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Article

Dynamic biological macular vascular changes of silicon oil tamponade in patients with rhegmatogenous retinal detachment

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Abstract: Pars Plana Vitrectomy (PPV), combined with intravitreal tamponade Silicone Oil (SO), is one of the most popular and effective surgical interventions for Rhegmatogenous Retinal Detachment (RRD), achieving high rates of anatomic reattachment. However, long-term SO Tamponade (SOT) can induce structural and microcirculation alterations, affecting visual function, even after SO Removal (SOR). Therefore, for an appropriate SO Filling (SOF) duration, we investigated the dynamic changes of macular vasculature during SOF and after SOR. 51 eyes (51 patients) with macular-on RRD underwent single PPV and were randomly divided into 2 groups according to intravitreal SOT duration, either for 2 or 3 months. Optical Coherence Tomography (OCT) and angiography were used to evaluate the macular perfusion system, which was segmented into Superficial and Deep Capillary Plexus Flow Density (SCPFD, DCPFD) and Choriocapillaris Plexus Flow Density (CCPFD). The VA (VA) and the flow density were measured at 1 week, 1 month, 2 months, and 3 months SOF, and 1 week and 1 month post SOR. Both 2- and 3-month SOT strongly reduced VA, particularly in the first month. There was no significant difference in VA between the two groups during the opinion. Compared with that before the surgery, the VA had a 51% reduction after 2 months and a 57% reduction after 3 months of SOF, which was not recovered even after a 1-month SOR. 2-month SOT did not significantly affect macular microvascular. However, SCPED was starkly suppressed at 3-month SOF, following a significant increase after 1-month SOR. Moreover, 2-month SOT caused slight changes in macular microcirculation during the observation, together with a fast recovery of VA after 1-week SOR, about 90% of VA at 1-week SO. However, the flow densities in all three segmented layers upon 3-month SOT were correlated with each other, showing the same fluctuation trend, i.e., strong suppression at 3-month SO and slow recovery after SOR, which a low VA accompanied after 1-week SOR, about 50% of VA at 1-week SOT. Either 2- or 3-month SOT reduced VA of RRD eyes. However, unlike 2-month SOF, 3-month SOT could induce strong suppression of macular microcirculation, which might be detrimental to VA recovery of RRD eyes after PPV surgery. Therefore, a 2-month SO might be an appropriate time for SOR to achieve a better functional recovery of RRD.

Keywords: retinal detachment; pars plana vitrectomy; silicone oil; optical coherence tomography; macular vasculature

1. Introduction

Rhegmatogenous Retinal Detachment (RRD) is the most common form of RD, with an increasing incidence in approximately 1 in 10,000 per annum populations [1]. It has a higher prevalence among individuals with risk factors such as high myopia, lattice degeneration, ocular trauma, and both uncomplicated and complicated phacoemulsification. RRD is a separation of the neurosensory retina from the

underlying retinal pigment epithelium due to a full-thickness retinal break that allows fluid from the vitreous cavity to accumulate beneath the retina, resulting in detachment. Acute progressive RRD with onset is defined as less than 2 weeks, whereas chronic RRD is present for longer than 2 weeks [2].

Previously, RRD was severe and untreatable, mostly leading to permanent vision loss. Currently, RRD achieves primary surgical success rates of over 80%–90%, with complex cases also amenable to treatment due to several optimal surgical management. Pars Plana Vitrectomy (PPV) has become one of the most popular and effective surgical interventions, particularly in complex cases wherein intravitreal tamponade mediums are needed for retinal repair [3]. As a biochemically inert polymer, SO is widely used in vitreoretinal surgery and is considered well-tolerated and not threatening to retinal physiology [4]. Silicone Oil (SO) cannot be kept in the eye for an extended time, and after a good rest of the retina, it needs to be removed from the eye. The retention time of SO is inconclusive, generally in the 3–6 months [5]. However, up to a third of patients suffered from unexplained severe visual damage after intravitreal SO use, i.e., SO-Related Visual Loss (SORVL) [6,7]. Recent studies have reported that the thinning of the macula reduces macular vessel density [8] and contributes to reduced visual acuity (VA). However, unchanged macular microvascular was also observed [9].

These discrepancies might be due to different study settings. For example, different SO Tamponade (SOT) durations, 3 or 4 months, or even longer, were employed in the clinical studies [10]. Moreover, different controls, e.g., either with a healthy fellow eye or gas tamponade, might not indeed detect the changes in RRD eyes with SO Filling (SOF) [11,12]. However, despite its irreplaceable role in RRD surgery, SOF duration is now recognized as a negative factor for the visual functional recovery of RRD patients. Therefore, to find an optimizing SOF duration, the dynamic changes of macular microcirculation were investigated in RRD eyes at 1 week, 1 month, 2 months, and 3 months SOF, as well as 1 week and 1 month post-SOR.

The optimal duration of Silicone Oil Tamponade (SOT) in rhegmatogenous retinal detachment (RRD) surgery is one of the most critical factors for maximizing visual function recovery and minimizing macular microcirculation damage. SO is an essential agent in retinal reattachment, but prolonged retention may adversely affect macular perfusion and Visual Acuity (VA). The conflicting results of the existing literature regarding the effects of SOT on macular microvascular integrity, where some studies indicate reduced vessel density and others have no significant changes, are discussed. Such discrepancies emphasize the necessity for systematic investigation of the dynamic changes of macular vasculature under different periods of SOT. Thus, this study aims to evaluate the effect of 3-month versus 2-month SOT on macular perfusion using OCTA and determine the most appropriate timing for Silicone Oil Removal (SOR) that will maximize VA recovery and minimize retinal microvascular damage.

The study's primary interest is assessing the effect of different SOT durations (2 months vs. 3 months) on macular microvascular changes and VA recovery in RRD patients after Pars Plana Vitrectomy (PPV). The study uses Optical Coherence Tomography Angiography (OCTA) to investigate the variations in macular perfusion (Superficial and Deep Capillary Plexus Flow Density [SCPFD, DCPFD] and

Choriocapillaris Plexus Flow Density [CCPFD]) at different time points during SOT and after SOR. The findings are intended to formulate clinical recommendations on the optimal timing of SOR to achieve maximal VA recovery without compromising the adverse effects on macular microcirculation.

2. Methods

2.1. Study design and patients

This retrospective study involved patients who received treatment for complicated RRD at The First Affiliated Hospital of Hunan Normal University from September 2022 to September 2023. Patients of either gender, aged between 40 and 70 years, with primary RRD, were included. The included patient's mindset had a preoperative proliferative vitreoretinopathy (PVR) classification of B or other situations requiring vitrectomy combined with SOT, accompanied by successful retinal repositioning. The study was conducted following the principles of the Declaration of Helsinki, and approval was attained from the Ethics Committee of Hunan Normal University. The involved patients were informed and required to give their written consent before inclusion in the study.

The patients in the following situations were excluded: (1) with a history of internal ophthalmic surgery in either of two eyes and cataract surgery; (2) with a history of retinal disease, such as choroidal neovascularization, diabetic retinopathy, retinal dystrophy, central serous chorioretinopathy, or glaucoma; (3) with an equivalent spherical lens ≤ -6 diopters (D) or astigmatism reference ≥ 1.5 D; (4) with poor image quality or missing medical records. Patients with a history of herpetic disease, keratoconus, glaucoma, pseudoexfoliation, cataract surgery, trauma, intravitreal injections or retinal lasers, vitreous hemorrhages, posterior uveitis, proliferative diabetic retinopathy, and macular hole-related RRD were excluded.

In this study, the randomization procedure was performed using a computer-generated randomization method to provide an unbiased allocation of participants to the 2-month and 3-month SOT groups. The sample size was moderate, and no pre-stratification factors were considered essential; thus, randomization was performed by a 1:1 allocation ratio without stratification or block randomization. Patients were excluded if they had a history of previous retinal surgery, diabetes, glaucoma, or other ocular pathologies that could independently affect macular perfusion and visual function. These exclusion criteria were implemented to minimize confounding variables and make changes in macular microcirculation and VA due to SOT duration and not preexisting ocular conditions. Nevertheless, this exclusion may introduce selection bias as the study population consists of a subset of RRD patients with no significant comorbidities, which could limit the generalizability of the findings to the broader clinical population. Additionally, while computer-generated randomization was used, the study was not blinded, and thus, the possibility of biased postoperative assessments remains. Future studies could incorporate stratified or block randomization, as well as double-blinding, to increase the robustness of the findings and to further validate an optimal duration of SOT in different patient populations.

2.2. Surgery

Standard three-port 23-gauge PPV was performed under anesthesia using the Alcon Constellation system (Alcon Laboratories, Inc., Fort Worth, TX, USA). The preoperative VA extent of RRD was double-checked during the procedure. Before surgery and SOR, the choice for the duration of SOF was first discussed with the patient, based on intraocular pathological condition, and was finally decided by the surgeon before SOR. Group A included 10 patients with 2-month SOT, and 31 patients with 3-month SOT were in group B. No patient suffered from recurrent retinal detachment after 1 month of SOR.

2.3. Image analysis

All patients underwent EDI-OCT scans using a spectral HRA-OCT device from Heidelberg Engineering, Heidelberg. EDI-OCT images were obtained with a 30° × 5° volume scan centered on the macular fovea, averaging 100 frames per scan. The EDI-OCT scan passing through the macular fovea was selected for analysis. The choroid was defined as the space between the outer edge of the retinal pigment epithelium and the choroid-scleral junction. After determining the scale using the public domain software Fiji (*http://fiji.sc/Fiji*), the CT was manually measured by taking the mean of three readings. With the macular fovea as the center, one position was measured every 750 μm towards the nasal and temporal sides for 5 positions. This study analyzed the macular perfusion system, which was segmented into superficial and deep capillary plexus flow density (SCPFD, DCPFD) and choriocapillaris plexus flow density (CCPFD).

2.4. Statistical analysis

Statistical analysis was performed using SPSS software (version 30.0). Frequencies and percentages described qualitative parameters, while quantitative parameters were described by means and standard deviation (SD). Qualitative variables were compared using the x^2 test, and quantitative variables were compared using the ANOVA test between two groups. A p-value of <0.05 was considered statistically significant.

3. Results

3.1. Patient basic information before the operation

A total of 51 patients were included in the study and divided into 2 groups according to SOT duration: Group A with 2-month SO (n = 10) and group B with 3-month SOT (n = 31). The demographic and preoperational clinical characteristics of the study population are given in **Table 1**. No significant differences in these parameters were found between the two groups. The average ages of the two groups were similar and not significantly different (50.10 ± 10.07 and 50.71 ± 13.59, p = 0.897). 50% and 68% of males were in two groups. The onset days were 13.10 ± 10.49 and 34.46 ± 70.20 (p = 0.348). The average values of corneal endothelial cells in the right and left eyes were 2748.40 ± 269.65 and 2574.71 ± 310.83, 2733.11 ± 205.16 and 2685.82 ± 166.77 in the two groups (both p > 0.05). The axial lengths of the right

and left eyes were 24.27 ± 2.36 and 24.88 ± 2.19 mm, 25.03 ± 2.64 and 24.84 ± 2.24 mm in the two groups (both $p > 0.05$). The superficial macular blood flow density, deep macular blood flow density, and macular choroidal capillary blood flow density of the fellow healthy eye were also not statistically significant between the two groups ($p > 0.05$). It indicated no significant differences in age, gender, days of onset, and eye indicators between the two groups before the operation.

Table 1. Basic features and intraoperative data of patients. Data were expressed as mean ± SD.

Characteristic	Group A (n = 10)	Group B (n = 31)	p
	2-month SO	2-month SO	
Age (year)	50.10 ± 10.07	50.71 ± 13.59	0.897
Male n (%)	5(50.00)	21(67.74)	0.311
Days of onset	13.10 ± 10.49	34.46 ± 70.20	0.348
RRD eyes in right, n (%)	6 (60%)	15 (48%)	0.508
Corneal endothelial cells (right)	2748.40 ± 269.65	2574.71 ± 310.83	0.141
Corneal endothelial cells (left)	2733.11 ± 205.16	2685.82 ± 166.77	0.508
Axis length (right, mm)	24.27 ± 2.36	24.88 ± 2.19	0.475
Axis length (left, mm)	25.03 ± 2.64	24.84 ± 2.24	0.835
SCPED (healthy eye)	25.43 ± 9.95	22.35 ± 6.18	0.281
DCPED (healthy eye)	19.31 ± 9.14	22.40 ± 8.22	0.352
CCPED (healthy eye)	29.87 ± 9.50	29.04 ± 10.28	0.833

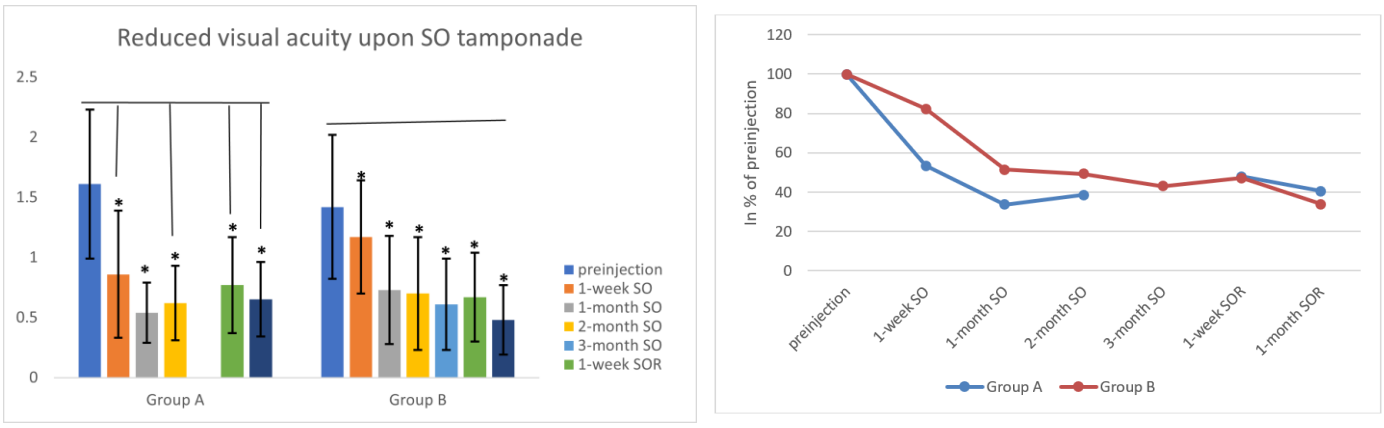
SCPFD: Superficial capillary plexus flow density; DCPFD: Deep capillary plexus flow density; CCPFD: Choriocapillaris plexus flow density.

3.2. Significantly reduced VA by 2-month and 3-month SOT

Table 2 and **Figure 1a** showed strongly reduced VA in both groups at different time points during SOF, which lasted even after 1 month of SOR. In group A with 2-month SOF, the average visual acuities of the operation eyes were 1.61 ± 0.62 before oil injection, 0.86 ± 0.53 after 7 days SOF, 0.54 ± 0.25, 0.62 ± 0.31 after 2 months SOF, 0.77 ± 0.40 1 week post-oil removal, and 0.65 ± 0.31 at 1 month post-oil removal. A similar reduction trend was seen in group B with 3-month SOF. The average vision acuities of the operated eyes were 1.42 ± 0.60 before the surgery, dropped to 1.17 ± 0.47 after 1 week of SOF, and further dropped to 0.73 ± 0.45, 0.70 ± 0.47, and 0.61 ± 0.38 at 1, 2 and 3 months post-SOF, then maintained to 0.67 ± 0.37 and 0.48 ± 0.29 after 1 week and 1 month of SOR. The ANOVA test showed significant differences in VA during SOF ($p = 0.001$ and $p = 0.000$).

Table 2. Reduced VA during 2/3-month SOF and post SOR. Data were expressed as mean ± SD.

VA	preinjection	1-week SOF	1-month SOF	2-month SOF	3-month SOF	1-week SOR	1-month SOR	P
Group A (n = 10)	1.61 ± 0.62	0.86 ± 0.53	0.54 ± 0.25	0.62 ± 0.31		0.77 ± 0.40	0.65 ± 0.31	0.001
Group B (n = 31)	1.42 ± 0.60	1.17 ± 0.47	0.73 ± 0.45	0.70 ± 0.47	0.61 ± 0.38	0.67 ± 0.37	0.48 ± 0.29	0.001



(a) **(b)**

Figure 1. Reduced vision acuity (VA) during 2-month (group A, n = 10) or 3 months (group B, n = 31) SOF and after 1 month SOR. The data expressed with mean ± SE were shown in **(a)**, and the dynamic changes during the 3- or 4-month observation were shown in **(b)**, indicating significance compared with that of pre-injection ($p < 0.05$).

The vision was getting worse over time with SOF and was not improved even after SOR, clearly seen in **Figure 1b**. The fastest decline of VA was in the first month after SO injection, with about 34% and 51% VA reduction in the two groups, then slowly decreased to 39% and 49% after 2-month SO injection. The VA continually reduced to 43% in patients after 3 months of SOF. After SO Removal (SOR), the VA increased slightly to 48% and 47%, then reduced again to 40% and 34% in the two groups, indicating that VA reduction due to SOF could not recover after 1-month SOR.

From **Table 1** is compared with VA before the surgery, the VA was significantly reduced during SOF and SOR (p < 0.05–0.0001) in **Table 3**. Despite a similar reduction, VA post-1-month SOR in group B with 3-month, other than 2-month SOF, was significantly lower than those at 1-week and 1-month SOF, indicating a delayed VA recovery due to long-term SOF.

Table 3. Pairwise comparison of average VA at each time point. Data were expressed as mean ± SD.

Timepoint I	Timepoint J	Difference(I-J) in group A	*p*	Difference(I-J) in group B	*p*
Preinjection	1 week SO	0.75 ± 0.212	0.000***	0.256 ± 0.312	0.026
Preinjection	1-month SO	1.07 ± 0.111	0.000***	0.698 ± 0.343	0.001
Preinjection	2-month SO	−0.99 ± 0.299	0.000***	0.727 ± 0.345	0.000***
Preinjection	3-month SO			0.818 ± 0.344	0.000***
Preinjection	1-week post SOR	−0.843 ± 0.133	0.000***	0.75 ± 0.205	0.001
Preinjection	1-month post-SOR	−0.96 ± 0.318	0.000***	0.94 ±0.311	0.001
1-week SO	1-month SO	−0.32 ± 0.253	0.105	0.442 ± 0.212	0.001
1-week SO	2-month SO	−0.24 ± 0.206	0.222	−0.119 ± 0.309	0.291
1-week SO	1-week post-SOR	−0.093 ± 0.209	0.642	−0.494 ± 0.229	0.001
1-week SO	1-month post-SOR	−0.21 ± 0.318	0.353	−0.684 ±0.312	0.001
1-month SO	2-month SO	0.08 ± 0.218	0.682	0.029 ± 0.333	0.797
1-month SO	1-week SOR	0.227 ± 0.118	0.261	−0.052 ± 0.231	0.652
1-month SO	1-month SOR	0.11 ± 0.318	0.626	−0.242 ± 0.318	0.036

Table 3. (*Continued*).

Timepoint I	Timepoint J	Difference(I-J) in group A	*p*	Difference(I-J) in group B	*p*
2-month SO	1-week SOR	−0.147 ± 0.233	0.466	−0.023 ± 0.344	0.842
2-month SO	1-month post-SOR	−0.03 ± 0.212	0.894	−0.213 ± 0.367	0.061
3-month SO	1-week SOR			0.068 ± 0.344	0.549
3-month SO	1-month SOR			−0.123 ± 0.308	0.278
1-week SOR	1-month SOR	0.117 ± 0.211	0.612	0.19 ± 0.302	0.098

*** $P < 0.001$.

3.3. Significantly increased SCPFD at 1-month post-SOR in eyes underwent 3-month, but not 2-month SOF

Table 4 and **Figure 2** showed changes in SCPFD at different time points in the two groups. The SCPFD was measured with OCT-angiogram imaging during 2 months (group A, $n = 10$) or 3 months (group B, $n = 31$) SOF and after 1-month SOR. The data expressed with mean ± SE were shown in (a), and the dynamic changes during the 3/4-month observation were shown in (b). It indicates significance compared with 1 month after SOR ($p < 0.05$). In group A with 2-month SO, the average values of SCPFD before SOR were not significantly different: 15.34 ± 6.79, 17.63 ± 6.45, and 15.64 ± 7.21 at 1-week, 1-month, and 2-month SOF. After SOR, there was no statistical significance, whereas blood flow showed an increasing trend after SOR, i.e., 20.85 ± 5.94 and 23.10 ± 11.85 at 1 week and 1-month SOR. Likewise, 3-month SOF caused a similar dynamic change to those in group A, but it was significant ($p = 0.028$). The average values were 14.84 ± 5.88, 13.87 ± 4.84, and 16.04 ± 5.30 at 1 week, 1 month, and 2 months SOF, but decreased to 12.62 ± 6.40 at 3 months SO, about 85% of that at 1 week SOF. Then, it was restored to 15.93 ± 5.78 and 20.17 ± 7.77 after 1 week and 1 month of SOR. In both groups, the superficial macular blood flow densities reached the highest level after 1-month SOR but were lower in the 3-month SO group than in the 2-month SO group (136% vs. 151% of that at 1-week SO), indicating a slow superficial macular blood flow recovery. In group B after 1-month SOR, the SCPFD was significantly different from those at 1-week, 1-month, and 3-month SOR ($p = 0.002$–0.009), and the p-value is about 0.06 when compared with that at 2-month SO and after 1-week SOR (**Table 5**). These results indicate that long-term SOF, i.e., 3-month SO, strongly repressed the SCPFD, which can even last after 1-month SOR.

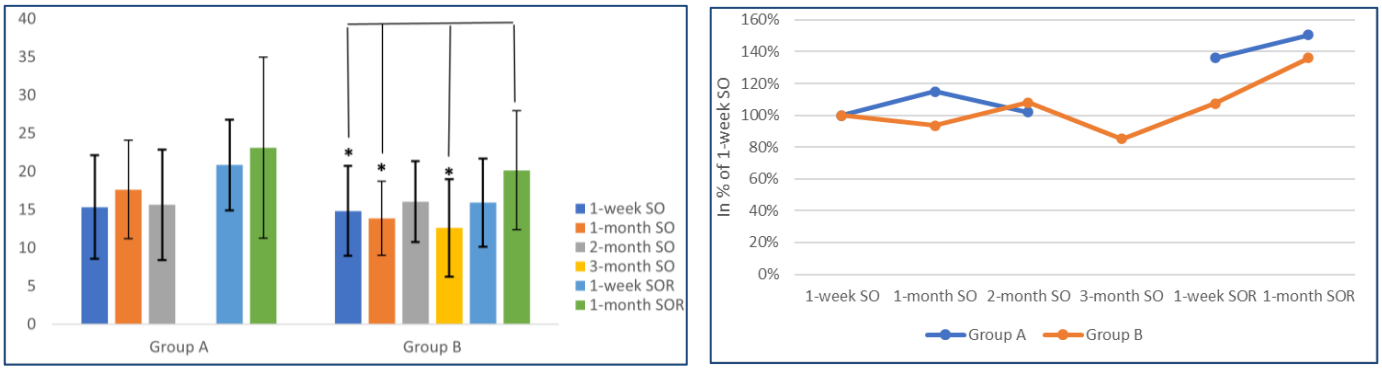
Table 4. The changes in superficial blood flow (SFPFD) during 2/3-month SOF and post-1-month SOR. Data were expressed as mean ± SD.

SFPFD	Pre-injection	1-week SO	2-month SO	3-month SO	1-week SOR	1-month SOR	*P*
Group A ($n = 10$)	15.34 ± 6.79	17.63 ± 6.45	15.64 ± 7.21		20.85 ± 5.94	23.10 ± 11.85	0.358
Group B ($n = 31$)	14.84 ± 5.88	13.87 ± 4.84	16.04 ± 5.30	12.62 ± 6.40	15.93 ± 5.78	20.17 ± 7.77	0.028

Table 5. Pairwise comparison of SFPFD at each time point. Data were expressed as mean ± SD.

Timepoint I	Timepoint J	Difference(I-J)	*P*
1-week SO	1-month SO	−0.976 ± 0.584	0.573
1-week SO	2-month SO	1.2 ± 0.839	0.527
1-week SO	3-month SO	−2.227 ± 0.779	0.285
1-week SO	post 1-week SOR	1.089 ± 0.998	0.573
1-week SO	post 1-month SOR	5.325 ± 0.706	0.009**
1-month SO	2-month SO	−2.176 ± 0.313	0.264
1-month SO	3-month SO	1.252 ± 3.064	0.556
1-month SO	post 1-week SOR	2.065 ± 0.649	0.298
1-month SO	post 1-month SOR	6.30 ± 10.313	0.003**
2-month SO	3-month SO	3.427 ± 0.649	0.131
2-month SO	Post 1-week SOR	−0.11 ± 0.584	0.959
2-month SO	post 1-month SOR	4.125 ± 0.164	0.063
3-month SO	post 1-week SOR	3.317 ± 0.768	0.149
3-month SO	post 1-month SOR	7.553 ± 0.649	0.002**
post 1-week SOR	post 1-month SOR	−4.236 ± 0.584	0.06

** *P< 0.01.*



(a) **(b)**

Figure 2. Significantly changed superficial flow density (SCPFD) due to 3-month SOF. **(a)** Changed SCPFD upon SOT and SOR; **(b)** dynamical changes of SCPFD.

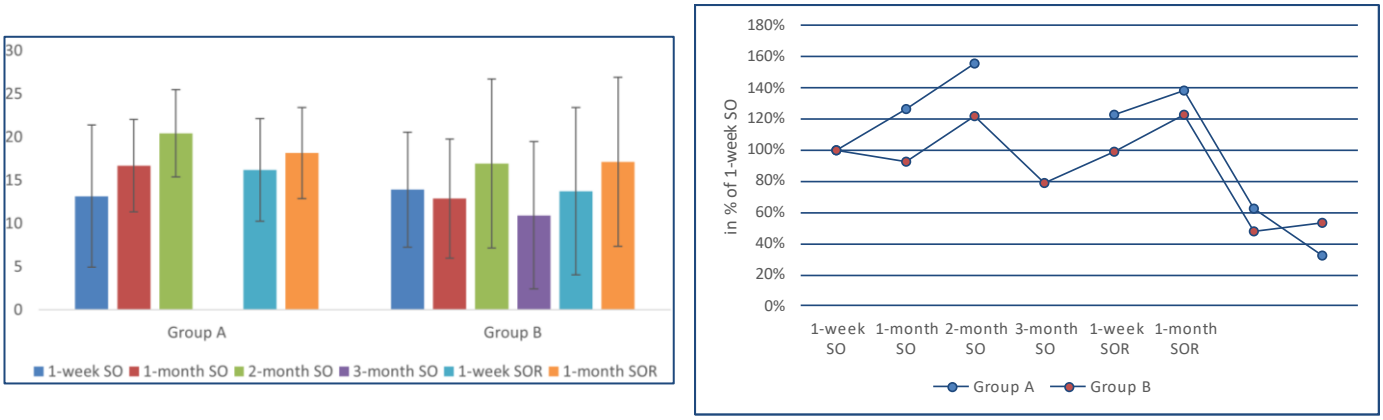
Including additional follow-up, such as 3- or 6-month post-Silicone Oil Removal visual acuity and optical coherence tomography (OCT) measurements, would provide a more complete picture of the trends in recovery. Further follow-up may show whether microvascular changes and VA deficits persist, improve, or worsen over time. Prolonged SOT previous studies show that sustained capillary density loss and delayed functional recovery point to some changes that may not be reversible. Persistent Superficial Capillary Plexus (SCP) vessel density reduction to more than 12 months post-SOR [6], correlating with poor outcomes in the visualures. This should be considered as a limitation for the lack of long-term data, and further studies should determine if the observed microvascular and functional impairments in the 3-month SOT group persist and result in visual prognosis beyond the short-term period. This will help in understanding the best SOT duration for RRD management.

3.4. SOF and SOR did not significantly affect DCPFD.

Table 6 and **Figure 3** showed DCPFD in two groups with 2-month or 3-month SOF. The DCPFD was measured with OCT-angiogram imaging during 2 months (group A, n = 10) or 3 months (group B, n = 31) SOF and after 1-month SOR. The data expressed with mean ± SE were shown in (a), and dynamic changes during the 3/4-month observation were shown in (b). In group A, 10 patients with 2-month SOF, the DCPFD was not significantly affected by either 2- or 3-month SOF. The average values were 15.34 ± 6.79, 17.63 ± 6.45, and 20.45 ± 5.05 for 1-week, 1-month, and 2-month SOF, and 20.85 ± 5.94 and 23.10 ± 11.85 at 1-week and 1-month post SOR (p = 0.59). Similarly, in group B, with 31 patients with 3-month SOF, there was no significant difference in the **DCPFD** at different time points (p = 0.346). The average DCPFDs were 13.93 ± 6.65, 12.88 ± 6.88, 16.96 ± 9.78, and 10.95 ± 8.52 at one week, 1 month, 2 months, and 3 months SOF and 13.75 ± 9.67 and 17.12 ± 9.78 at 1 week and 1 month post SOR. The dynamic observation showed about a 31% reduction in DCPFD at 3-month SO, which was restored after 1-month SOR to the same level as that at 2-month SO (**Figure 3a** and **3b**). Moreover, even with increased DCPFD after 1 month of SOR, the value was still lower in group B than in group A. These results suggest that 2/3-month SOF might affect the recovery of DCPFD.

Table 6. Changes in deep capillary plexus flow density (DCPFD) during 2/3-month SOF and post-1-month SOR. Data were expressed as mean ± SD.

DCPFD	1-week SO	1-month SO	2-month SO	3-month SO	1-week SOR	1-month SOR	*p*
Group A (n = 10)	13.17 ± 8.22	16.69 ± 5.34	20.45 ± 5.05		16.20 ± 5.92	18.16 ± 5.28	0.59
Group b (n = 31)	13.93 ± 6.65	12.88 ± 6.88	16.96 ± 9.78	10.95 ± 8.52	13.75 ± 9.67	17.12 ± 9.78	0.346



(a) **(b)**

Figure 3. No significant changes in deep flow density (DCPFD) during SOF and after SOR. **(a)** Data expressed with mean ± se; **(b)** dynamic changes during the 3/4-month.

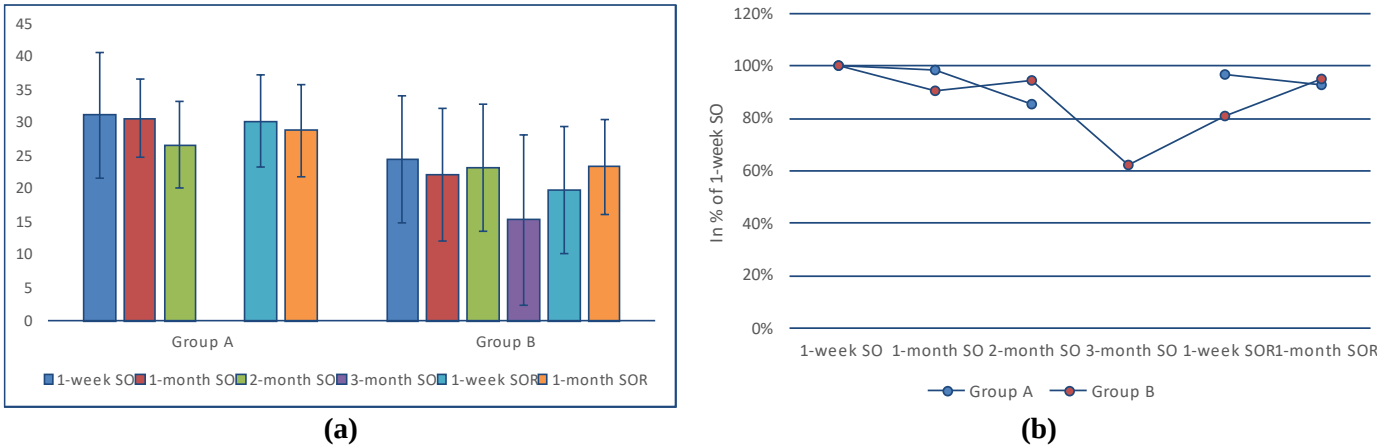
3.5. SOF and SOR did not significantly affect CCPFD

Table 7 shows the evaluation of CCPFD during SOF and after SOR. In group A, the average values of CCPFD at each time point were: 31.28 ± 9.52, 30.79 ± 5.92, 26.74 ± 6.54, 30.38 ± 6.93 at, and 28.98 ± 7.00 at 1-week SO, 1-month SO, 2-month SO, 1-week after SOR, and 1-month after SOR. In group B, among 31 patients, the average CCPFD was 24.5 ± 9.59, 22.19 ± 10.14, and 23.27 ± 9.70, 15.35 ± 12.93,

19.85 ± 9.71, and 23.38 ± 7.32 at 1-week SO, 1-month SO, 2-month SO, 3-month SO, 1 week after SOR, and 1 month after SOR. The dynamic observation showed that 3-month SO induced a substantial reduction (39%), following a fast recovery after 1-month SOR, compared with 3-month SO (**Figure 4a** and **4b**). In **Figure 4**, the CCPFD was measured with OCT-angiogram imaging during 2 months (group A, n = 10) or 3 months (group B, n = 31) SOF and after 1-month SOR. The data expressed with mean ± SE were shown in (a); dynamic changes during the 3/4-month observation were shown in (b). However, both groups had no statistically significant CCPFD density at different time points (p = 0.959, p = 0.157). It suggested that 3-month SOF did not yet significantly affect macular CCPFD.

Table 7. Choriocapillaris plexus flow density (CCPFD) changes during 2/3-month SOF and post-1-month SOR. Data were expressed as mean ± SD.

CCPFD	1-week SO	1-month SO	2-month SO	3-month SO	1-week SOR	1-month SOR	*p*
Group A (n = 10)	31.28 ± 9.52	30.79 ± 5.92	26.74 ± 6.54		30.38 ± 6.93	28.98 ± 7.00	0.959
Group B (n = 31)	24.55 ± 9.59	22.19 ± 10.14	23.27 ± 9.70	15.35 ± 12.93	19.85 ± 9.71	23.38 ± 7.32	0.157



(a) **(b)**

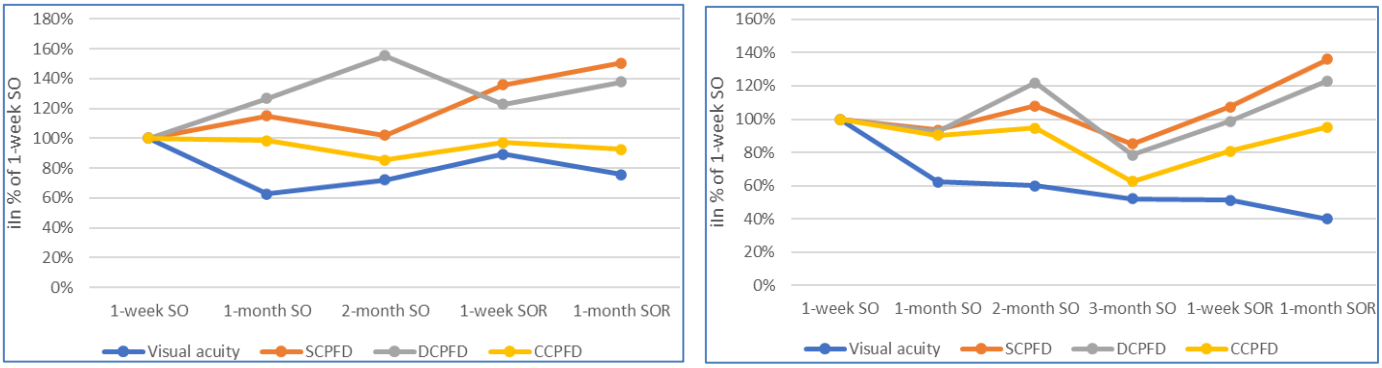
Figure 4. No significant changes in CCPFD during SOF and after SOR. **(a)** Data expressed with mean ± SE; **(b)** dynamic changes during the 3/4-month observation.

3.6. 3-month, but not 2-month, SOF induced substantial and correlated changes in three vascular layers

The investigation of the correlations of VA with the macular vascular system upon 2-month and 3-month SOF was shown in **Figure 5**.

Figure 5 shows the blood flow density, which was measured with OCT-angiogram imaging during 2 months (a, group A, n = 10) or 3 months (b, group B, n = 31) SOT and after 1-month SOR. SCPFD: superficial capillary plexus flow density; DCPFD: deep capillary plexus flow density; and CCPFD: choriocapillaris plexus flow density. The data were expressed with the mean. In the 2-month SO group, there was no clear correlation between the macula blood flow densities and the visual acuities during SOF and after SOR (**Figure 5a**). The changes in the macular circulation were small, accompanied by a fast recovery of VA. By contrast, in the 3-month group, the blood flow densities in three macular layers were correlated with each other, i.e., strong suppressions at 3-month SOF, following high increases after SOR (**Figure 5b**).

However, these changes were accompanied by a low recovery of VA, indicating the demeritorious effects of 3-month SOF on eye function.



(a) **(b)**

Figure 5. The blood flow density of three macular layers was correlated with each other during 3-month SOF and after 1-month SOR. **(a)** dynamic changes upon 2-moth SOT; **(b)** dynamic changes upon 3-month SOT.

4. Result and discussions

This study found that 3-month, but not 2-month SOT, could cause marked flow density changes in the total macular vascular layers, which was correlated with each. These profound microvascular alterations and a substantial reduction in VA during SOF could not recover even after SOR, indicating a detrimental effect of long-term SOT on RRD eyes. To our knowledge, this is the first dynamic clinical evidence to guide SOT duration.

There are reports on the good efficacy of SOT for primary and recurrent macular hole closure [13]. However, the duration of SOT varied in different studies. During the 4-month SOF, SOT could cause a decrease in both superficial and deep retinal blood flow during filling, as well as retinal thickness, compared to its alternative gas filling [14]. Gas filling shows comparable ability in anatomical closure to SOT. However, only 2 weeks of gas tamponade is much shorter than that of SO [15]. Consistently, our study further confirmed that 2-month SO less affected retina microcirculation.

Previously, it was suggested that the toxic effects of SO were various, e.g., mechanical stress, tissue infiltration, buffer changes within the vitreous cavity, phototoxicity, and inflammation [16]. Among them, mechanic stress might be one main effector, which could cause is chemic apoptosis in retinal cells [17]. The retinal vessels at the macula are in three capillary layers: superficial, intermediate, and deep vessel plexus, which merge into one at the edge of the FAZ, while intermediate and deep merge into a single layer temporal to the fovea [18]. These vessel plexuses provide nourishment and remove metabolic products from the inner retinal layers. The outer retinal layers are avascular and supplied with nutrients and oxygen by diffusion from the choriocapillaris. Retinal homeostasis and metabolism may be disrupted in the process of RRD, resulting in retinal and choroidal tissue modifications. After PPV, retinal homeostasis will need to be rebuilt, and a one-day delay will lead to different visual effects. The prerequisite for the functional recovery of RRD is a recovered retina microvascular system.

Silicone Oil Tamponade (SOT) may impair retinal perfusion by Increasing Intraocular Pressure (IOP), ischemia, oxidative stress, and Silicone Oil toxicity with prolonged SOT. IOP elevation reduces perfusion pressure and thereby causes DCp and CC ischemia. Due to oxidative stress, Silicone Oil emulsification causes retinal apoptosis and disrupts the blood-retinal barrier. Differential effects of SOT on macular layers can be explained by vascular autoregulation, as SCP compensates for deep ischemia but is not practical for prolonged SOT. Retinal atrophy and inflammation are seen in histopathological studies, indicating irreversible microvascular damage. Photoreceptor apoptosis and endothelial dysfunction are confirmed in animal models post-SOT. It is recommended in the literature that short-term SOT allows for partial recovery, whereas extended tamponade leads to a persistent reduction of vessel density. Perfusion deficits persist even 12 months after long-duration SOT. These findings imply that SOT should be limited to two months to protect macular microcirculation and facilitate visual recovery after RRD surgery.

Parafoveal SCP vessel density was significantly correlated with the final best-corrected VA (BCVA), wherein the duration of SOT was considered the only risk factor for visual recovery [6]. The duration of SOT was inversely correlated with the SCP VD. SOT in complicated RRD eyes reduces the Choroidal Vascular Circulation, changing the area of the FAZ of the retina and resulting in poor visual prognosis. The longer the SOT time, the more CVC reduction. Even in a 12-month long-term follow-up in RRD after surgery, SCP vessel density and vessel length density were still low due to SOF. Therefore, the toxic effects due to long-term SOF will delay or break the retina recovery process, leading to VA reduction or loss even after SOR.

The findings in this study show that a 3-month SOT duration produces significant microvascular changes and persistent VA reduction, and a 2-month SOT duration has less of an effect on macular perfusion and function. These results agree with previous studies, which have also reported the negative consequences of prolonged SOT on retinal microcirculation. For example, similarly demonstrated that extended SOT was associated with progressive decreases in superficial and deep capillary plexus blood flow densities parallel to the SCP vessel density decline we observed in our 3-month group [19]. The research findings agree with the observations that SOT duration is inversely correlated to SCP vessel density, and prolonged SOT inhibits visual recovery [6].

Some studies, reported that macular perfusion reduction may partially recover after SOR, which is contrary to our findings in the 3-month group [20]. Variations in patient cohorts, imaging techniques, and postoperative management protocols may account for this discrepancy.

Studying the SOT and gas tamponade showed that gas tamponade could also have the same anatomical sealing time but with fewer damaging effects on the microcirculation, pointing out that the risk of SOT duration selection should be done cautiously. The current study expands knowledge by demonstrating the optimum SOT duration and its impact on preserving macular microcirculation and visual function, providing practical clinical advice for RRD management.

This recommended study showed that a 2-month SOT is suitable for SOR. At this point, anatomic closure is maintained; meanwhile, VA and retina microvascular

circulation were not strongly affected. The clinical evidence in this study would be a basis to guide the application of SOT in RRD surgery.

5. Conclusion

This study investigated the dynamic effects of Silicone Oil Tamponade (SOT) time on macular microcirculation and visual function recovery in patients with rhegmatogenous retinal detachment (RRD). Fifty-one patients with macular in-situ RRD underwent pars plana vitrectomy (PPV) combined with SOT and were randomly divided into 2-month and 3-month SOT groups. Optical coherence tomography (OCT) and vascular imaging techniques were used to evaluate the changes in superficial capillary plexus blood flow density (SCPFD), deep capillary plexus blood flow density (DCPFD), and choriocapillaris blood flow density (CCPFD), and the recovery of visual acuity (VA) was recorded. The results showed that SOT significantly reduced visual acuity for 2 and 3 months, especially in the first month after tamponade. The 2-month filling group had less effect on macular microcirculation, and visual acuity recovered to 90% of the pre-filling level 1 week after Silicone Oil Removal (SOR). In contrast, the 3-month filling group significantly inhibited macular microcirculation, especially superficial capillary plexus blood flow density (SCPFD), and visual acuity only recovered to 50% of the pre-filling level 1 week after SOR.

After PPV, Rhegmatogenous Retinal Detachment (RRD) patients need a 2-month SOT for better visual recovery. Macular microcirculation is suppressed by prolonged 3-month SOT with delayed visual improvement. Clinicians should use OCTA to monitor macular vasculature, and SOR should be scheduled at 2 months to minimize the microvascular damage and optimize functional outcomes.

Although there was no significant difference in visual acuity between the two groups during the filling period, the microcirculation inhibition caused by the 3-month filling may have an adverse effect on the recovery of visual function. Therefore, the study suggests that a 2-month Silicone Oil filling time may be more appropriate to promote better functional recovery in patients with RRD after surgery.

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