantly between the two groups (**$p = 0.080$**). These findings indicate that OCTA-derived vascular parameters were more closely associated with DMI than central macular thickness.

Table 7. Correlation of OCTA Parameters with Visual Acuity and Duration of Diabetes

OCTA parameter	Correlation with BCVA (r)	p-value	Correlation with duration of diabetes (r)	p-value
FAZ area	0.62	<0.001	0.48	<0.001
FAZ perimeter	0.57	<0.001	0.44	0.001
FAZ circularity	-0.51	<0.001	-0.38	0.006
SCP vessel density	-0.55	<0.001	-0.46	0.001
DCP vessel density	-0.61	<0.001	-0.52	<0.001
Parafoveal vessel density	-0.43	0.002	-0.39	0.005

Table 7 evaluates the correlation between OCTA parameters, visual acuity and duration of diabetes. FAZ area demonstrated a significant positive correlation with logMAR BCVA (**$r = 0.62$, $p < 0.001$**), indicating that increasing FAZ area was associated with poorer visual acuity. FAZ perimeter also showed a significant positive correlation with BCVA (**$r = 0.57$, $p < 0.001$**), whereas FAZ circularity showed a significant negative correlation (**$r = -0.51$, $p < 0.001$**). Vessel density in both the SCP and DCP demonstrated significant negative correlations with logMAR BCVA, with the strongest correlation observed for DCP vessel density (**$r = -0.61$, $p < 0.001$**). With increasing duration of diabetes, FAZ area and perimeter increased significantly, while FAZ circularity and retinal vessel densities decreased. These findings suggest that longer duration of diabetes was associated with greater macular microvascular compromise and that OCTA-derived vascular abnormalities were significantly related to visual function.

Discussion

Diabetic macular ischemia is an important cause of visual dysfunction in diabetic retinopathy and is characterized by enlargement and irregularity of the foveal avascular zone (FAZ) and progressive capillary non-perfusion. Conventional fluorescein angiography has traditionally been used for assessment of macular ischemia; however, OCTA provides a non-invasive, depth-resolved method for visualization and quantitative assessment of the retinal microvasculature.^{15,16}

In the present hypothetical study of 50 patients, diabetic macular ischemia was identified in **21 (42.0%)** participants. OCTA demonstrated progressive enlargement of the FAZ, reduction in FAZ circularity and reduction in superficial and deep capillary plexus vessel densities with

increasing severity of diabetic retinopathy. These findings are consistent with the observations of **Samara et al.**, who demonstrated significantly larger FAZ areas and reduced superficial and deep vascular densities in diabetic eyes, with these quantitative parameters also correlating with visual acuity.¹⁴

The present study demonstrated a significant increase in FAZ area from $0.32 \pm 0.09 \text{ mm}^2$ in participants with no/mild NPDR to $0.72 \pm 0.16 \text{ mm}^2$ in those with PDR ($p < 0.001$). Similarly, vessel density progressively decreased with increasing retinopathy severity. These findings are in agreement with **Zhang et al.**, whose meta-analysis demonstrated enlarged FAZ measurements and reduced superficial and deep macular perfusion in diabetic patients, including individuals without clinically apparent retinopathy, supporting the potential of OCTA for detecting early microvascular abnormalities.¹⁷

A significant reduction in both superficial and deep capillary plexus density was observed in patients with DMI. The reduction was more pronounced in the deep capillary plexus, where vessel density was $31.2 \pm 5.2\%$ in the DMI group compared with $39.8 \pm 4.8\%$ in patients without DMI ($p < 0.001$). Similar involvement of the deep retinal vascular plexus has been described in previous OCTA studies, suggesting that quantitative assessment of the deeper vascular network may provide useful information regarding the extent of diabetic microvascular damage.^{14,17}

An important finding of the present study was the significant relationship between OCTA abnormalities and visual function. Patients with DMI had poorer BCVA than those without DMI (0.45 ± 0.25 vs. $0.16 \pm 0.13 \text{ logMAR}$; $p < 0.001$). Furthermore, FAZ area showed a positive correlation with logMAR visual acuity, while SCP and DCP vessel densities showed significant negative correlations. These findings closely correspond with those reported by **Samara et al.**, who found that larger FAZ areas and lower vascular densities were associated with worse visual acuity in diabetic eyes.¹⁴

The progressive relationship between OCTA abnormalities and diabetic retinopathy severity observed in our study is also consistent with previous Indian data. **Agrawal et al.** demonstrated significant differences in FAZ area and retinal vessel density across different grades of diabetic retinopathy, supporting the utility of quantitative OCTA parameters for assessment of disease severity.¹⁸

The findings also support the use of OCTA as an alternative or complementary technique to fluorescein angiography for evaluation of diabetic macular ischemia. **Cennamo et al.** reported that OCTA could demonstrate ischemic macular changes and FAZ abnormalities comparable with fluorescein angiography.¹⁵ OCTA has the additional advantages of being non-invasive, rapidly repeatable and capable of separately visualizing the superficial and deep retinal vascular plexuses.

Overall, the present findings suggest that **FAZ enlargement, reduced FAZ circularity and decreased SCP/DCP vessel density are useful OCTA markers of diabetic macular ischemia and increase with the severity of diabetic retinopathy.** The significant association between these parameters and visual acuity further indicates their potential clinical relevance. However, interpretation of OCTA should consider segmentation and motion artefacts, and larger prospective studies are required to establish standardized quantitative thresholds for early DMI detection.

Conclusion

OCTA demonstrated a significant role in the **early detection and severity assessment of diabetic macular ischemia** in this study. Increasing severity of diabetic retinopathy was associated with progressive **FAZ enlargement, increased FAZ irregularity, and reduction in superficial and deep retinal capillary plexus vessel density**. Patients with diabetic macular ischemia also demonstrated significantly poorer visual acuity compared with those without ischemia.

The significant correlations between OCTA-derived vascular parameters, visual acuity and duration of diabetes indicate that these parameters may serve as useful objective markers of diabetic macular microvascular damage. In particular, **FAZ area and vessel density of the deep capillary plexus** appeared to provide clinically relevant information regarding the extent of ischemic involvement.

Thus, OCTA, being **non-invasive, rapid, repeatable and capable of quantitative assessment of retinal microvasculature**, can serve as a valuable complementary imaging modality for identifying early macular ischemic changes and assessing their severity in patients with diabetic retinopathy. Larger prospective studies with standardized OCTA thresholds and longitudinal follow-up are warranted to establish its role in routine screening and monitoring of diabetic macular ischemia.

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