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Long-term superficial capillary plexus remodeling after vitrectomy for full- thickness macular hole: dissociation between microvascular changes and visual recovery

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Long-term superficial capillary plexus remodeling after vitrectomy for full- thickness macular hole: dissociation between microvascular changes and visual recovery

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Key message:

What is known:

- Vitrectomy with internal limiting membrane (ILM) peeling is an effective treatment for idiopathic full-thickness macular hole (FTMH), achieving high anatomical closure rates.
- The influence of vitrectomy on long-term retinal microvascular remodeling, especially in the superficial capillary plexus (SCP), has been unclear.

What is new:

- This study demonstrates a significant long-term reduction in SCP vessel density 12 months post-vitrectomy, particularly in the parafoveal temporal and nasal regions.
- No significant changes were observed in the foveal avascular zone (FAZ) area, suggesting FAZ may not reflect long-term microvascular alterations.
- Postoperative visual outcomes correlated strongly with preoperative anatomical parameters (macular hole diameter and duration), rather than SCP density, indicating that anatomical factors remain the main predictors of visual recovery.

Abstract:

Purpose:

To evaluate long-term changes in the superficial capillary plexus (SCP) and foveal avascular zone (FAZ) after vitrectomy for idiopathic full-thickness macular hole (FTMH), and to investigate the relationship between postoperative microvascular remodeling and visual outcomes using optical coherence tomography angiography (OCTA).

Methods:

This prospective observational study included 33 patients with idiopathic FTMH treated with 23-gauge pars plana vitrectomy, internal limiting membrane peeling, and SF6 gas tamponade. OCTA imaging (6×6 mm scans) was performed preoperatively and at 12 months postoperatively. SCP vessel density and FAZ area were analyzed together with distance and near best-corrected visual acuity (DBCVA, NBCVA). Correlations between microvascular parameters and visual outcomes were assessed using Spearman analysis.

Results:

At 12 months postoperatively, total SCP vessel density showed a significant reduction compared with baseline ($p<0.05$), with the most pronounced decreases observed in the parafoveal temporal and nasal regions. No significant change in FAZ area was observed ($p = 0.387$). Both distance and near visual acuity improved significantly after surgery ($p< 0.001$). Postoperative visual outcomes showed strong correlations with preoperative macular hole diameter ($rs = 0.57–0.69$, $p<0.001$) and moderate correlation with disease duration, whereas SCP vessel density demonstrated no consistent association with functional outcomes.

Conclusion:

Vitrectomy for full-thickness macular hole is associated with long-term superficial capillary plexus remodeling characterized by reduced parafoveal vessel density. However, these microvascular changes do not correlate with visual recovery. Postoperative functional outcomes are primarily determined by preoperative anatomical severity, supporting a dissociation between retinal microvascular remodeling and visual function after macular hole surgery.

Keywords: full-thickness macular hole, optical coherence tomography angiography, superficial capillary plexus, foveal avascular zone

1. Introduction:

Idiopathic full-thickness macular hole (FTMH) is a defect in the central part of the fovea involving all retinal layers from the internal limiting membrane (ILM) to the retinal pigment epithelium (RPE) [1]. Vitrectomy is an effective method of treating FTMH, restoring anatomical closure of the macular hole (MH) at the success rate up to 90–100% [2].

However, during vitrectomy, procedures such as internal limiting membrane (ILM) peeling are performed, which may significantly affect retinal microcirculation [3]. Optical coherence tomography angiography (OCTA) may be used not only to assess microvascular changes after vitrectomy, but also as a prognostic tool [4]. The aim of this research study is to evaluate the effect of vitrectomy on the foveal avascular zone (FAZ) and superficial retinal vessel density (SCP) in patients with FTMH using OCTA.

2. Materials and Methods:

A total of 33 patients were included in the study, comprising 25 women (76%) and 8 men (24%), all of whom provided informed consent. The study was carried out at the Department of Ophthalmology, University Clinical Center of the Medical University of Silesia in Katowice, between 1 January 2023 and 30 June 2025. In addition to a clinical diagnosis of FTMH confirmed by optical coherence tomography (OCT; XR Avanti, Optovue, USA) the inclusion criteria also included age over 18 years and willingness to comply with the study protocol. Exclusion criteria included: congenital or genetically determined retinal diseases, connective tissue diseases, chronic immunosuppression, chronic oncological treatment, condition after anti-VEGF injections, diseases of the anterior segment of the eye that prevent pupil dilation, epilepsy, high myopia (≥ −6.0 Dsph), history of uveitis and retinitis, hyperbaric therapy, other eye diseases that interfere with retinal function (e.g., intraocular tumors, conditions after intraocular foreign body), past trauma to the eye, previous retinal surgery, retinal dystrophy or age-related macular degeneration, and significant media opacities that could affect image quality. All patients diagnosed with FTMH were planned for surgery and underwent standard 23-gauge pars plana vitrectomy performed by an experienced retinal surgeon, involving induction of posterior vitreous detachment, brilliant blue staining, peeling of the internal limiting membrane (ILM) with the standard inverted flap technique, and gas tamponade with sulfur hexafluoride (SF6) without cataract surgery. Anatomical closure of the FTMH was achieved in all patients. Lens transparency was preserved throughout the entire follow-up period, and no patient underwent cataract extraction during the study. Postoperative 7-days face-down positioning was recommended to promote macular hole closure.

2.1 Imaging and Measurements:

OCT angiography was performed with the Optovue XR Avanti system (Optovue, USA). All scans covered a 6x6 mm area centered on the fovea. Only scans with image quality scores above 8 on a 10-point scale were included in the analysis. The parameters measured and analyzed included base diameter (BD) of the macular hole, central retinal thickness (CRT), foveal avascular zone (FAZ) area, minimal diameter (MD) of the macular hole, and parafoveal and perifoveal retinal vascular densities of the superficial capillary plexus (SCP). The parafoveal and perifoveal regions were defined based on the standard segmentation of the 6 × 6 mm OCTA scan provided by the device software (Optovue XR Avanti). These regions correspond to concentric rings centered on the fovea, as automatically delineated by the manufacturer's algorithm. Specifically, the parafovea was defined as the annular region surrounding the fovea with a diameter of approximately 3 mm, while the perifovea corresponded to the outer annular region extending up to 6 mm in diameter. Automated retinal layer segmentation was verified for all postoperative OCTA images by two experienced retinal specialists. Images with significant segmentation errors or motion artifacts were excluded from the analysis. Manual correction was performed when necessary using the device software. Scans were obtained preoperatively and at 12 months postoperatively, while distance best-corrected visual acuity (DBCVA) and near best-corrected visual acuity (NBCVA) were evaluated at the same time points. DBCVA was assessed using Snellen charts and NBCVA was assessed using Jaeger charts, in which lower values correspond to better near visual acuity.

2.2. Statistical Analysis

The normality of the distributions of the analyzed data was assessed using the Shapiro–Wilk test and quantile–quantile (Q–Q) plots. For normally distributed and skewed data, the results of statistical analyses are presented in the Table as mean ± standard deviation, M ± SD, and median (lower and upper quartile), Me (Q1–Q3), respectively. Descriptive statistics are shown in tables and figures, where the mean (•), median (■), and Q1–Q3 range (⊡) are indicated; "whiskers" represent the 95% confidence interval (for the mean) or the non-outlying value range (for the median boxplot). Outliers are marked with (**o**) and extreme values with (∗).

To compare two dependent groups, either the Student's t-test or the paired Wilcoxon test was applied for normally distributed or skewed data, respectively. To assess associations and determine the strength of the relationship between two skewed variables, Spearman's rank correlation test was used. A p-value < 0.05 was considered statistically significant, and all tests were two-tailed. Statistical analyses and figures were performed using Statistica (data analysis software system), version 13.

2.3. Ethics approval and consent to participate

The study adhered to the principles of the Declaration of Helsinki, received approval from the Medical University of Silesia Bioethics Committee (No. PCN/CBN/0052/KB1/122/22), and obtained written informed consent from all participants prior to enrollment.

2. Results

The mean age ± standard deviation for the entire group was 66.6 ± 5.5 years. The age of women ranged from 51 to 78 years, with a mean ± standard deviation of 66.2 ± 5.7 years. The age of men ranged from 61 to 74 years, with a mean ± standard deviation of 68.0 ± 4.6 years. No significant differences in age were observed between sexes ($p = 0.415$).

The mean superficial capillary plexus (SCP) vessel density of the affected eye in patients examined before surgery (FTMH t0) differed significantly from the total vessel density after the procedure (FTMH t12) ($p < 0.05$). However, surgery did not significantly affect vessel density in the foveal region ($p = 0.088$). Superficial capillary plexus vessel density (SCP-PARA) in the parafovea, parafovea temporal, parafovea superior, and parafovea nasal regions of the affected eye before surgery (FTMH t0) differed significantly from vessel density after surgery, with p-values of < 0.01, < 0.001, < 0.05, and < 0.01, respectively. In these regions, vessel density decreased following surgery. Superficial capillary plexus vessel density (SCP-PERI) in the affected eye before full-thickness macular hole surgery differed significantly from postoperative values in the perifovea nasal and perifovea inferior regions ($p < 0.01$ and $p < 0.01$, respectively). In these regions, vessel density decreased after surgery. No significant changes in superficial capillary plexus vessel density were observed after FTMH surgery in the parafovea inferior, perifovea, perifovea temporal, or perifovea superior regions, with p-values of 0.271, 0.052, 0.538, and 0.184, respectively. These results indicate that surgery significantly affected retinal vessel density but only in specific PARA and PERI regions of the SCP image. Detailed data are presented in Table 1 and Figure 1.

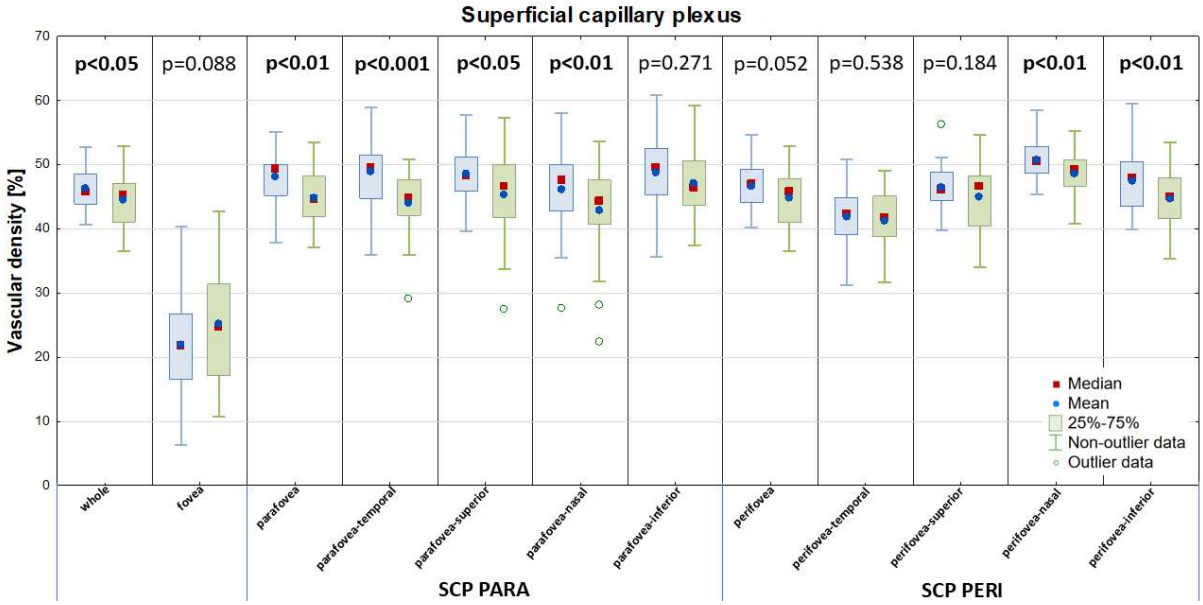
Table 1. Comparison of tomographic features (SCP) between the pre-operative FTMH (t_0) and post-operative MH (t_{12}).

n=33 **Vascular density [%]**	**FTMH (t_0)**	**FTMH (t_{12})**	***p*-value**
WHOLE IMAGE	46.25±2.95	44.50±3.85	**<0.05**
FOVEA	22.01±7.28	25.25±9.01	0.088
PARAFOVEA	48.09±3.79	44.88±4.13	**<0.01**
PARAFOVEA TEMPORAL	48.87±4.50	44.07±4.73	**<0.001**

PARAFOVEA SUPERIOR	48.3 (45.9–51.2)	44.3 (40.7–47.6)	**<0.05**
PARAFOVEA NASAL	46.18±6.31	42.93±6.75	**<0.01**
PARAFOVEA INFERIOR	48.68±5.09	47.07±5.02	0.271
PERIFOVEA	46.62±3.46	44.82±4.23	0.052
PERIFOVEA TEMPORAL	41.95±4.41	41.27±4.58	0.538
PERIFOVEA SUPERIOR	46.51±3.51	45.04±5.15	0.184
PERIFOVEA NASAL	50.69±3.08	48.52±3.92	**<0.01**
PERIFOVEA INFERIOR	47.41±4.77	44.61±4.61	**<0.01**

Legend: M±SD–mean±standard deviation, Me (Q_1–Q_3) –median (lower–upper quartile), *p*–statistical significance

Figure 1. Comparison of pre-operative and post-operative vascular density [%] of eyes with macular hole (MH) group (n=33) at different sectors. Panel a) SCP whole and fovea b) SCP (PARA), panel c) SCP (PERI). The symbols (■), and (•), indicates the median and mean value, the "whiskers" indicate the non-outlier data.



A statistically significant difference was found between DBCVA [logMAR] values in the affected eye before surgery and 12 months postoperatively ($p < 0.001$). The median DBCVA [logMAR] in the affected eye decreased from 1.097 preoperatively to 0.523 at 12 months after surgery, indicating an

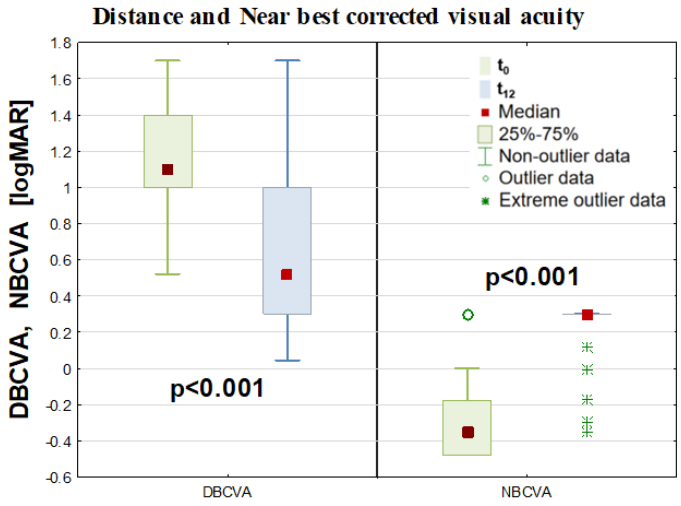
improvement in visual acuity of the affected eye as a result of the procedure. For near visual acuity (NBCVA), a statistically significant difference in [logMAR] values was also observed between preoperative and 12-month postoperative measurements of the affected eye ($p < 0.001$). The median NBCVA [logMAR] increased from –0.352 before surgery to 0.301 at 12 months postoperatively. Thus, the surgery improved near visual acuity in the affected eye. In contrast, mean FAZ values measured in the affected eye before surgery and at the 12-month follow-up did not differ significantly ($p = 0.387$). Therefore, the procedure had no significant impact on changes in this parameter. Detailed data are presented in Table 2 and Figure 2.

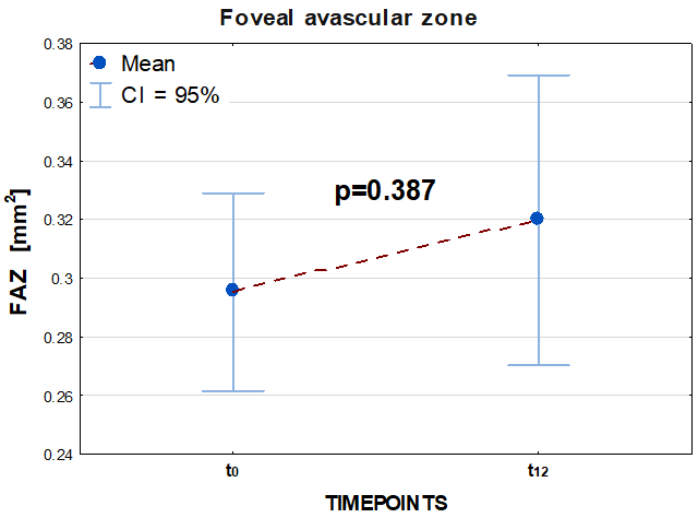
Table 2. Distance best corrected visual acuity (DBCVA) and near best corrected visual acuity (NBCVA) [logMAR] as well as fovea avascular zone, FAZ [mm^2] of eyes with macular hole (MH group) at pre-operative (t_0) and post-operative (t_{12}) time points.

n=33	**FTMH (t_0)**	**FTMH (t_{12})**	**p-value**
DBCVA [logMAR]	1.097 (1.000–1.398)	0.523 (0.301–1.000)	**<0.001**
NBCVA [logMAR]	-0.352 (-0.477– -0.176)	0.301 (0.301–0.301)	**<0.001**
FAZ [mm^2]	0.295±0.095	0.320±0.139	0.387

Legend: M±SD–mean±standard deviation, Me (Q_1–Q_2)–median (lower–upper quartile), *p*–statistical significance

Figure 2. Summary data for best-corrected distance visual acuity (DBCVA) and near visual acuity (NBCVA) expressed in (logMAR)—panel (a)—and for foveal area free (FAZ) (mm2)—panel (b)—of the patient eye group (MH group) examined before surgery (t0) and at follow-up visits at 12 (t12) months after surgery. The symbols (■) and (•) denote the median and mean value, respectively; the 'whiskers' denote the range of non-outliers data panel (a), and the 95% confidence interval panel (b), respectively.





The correlation between superficial capillary plexus (SCP) vessel density of the affected eye before surgery (t0) in each of the analyzed regions and postoperative DBCVA and NBCVA of the affected eye at 12 months (t12) was weak and not statistically significant. Detailed data are presented in Table 3 (DBCVA) and Table 4 (NBCVA).

Table 3. Measure of the association between superficial capillary plexus (SCP) vessel density in different regions of the affected eye at 12 months postoperatively (t12) and preoperative DBCVA [logMAR] (t0).

Vascular density [%] (FTMH t_0)	**DBCVA** [logMAR] (FTMH t_{12})	
SCP PARA	**r_s**	***p*-value**
WHOLE IMAGE	0.14	0.445
FOVEA	0,08	0,661
PARAFOVEA	0,08	0,663
PARAFOVEA TEMPORAL	-0,11	0,527
PARAFOVEA SUPERIOR	0,04	0,840
PARAFOVEA NASAL	-0,15	0,410
PARAFOVEA INFERIOR	0,16	0,370

Vascular density [%] (FTMH t_0)	**DBCVA** [logMAR] (FTMH t_{12})	
SCP PERI	**r_s**	***p*-value**
PERIFOVEA	0,18	0,326
PERIFOVEA TEMPORAL	0,07	0,692
PERIFOVEA SUPERIOR	0,24	0,184
PERIFOVEA NASAL	0,06	0,750
PERIFOVEA INFERIOR	0,16	0,372

Legend: r_s- Spearman correlation coefficient, *p* - statistical significance

Table 4. Measure of the association between superficial capillary plexus (SCP) vessel density in different regions of the affected eye at 12 months postoperatively (t12) and preoperative NBCVA [logMAR] (t0).

Vascular density [%] (FTMH t_0)	**NBCVA** [logMAR] (FTMH t_{12})	
SCP PARA	**r_s**	***p*-value**
WHOLE IMAGE	-0.01	0.967
FOVEA	-0.15	0.395
PARAFOVEA	0.12	0.516
PARAFOVEA TEMPORAL	0.33	0.060
PARAFOVEA SUPERIOR	0.03	0.855
PARAFOVEA NASAL	0.25	0.168
PARAFOVEA INFERIOR	-0.03	0.868
Vascular density [%] (FTMH t_0)	**DBCVA** [logMAR] (FTMH t_{12})	
SCP PERI	**r_s**	***p*-value**
PERIFOVEA	-0.06	0.730
PERIFOVEA TEMPORAL	0.16	0.378
PERIFOVEA SUPERIOR	-0.26	0.149

PERIFOVEA NASAL	0.00	0.992
PERIFOVEA INFERIOR	-0.03	0.861

Postoperative DBCVA [logMAR] values of the affected eye showed a statistically significant, strong positive correlation with both the minimum (rs = 0.69, p < 0.001) and maximum macular hole diameter (rs = 0.57, p < 0.001). Higher postoperative DBCVA [logMAR] values (indicating worse visual acuity) were associated with larger minimum and maximum MH diameters. A moderate but statistically significant positive correlation was also observed between postoperative DBCVA [logMAR] and MH duration prior to surgery (rs = 0.46, p < 0.01), indicating poorer visual acuity with longer MH duration.

No statistically significant correlation was found between postoperative DBCVA of the affected eye and other parameters, including patient age, CRT, time between surgery and the first examination, FAZ, or total vessel density of SCP and DCP. Detailed data are presented in Table 5.

The median (Me [Q1–Q3]) MH duration (defined as the time from onset of visual deterioration to surgery) was 4.1 (3.0–7.6) months, with a maximum duration of 26.9 months. The median (Me [Q1–Q3]) interval between the first examination and surgery (PPV) was 4 (0–25) days, with a maximum interval of 119 days.

Table 5. Measure of the association between postoperative DBCVA [logMAR] of the affected eye (12-month follow-up, t12) and selected preoperative parameters of the affected eye (t0).

DBCVA [logMAR] FTMH (t_{12})	**Selected FTMH parameters (t_0)**	r_s	***p*-value**	**correlation strength $\|r_s\|$**
	hole diameter (minimal) [µm]	0.69	**<0.001**	high
	hole diameter (basal) [µm]	0.57	**<0.001**	high
	patient age at the time of surgery [years]	0.17	0.340	weak
	duration of the macular hole before surgery [months]	0.46	**<0.01**	moderate
	time between PPV and preoperative examination [days]	-0.27	0.128	weak
	CRT [µm]	-0.18	0.326	weak
	FAZ [mm^2]	0.31	0.078	moderate
	whole vascular density SCP [%]	0.14	0.445	weak

Legend: r_s- Spearman correlation coefficient, *p* - statistical significance

The MD of FTMH was 448.2±184.0 μm. No association was found between the MD or BD and the superficial capillary plexus vessel density (SCP t0) in any of the analyzed regions before surgery (at t0). Thus, the size of the FTMH did not affect the density of the superficial retinal vasculature. Furthermore, no association was observed between the MD or BD diameter and postoperative changes in superficial capillary plexus vessel density (SCP t0–t12).

A statistically significant moderate positive correlation was observed between the percentage change in retinal vascular plexus density in the parafoveal nasal region and the change in DBCVA ($rs = 0.43$, $p < 0.05$). This was the only SCP region in which postoperative changes in vessel density were significantly associated with changes in distance visual acuity. In all other SCP regions, no significant relationships were found between percentage changes in vessel density and changes in either DBCVA or NBCVA. Therefore, FTMH surgery was generally not associated with changes in visual acuity in relation to percentage changes in SCP vessel density.

3. Discussion:

This study demonstrates long-term postoperative microvascular remodeling of the superficial capillary plexus (SCP) in eyes with idiopathic full-thickness macular hole (FTMH) 12 months after pars plana vitrectomy with internal limiting membrane peeling.

We observed a statistically significant reduction in overall SCP vessel density over the follow-up period, with the most pronounced changes occurring in the parafoveal temporal and nasal regions, while the foveal region remained relatively stable.

The observed pattern suggests that postoperative microvascular alterations after macular hole surgery are not uniformly distributed across the macula but instead follow a regional configuration, predominantly affecting the parafoveal vascular network. This spatial heterogeneity has also been reported in previous optical coherence tomography angiography (OCTA) studies, where perifoveal and parafoveal regions were shown to be more susceptible to postoperative vascular remodeling than the central fovea [5]. However, the direction and magnitude of these changes vary across studies, particularly depending on the length of follow-up.

Short-term investigations have often described transient increases in SCP vessel density in the early postoperative period, which have been interpreted as a possible compensatory vascular response following surgical decompression of the macula [6,7]. In contrast, our 12-month results suggest that long-term vascular remodeling is characterized by a reduction in SCP density rather than an increase, indicating that early postoperative changes may represent temporary physiological adaptation rather than sustained regeneration. This supports the concept of a biphasic vascular response after macular

hole surgery, consisting of an early dynamic phase followed by a longer-term remodeling or stabilization phase.

Internal limiting membrane (ILM) peeling may also contribute to the observed microvascular alterations [8]. Mechanical manipulation of the ILM can disrupt Müller cell endfeet and the inner retinal structural framework, which plays a critical role in maintaining retinal neurovascular coupling. Such disruption may lead to long-term redistribution of superficial capillary flow and structural reorganization of the parafoveal microvasculature [9].

Importantly, our results demonstrate a clear dissociation between postoperative microvascular changes and functional visual outcomes. Although best-corrected distance and near visual acuity improved significantly after surgery, SCP vessel density showed no consistent correlation with postoperative visual function. This finding suggests that restoration of visual acuity following macular hole surgery is primarily driven by preoperative anatomical factors rather than postoperative microvascular status [10,11,12].

In particular, minimum and basal macular hole diameter showed strong correlations with postoperative visual acuity outcomes, and macular hole duration also demonstrated a significant, although weaker, association with final visual function. These findings reinforce the concept that structural integrity of the fovea prior to surgery is the most important determinant of postoperative visual recovery, consistent with previous studies on macular hole prognostication [13].

In contrast, the foveal avascular zone (FAZ) did not show significant long-term changes after surgery in our cohort [4,6,7]. While some previous studies have reported postoperative FAZ reduction in the short term, our findings suggest that FAZ may stabilize over longer follow-up periods and may not be a sensitive marker of sustained microvascular remodeling in FTMH patients [14].

Taken together, our results support a model in which anatomical severity of the macular hole determines functional recovery, whereas postoperative SCP changes reflect secondary microvascular remodeling that is largely uncoupled from visual function. This dissociation highlights the limited role of OCTA-derived vascular density metrics as predictors of long-term functional outcomes in macular hole surgery.

Limitation

Several limitations of this study should be acknowledged. First, the study lacked a control group, such as the fellow eye, which may limit the ability to fully isolate disease-specific microvascular changes. Second, the analysis was restricted to the superficial capillary plexus, as no data on the deep capillary plexus (DCP) were available, potentially limiting a more comprehensive assessment of retinal microcirculation. Third, the relatively small sample size may reduce the statistical power and limit the generalizability of the findings. Finally, inherent limitations of OCTA, including susceptibility to motion artifacts, segmentation errors, and signal attenuation, should also be considered when interpreting the results.

5. Conclusions:

Vitrectomy for idiopathic full-thickness macular hole results in long-term remodeling of the superficial capillary plexus, characterized by a persistent reduction in parafoveal vessel density at 12 months postoperatively. However, these microvascular changes do not correlate with postoperative visual acuity outcomes.

Visual recovery is primarily determined by preoperative anatomical parameters, particularly macular hole diameter and duration, indicating that structural factors remain the dominant prognostic determinants after surgery. The lack of significant long-term changes in the foveal avascular zone suggests that FAZ may not serve as a reliable biomarker of chronic microvascular remodeling following macular hole repair.

Overall, these findings support a dissociation between postoperative microvascular remodeling and functional visual recovery after macular hole surgery.

6. Statements and Declarations

The authors did not receive support from any organization for the submitted work.

The authors declare they have no financial interests.

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of Data and Materials

The datasets generated and analysed during the current study are not publicly available due to patient privacy and ethical restrictions but are available from the corresponding author on reasonable request.

Consent for Publication

Not applicable.

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Contribution

Aleksandra Górska - drafted the work, interpretate of data, desing the work, data analysis, approved the version to be published, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Sebastian Sirek - drafted the work, interpretate of data, data analysis, approved the version to be published, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Mikołaj Guzikowski - drafted the work, interpretate of data, data analysis, approved the version to be published, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Sabina Kowalczyk - drafted the work, interpretate of data, data analysis, approved the version to be published, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

Dorota Pojda – Wilczek - revised it critically for important intellectual content, interpretate of data, data analysis, approved the version to be published, agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved

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