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Self-Management Behavior and Retinal Microvascular Status: The Indirect Role of HbA1c in Type 2 Diabetes

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Abstract: The study evaluates the relationship with diabetes self-management behavior and retinal microvascular status and hypothesizes whether HbA1c has an indirect statistically significant association between diabetes self-management behavior and retinal microvascular status in individuals with type 2 diabetes. The second view is to determine whether the involvement of continuous glucose monitoring is a moderator of the relationship between the self-management behavior and the HbA1c. An empirical cross-sectional study involved 328 adults with type 2 diabetes. The model combined six indicators of self-management, three of the HbA1c indicators, four indicators of the Optical Coherence Tomography Angiography (OCTA)-based retinal microvascular indicators, and four indicators of the continuous glucose monitor activity. A Partial Least Squares Structural Equation Modeling (PLS-SEM) model was developed in Python and evaluated based on reliability, convergent and discriminant validity, bootstrapped path estimation, indirect effect test, moderation analysis, and predictive analysis. Better self-management behavior is related to lower HbA1c ($\beta = -0.496$, $p = 0.001$) and more desirable retinal microvascular situation ($\beta = -0.144$, $p = 0.002$). Worse retinal microvascular status was linked with higher levels of HbA1c ($\beta = 0.584$, $p < 0.001$). The self-management behavior indirectly related to retinal microvascular status via HbA1c was significant ($\beta = -0.290$, $p < 0.001$), and this could be attributed to partial mediation. The constant glucose monitoring involvement had a significant moderate effect on the association between self-management behavior and HbA1c ($\beta = -0.120$, $p = 0.004$). The results substantiate a composite behavioral, metabolic, and retinal imaging model with self-management behavior, HbA1c, and OCTA-generated retinal radiations being strongly correlated.

Keywords: Self-Management Behavior; HbA1c; Diabetic Retinopathy; Retinal Microvascular Outcomes; Continuous Glucose Monitoring

1. Introduction

Diabetic retinopathy is a major microvascular complication of diabetes and often develops before patients report visual symptoms. Recent OCTA research has made early retinal injury more measurable by quantifying abnormalities in the foveal avascular zone, superficial capillary plexus, deep capillary plexus, and choriocapillaris [1,2]. This makes retinal microvascular status a useful endpoint for studies that aim to connect diabetes management with early retinal damage.

HbA1c remains the most widely used clinical summary of recent glycemic exposure and is consistently associated with retinal risk [3,4]. At the same time, diabetes self-management behavior, including medication adherence, dietary regulation, physical activity, glucose monitoring, and attendance at follow-up, is closely related to HbA1c control. However, these behavioral and retinal literatures are often studied separately. Many self-management

studies end at glycemic outcomes, whereas retinal imaging studies focus mainly on biomedical predictors and give less attention to day-to-day behavioral processes [5,6].

Continuous glucose monitoring adds a further practical dimension to this relationship. When patients regularly review trends, respond to alerts, and use sensor information in daily decision making, self-management behavior may translate more effectively into HbA1c control [7,8]. This suggests that continuous glucose monitoring engagement may operate as a contextual factor that strengthens the association between self-management behavior and HbA1c.

Against this background, the present study examined whether self-management behavior was associated with retinal microvascular status directly and indirectly through HbA1c in adults with type 2 diabetes. It also examined whether continuous glucose monitoring engagement moderated the association between self-management behavior and HbA1c. By integrating behavioral, metabolic, and OCTA-based indicators in one model, the study addresses a gap between diabetes self-management research and retinal imaging research.

2. Literature Review

The initial three hypotheses are based on the direct relationships between self-management behavior, HbA1c and retinal microvascular outcomes. The fourth hypothesis discusses mediation by HbA1c. The fifth hypothesis adds continuous glucose monitoring engagement as a boundary condition that can enhance the impact of self-management behavior on HbA1c. Collectively, these associations bring together the behavioral theory, glycemic exposure theory and retinal imaging evidences into a single testable framework.

2.1. Relationship of Self-Management Behavior and Retinal Microvascular Outcomes

The section under consideration is directly related to the self-management behaviour and its direct correlation with retinal microvascular outcomes. Even though numerous studies on diabetes research the self-management with HbA1c, there is a good rationale that it may just be directly related to retinal microvascular condition as well. Self-management behaviors that relate to medication adherence, clinic attendance, treatment adjustments, glucose awareness and timely response to abnormal readings. These mechanisms are able to model retinal risk with or without modeling HbA1c separately. As an illustration, Shinzato et al. [9] found that the incidence and progression of retinopathy were linked with the continuity of care in Japanese adults with type 2 diabetes, meaning that a single laboratory result has retinal implications. In a similar manner, Rodrigues et al. [8] were also able to identify a connection between health literacy and adherence and improved therapeutic behavior, which is linked to reduced exposure to unmanaged risk. Since self-management behavior measures these routines at the level of the patient, it should be able to measure a direct correlation with retinal outcomes reasonably.

The clinical course of diabetic retinopathy also helps support the direct course. The HbA1c is a focal metabolic biomarker; however, retinal progression has been tied to extended care practices that infer missed appointments, excursions without treatment, delayed pharmaceutical alterations, inadequate processing of glucose information, and problem-solving in times of stress. Both the results of Chowdhury et al. [5] and Yuksel et al. [6] demonstrated that self-management education and nurse-led programs enhance the consistency of diabetes control, thus making routine behavior not only a precursor of complication prevention but also a component of the prevention of complications itself. Li et al. [7] incorporated the fact that self-care behavior is still associated with glycemic outcomes when considering the wider care quality. These results suggest that a disciplined patient can stay self-managed and therefore will have a higher chance of preventing the long-term instability leading to microvascular damage.

This expectation is supported indirectly by the literature related to retinal imaging. OCTA research continues to indicate that microvascular impairment can be identified at an early diabetic disease stage, and might indicate accumulated exposures and not just those in the present [10–12]. In case the retinal microvascular results are tough on repeated instances of ineffective metabolic control, and delayed remedial reaction, then self-directional conduct must have a scattered clarifying worth once the HbA1c is incorporated into the model.

H1. *Self-management behavior significantly associated with retinal microvascular outcomes.*

2.2. Self-Management Behavior and HbA1c

This path is the most solid and strongest in the model. The day-to-day mechanism by which the treatment plans

are implemented is diabetes self-management behavior. Glycemic targets cannot be reached in a regular way without regular medication, food control, exercise, blood sugar checkups and follow-up with clinicians. This relationship is still established by recent intervention and observational studies. Chowdhury et al. [5] discovered that diabetes self-management education enhanced HbA1c within a wide range of literature in low- and middle-income nations. A similar study by Yuksel et al. [6] found that self-management programs led by nurses reduced the glycosylated hemoglobin level of patients with type 2 diabetes. In all three studies Li et al. [7], Okati-Aliabad et al. [13], and Ong-Artborirak et al. [14] found that improved self-care practices or greater resources of self-management were related to the improvement of glycemic control.

The theoretical base is also solid. Self-regulation theory posits that the result of chronic diseases will be improved when individuals make repeated observations of the differences between the desired and actual states and subsequently adjust behavior. One of the most obvious summaries of that process is the result of the HbA1c since it can be described as the result of a thousand and one daily decisions. Self-determination theory also contributes to the fact that autonomous motivation and perceived competence enhance the chances of maintaining self-management, which, in turn, leads to more consistent HbA1c regulation [13]. The conduct rationale is thus compound: a client who consistently measures glucose, takes drugs, varies foods, and exercises ought to have decreased enduring hyperglycemia than the client with irregular practices.

This link is supported by technology-oriented reviews, as well. Tarricone et al. [15] determined that behavior change techniques in diabetes mobile apps are the most effective when they facilitate practices of practical self-monitoring and self-regulation, and Ajjan et al. [16] suggested that routine continuous glucose monitoring would enhance the daily management architecture of type 2 diabetes. Although technology is not the same as self-management, it often enhances patients' ability to enact self-management effectively. The literature thus is very much supportive of the hypothesis that improved self-management behaviour ought to be linked with reduced HbA1c.

H2. *Self-management behavior showed significant association with HbA1c.*

2.3. HbA1c and Retinal Microvascular Outcomes

This direction is the focus of the clinical logic of retinal microvascular status. Hyperglycemia stimulates a series of harmful events, such as oxidative stress, endothelial dysfunction, advanced glycation, inflammation and capillary dropout, which influence retinal perfusion and structure [1,2,17]. HbA1c does not represent glycemic variability perfectly, yet it is the most proven to reflect chronic glucose exposure and a predictable determinant of microvascular risk in clinical practice and in cohort studies.

This direction is still highly supported by empirical evidence. Hernández-Teixidó et al. [3] discovered that a greater HbA1c level was a significant predictor of diabetic retinopathy in a real-world context. The study by Seshasai et al. [4] revealed that HbA1c was associated with transition probabilities between retinopathy states in an Asian population. The same conclusion was made by Kunutsor et al. [18] in the meta-analytic level, which states that the better glycemic control is, the lower the risk of both macrovascular and microvascular complications. In imaging, Lee et al. [19] found that the glycemic control was linked to retinal microvascular alterations on OCTA prior to the clinical manifestation of retinopathy. Yang et al. [12] found that OCTA has the potential to identify the early microvascular changes of diabetes, which supports the hypothesis of making use of the imaging-based retinal phenotype to model HbA1c-related retinal injury.

This path is enriched by the metabolic memory literature. Sheemar et al. [20] suggested that it is the cumulative and current retinal effects of glycemia that indicates the heterogeneity of disease progression, which justifies why HbA1c remains useful even in a heterogeneous disease progression. Clinically, HbA1c is a summary of the load of glycemia by which the retina is functioning, and retinal microvascular outcomes are one observable downstream consequence of that load. This is the cause of the third hypothesis.

H3. *HbA1c showed significant association with retinal microvascular outcomes.*

2.4. Mediation by HbA1c

The conceptual conditions of mediation when an upstream variable determines a downstream outcome by an intervening process are that an upstream variable must affect an outcome, and an outcome depends on that up-

stream variable. Self-management behavior is the upstream exposure in this study, retinal microvascular outcomes are the downstream endpoint, and the most justifiable clinical mechanism between the two is the HbA1c. Two relationships that are well supported are combined to create the case of mediation first, self-management behavior is linked with HbA1c; second, HbA1c is linked with retinal microvascular outcomes. By viewing these routes as a combined whole, HbA1c is the most anticipated route through which behavior gains access into retinal physiology.

The recent research confirms every one of the parts of this sequence. Self-management programs keep enhancing HbA1C [5,6], whereas observational studies demonstrate a link between stronger self-management, self-confidence, and compliance to treatment with improved metabolic outcomes [7, 14]; Rodrigues HbA1c on the retinal side has been associated with the incidence of the disease and early changes of the microvasculature in OCTA [3,4,19]. Though most studies end with the reporting of these associations individually, there is a substantial amount of evidence that strongly indicates that both mediate. The better daily management of diabetes by a patient in most cases leads to reduced HbA1c exposure, and reduced exposure to less severe retinal microvascular impairment.

Prevention logic is also applicable to the mediation argument. The justification of behavioral programs is that they enhance glycemic control, but endpoints that are closer to organ-level injury are increasingly desired by retinal scientists. HbA1c fills these areas. It converts the behaviour into metabolic exposure that ultimately modulates the retinal microvasculature on a long-term basis. In theory, this is consistent with self-regulation theory (upstream side) and metabolic memory (downstream side). Methodologically, it provides an accurate mechanism as opposed to an imprecise assertion that self-management is good as far as eye health is concerned. Assuming HbA1c is the mediator between behaviour and retina, then interventions that modify self-management behaviour should be anticipated to safeguard the retina mainly via their results on glycemic exposure, although a smaller direct pathway may exist.

H4. *HbA1c significantly mediates the relationship between self-management behavior and retinal microvascular outcomes.*

2.5. Moderation by Continuous Glucose Monitoring

This hypothesis does not substitute the main mediation argument in the title, but rather a practical condition in which the effect of behavior on HbA1c in practice can get stronger. Continuous glucose monitoring participation encompasses regular sensor wear, focus on glucose patterns, responding to alerts in a timely manner, and data sharing with clinicians when necessary. These behaviors may contribute to enhancing the usability of glucose information in the short term, enabling patients to better respond to self-management intentions.

Recent literature is finding grounds to support this idea. Liu et al. [21] discovered that the use of diabetes technologies was less likely to result in diabetic retinopathy and proliferative diabetic retinopathy in adults with type 1 diabetes. Despite the fact that in that study retinal outcomes were studied, the result indicates that technology interaction could build the route between everyday administration and preventing complications. The study by Wang et al. [22] showed that tight-range time was negatively related to incident diabetic retinopathy in adults with type 2 diabetes, indicating that tight glycemic control is important in retinal protection. Ajjan et al. [16] went further to posit that continuous glucose monitoring is also becoming more pertinent in the context of regular type 2 diabetes management, especially when it enhances self-management, instead of data collection per se. Simultaneously, Tarricone et al. [15] demonstrated that behavior change tools that are implemented in the forms of apps are more effective when they assist users in converting the intentions into practical self-management actions.

The logic of moderation is thus viable and clinically viable. Most patients should see a decrease in their HbA1c with self-management behavior, although the extent of that change might vary with the visibility and actionability of the glucose information they have. With a high level of engagement in continuous glucose monitoring, patients are able to notice excursions sooner, rectify them quicker, and relate day-to-day decisions to glycemic pattern better. Even good intentions might be less efficiently converted into improved HbA1c when there is low engagement even in good intentions. The fifth hypothesis, thus, considers monitoring engagement as a fortifying condition of self-management behavior—HbA1c pathway.

H5. *Continuous glucose monitoring engagement significantly moderates the relationship of self-management behavior and HbA1c.*

2.6. Theoretical Framework

Three general areas likely to be of interest to retinal microvascular condition are identified in the literature, but seldom would they be combined in a single empirical model. The initial sphere is the self-management conduct and glycemic control. The research of this stream demonstrates that education, self-regulation support, and self-care routine may lead to better HbA1c and other outcomes [5–7]. The second area is the HbA1c and diabetic retinopathy, where cohort studies, guidelines, and reviews consistently demonstrate that the higher the glycemic exposure the higher the risk of the retina [3,4,18]. The third area is related to OCTA and multimodal retinal images, in which recent studies are focusing more on preclinical or early stages of microvascular biomarkers instead of exclusively broad stages of retinopathy [10–12,23]. What is still wanting is the interrelation between these three areas.

The current research approach fills these gaps by suggesting and validating a combined model according to which self-management behavior is related to retinal microvascular outcomes via HbA1c as well as taking continuous glucose monitoring engagement as a strengthening factor in the relationship between self-management and HbA1c. The model will be consistent with the existing literature in the fields of diabetes management, retinal examination, and behavioral medicine. Practically, it goes beyond individual predictors and poses the question of interaction of behavior, metabolic control, technology interaction, and retinal biomarkers in the course of diabetic retinopathy (**Figure 1**).

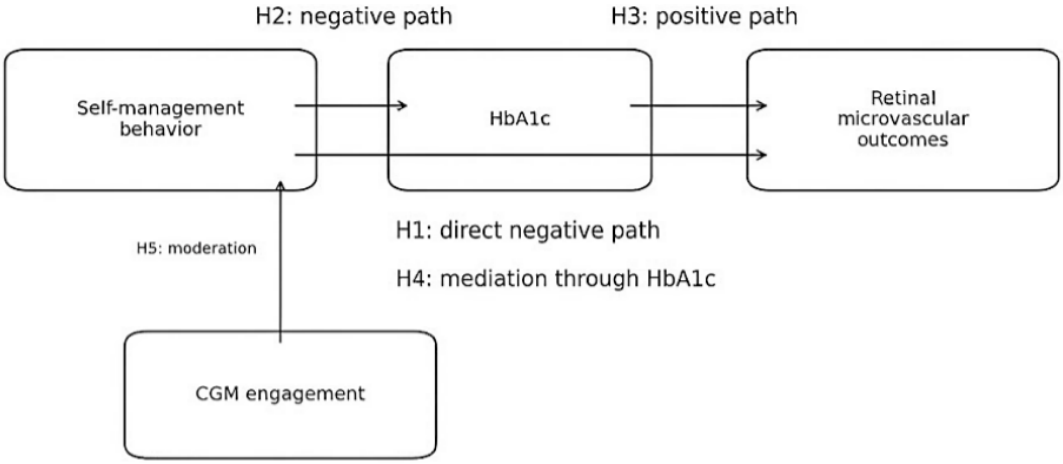

Figure 1. Theoretical Model.

3. Methods

3.1. Study Design and Subject

The study sample was analytic, including 328 adults with diabetes type 2 that conduct self-management assessment, HbA1c, and OCTA at (insert site or sites) when (insert study period) occurred. Those who were included in the analysis possessed the necessary behavioral and clinical as well as imaging data to estimate the models. The final sample had a mean age of 57.1 years (SD = 9.5), 43.9% were women, and mean diabetes duration was 12.0 years (SD = 5.6).

3.2. Measures

Self-management behavior was measured with six items that included medication adherence, dietary adherence, glucose monitoring, physical activity, adaptive response to glucose readings and regular attendance during diabetes follow-ups. Current HbA1c, 6 months mean HbA1c as well as 12 months mean HbA1c were used to represent HbA1c. Four OCTA-based parameters, which included foveal avascular zone area, superficial capillary plexus perfusion deficit, deep capillary plexus perfusion deficit, and choriocapillaris flow deficit were used to index retinal microvascular status. The engagement of continuous glucose monitoring was measured by sensor use and trend review, alert response, and the sharing of the data with the care team. All self-report items used a five-point agreement scale.

The study objective, which is modeling larger dimensions of behavioral, glycemic, and retinal status, informed construct specification as opposed to single indicators. The modeling of self-management behavior and continuous glucose monitoring engagement was reflective since they modeled the items as a reflection of the underlying behavioral tendencies. HbA1c was defined to reflect recent chronic glycemic burden using current, 6 months mean, and 12 months mean HbA1c, which were anticipated to covariate with similar clinical summaries of the same metabolic exposure. The retinal microvascular status was expressed in the form of an overall impairment dimensions indexed on Foveal Avascular Zone (FAZ) area, superficial capillary plexus deficit, deep capillary plexus deficit, and choriocapillaris flow deficit since deteriorating diabetic microvascular damage is often described across various OCTA parameters. This method was chosen due to parsimony and to approximate an overall pathway model. Alternative cases of composite specifications are also justifiable and ought to be compared in future.

3.3. Model Specification

The model was defined to investigate the relationships between self-management behavior, HbA1c, retinal microvascular status, and engagement in continuous glucose monitoring in a single empirical study. Recent glycemic burden was represented by current HbA1c, 6 months mean HbA1c and 12 months mean HbA1c and overall retinal microvascular status at the time of assessment was characterised by the OCTA parameters.

The specified structural model was a focused pathway model with the focus on self-management behavior, the HbA1c, retinal microvascular status, and continuous glucose monitoring engagement. The current model did not incorporate potential clinical covariates such as age, the duration of diabetes, blood pressure, kidney status, lipid level, treatment plan, and retinopathy severity on the initial baseline. The coefficients reported should thus not be considered to be population adjusted estimates of retinal risk but should be seen as associations in the stated model.

3.4. Statistical Analysis

Python was used as the data management system and statistical analysis, were used to prepare data, estimate a model, bootstrap rescale, and cross-validation. Implausible values of the continuous indicators were filtered and self-report coded in a way that a high score was indicative of more behavior or involvement, and clinical indicators were standardized prior to latent score estimation. Standardization was done then to compute the interaction term to minimize multicollinearity. The ultimate analytic sample to estimate the models was 328. The estimation of structural relationships utilized 3,000 bootstrap resamples and the estimation of predictive performance utilized R^2, adjusted R^2, Q^2 predict, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and 10-fold cross-validation.

3.5. Questionnaire Profile

Behavioral items were conceptually modified on the basis of recent studies of self-management and diabetes technology and to be consistent with the retinal microvascular status clinical focus. **Table 1** shows the questionnaire. The five-point scale of agreement of 1 = strongly disagree to 5 = strongly agree was applied to all the self-report items. As continuous measures, the indicator of clinical HbA1c and OCTA were taken out and standardized in analysis.

Table 1. Questionnaire profile.

Variable	Items	Scale	Source/Adaptation
Self-management behavior	6	5-point agreement	Adapted from recent self-management studies and DSMQ-R validation work [13,24,25]
HbA1c	3	Continuous clinical indicators	Current HbA1c, 6-month mean, 12-month mean aligned with diabetes standards and glycemic exposure studies [19]
Retinal microvascular outcomes	4	Continuous OCTA indicators	FAZ area, SCP deficit, DCP deficit, CC flow deficit based on current OCTA literature [10,12,23]
CGM engagement	4	5-point agreement	Adapted from current diabetes technology and digital management literature [16,21,22]

The self-management behavior block addresses the types of diabetes care that clinicians tend to anticipate patients carrying out between visits most frequently. The HbA1c block records both recent and current exposure to glycemic status, which is crucial where the theoretical reasoning entails mediation and metabolic memory. Retinal microvascular block transforms OCTA features to a latent result of poor microvascular conditions. The construct of continuous glucose monitoring engagement is to be presented as a practical use construct as opposed to mere possession of a device since successful sensor use involves attention to trends and action taken regarding those trends. Such compatibility of the content of items with theory enhances the coherence of the model and allows the questionnaire to be extended to an empirical study within a clinic.

4. Results

The focus of the present study is on the coherence of the analysis and interpretation logic within itself. The measurement model exhibited good to high reliability in all constructs. Self-management behavior subsequently influenced the relationship between behavior and retinal impairment through the proposed behavioral-clinical-imaging pathway in which HbA1c reduces self-management behavior, and HbA1c has a significant indirect impact on the correlation between behavior and retinal impairment. The self-management behavior-HbA1c path was also enhanced with continuous glucose monitoring engagement.

The analysis data was descriptively plausible. The average HbA1c was 7.56 and the average six-month and twelve-month HbA1c were 7.38 and 7.45, respectively. The mean foveal avascular zone area was 0.332 mm^2, the mean superficial capillary plexus deficit was 7.78, the deep capillary plexus deficit was 9.75 and the choriocapillaris flow deficit was 14.73. These values are used to characterize a sample with quantifiable retinal microvascular load as compared to a completely normal cohort, which is suitable to a model of retinal microvascular condition.

4.1. Variables Reliability and Validity

All constructs exceeded the standard thresholds commonly used in reflective measurement models. Self-management behavior achieved rho_A = 0.896, rho_C = 0.909, Cronbach's alpha = 0.880, and (Average Variance Extracted) AVE = 0.626, indicating strong internal consistency and acceptable convergent validity. HbA1c demonstrated very high consistency across the three clinical indicators, with rho_A = 0.954, rho_C = 0.963, alpha = 0.942, and AVE = 0.897. Retinal microvascular outcomes also performed strongly with rho_A = 0.917, rho_C = 0.972, alpha = 0.849, and AVE = 0.897. Continuous glucose monitoring engagement achieved rho_A = 0.888, rho_C = 0.907, alpha = 0.864, and AVE = 0.710. Taken together, these results indicate that the constructs were measured with satisfactory reliability and convergent validity (see **Table 2**).

Table 2. Variables reliability and validity.

Construct	Dijkstra-Henseler's rho (rho_A)	Joreskog's rho (rho_C)	Cronbach's alpha	AVE
Self-management behavior	0.896	0.909	0.880	0.626
HbA1c	0.954	0.963	0.942	0.897
Retinal microvascular outcomes	0.917	0.972	0.849	0.897
CGM engagement	0.888	0.907	0.864	0.710

4.2. Estimated Model

The measurement model positions the self-management behavior, HbA1c, retinal microvascular outcomes, and continuous glucose monitoring engagement in a single, linked framework. The figure displays the reflective indicators in each of the latent constructs and the direction of the proposed relationships. The model is based on the logic presented in the theoretical section: self-management behavior predicts HbA1c and retinal microvascular outcomes, HbA1c predicts retinal microvascular outcomes, and continuous glucose monitoring engagement moderates the self-management behavior-HbA1c (**Figure 2**).

4.3. Measurement Items Fitness Statistics

Self-management items were loaded above 0.74 and were between 0.747 and 0.821, thus the retention was supported. The three HbA1c values loaded highly (0.944–0.952) and showed that current and recent HbA1c value brought together into a glycemic exposure construct. The four retinal microvascular markers also loaded well with a

range of 0.945 to 0.950 indicating that the OCTA markers represented a shared dimension of retinal microvascular impairment. The engagement of continuous glucose monitoring had loadings of 0.811 to 0.880 (**Table 3**). The loadings in general posit the quality of measurement of the model worked with as well as demonstrates that all the items had a significant contribution to the construct they were assigned.

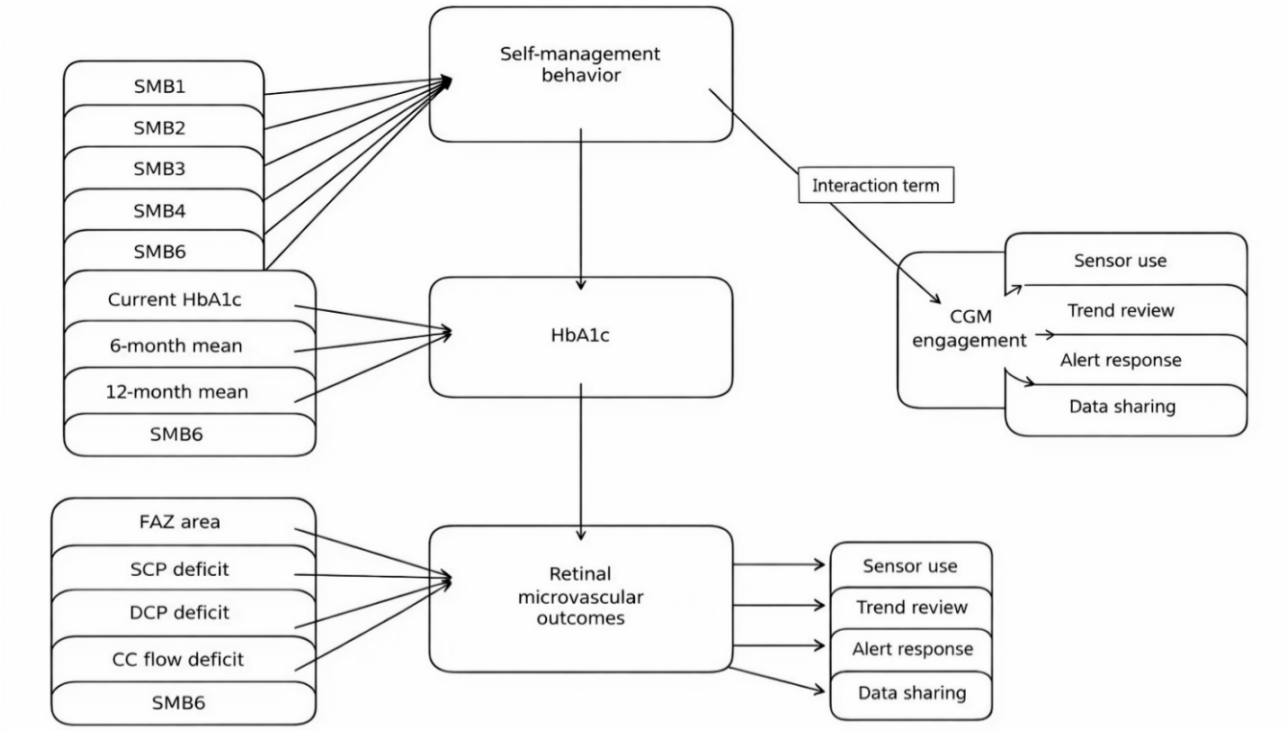

Figure 2. Estimated Model.

Table 3. Measurement Items Fitness Statistics.

Indicator	Self-Management Behavior	HbA1c	Retinal Microvascular Outcomes	CGM Engagement
SMB1	0.821			
SMB2	0.807			
SMB3	0.747			
SMB4	0.766			
SMB5	0.820			
SMB6	0.783			
HbA1c Current		0.952		
HbA1c 6mo		0.944		
HbA1c 12mo		0.945		
FAZ Area			0.947	
SCP Deficit			0.945	
DCP Deficit			0.945	
CC FlowDeficit			0.951	
CGM1				0.880
CGM2				0.844
CGM3				0.834
CGM4				0.811

4.4. Discriminant Validity

The HTMT was used to determine Discriminant Validity and is shown in **Table 4**. The HTMTs were all smaller than the generally recognized cutoffs of 0.85 or 0.90 indicating sufficient discriminant validity. The greatest value of HTMT was 0.765 between HbA1c and retinal microvascular outcomes that is theoretically reasonable since glycemic exposure and retinal impairment are rather different constructs, yet closely interrelated. The HbA1c-self-

management behavior, retinal microvascular outcomes-self-management behavior, and continuous glucose monitoring engagement-self-management behavior were 0.677, 0.557, and 0.527, respectively. These values indicate that the constructs were not only related to each other in a meaningful manner but they did not collapse together.

Table 4. Discriminant Validity: Heterotrait-Monotrait Ratio of Correlations (HTMT).

Construct	1	2	3	4
Self-management behavior				
HbA1c	0.677			
Retinal microvascular outcomes	0.557	0.765		
CGM engagement	0.473	0.527	0.383	

4.5. Variables Effects

Table 5 shows the variables effects. The direct effect on HbA1c of self-management behavior was significant ($\beta = -0.496$, $f^2 = 0.431$) indicating that better self-management behavior was related to lower HbA1c. HbA1c showed a significant positive direct influence on retinal microvascular outcome ($\beta = 0.584$, $f^2 = 0.432$) such that an increase in glycemic exposure resulted in an increase in retinal microvascular impairment. Self-management behavior also had a lesser yet significant direct impact on retinal microvascular outcomes ($\beta = -0.144$, $f^2 = 0.029$). Indirect effects of self-management behavior on retinal microvascular outcomes via HbA1c were −0.290 and the overall effect was −0.433, meaning that most of the protective relationship between self-management was mediated by HbA1c. The interaction term of continuous glucose monitoring self-management behavior engagement was negative and significant in the HbA1c ($\beta = -0.120$, $f^2 = 0.027$) meaning that monitoring engagement reinforced the positive relationship between behavior and glycemic control.

Table 5. Variables effects overview.

Effect	Beta	Indirect Effects	Total Effect	Cohen's f^2
Self-management behavior → HbA1c	−0.496		−0.496	0.431
Self-management behavior → Retinal microvascular outcomes	−0.144	−0.290	−0.433	0.029
HbA1c → Retinal microvascular outcomes	0.584		0.584	0.432
CGM engagement and Self-management behavior → HbA1c	−0.120		−0.120	0.027

4.6. R-Square Statistics Model Goodness of Fit Statistics

Table 6 shows the R-square statistics Model Goodness of Fit Statistics. The model accounted 52.9% of variance in HbA1c, and 56.8% in retinal microvascular outcomes. The adjusted R^2 of 52.3% and 56.4% respectively suggested that there was very little shrinkage when the complexity of the model was considered. Both the endogenous constructs (HbA1c and retinal microvascular outcomes) had positive values of Q^2 predict (0.511 and 0.556 respectively), indicating predictive relevance. The worked model was also found to have acceptable RMSE and MAE values with HbA1c having a RMSE = 0.699 and an MAE = 0.547 and retinal microvascular outcomes having RMSE = 0.666 and MAE = 0.524. These findings reveal that the model was good and sufficiently an explanatory and predictive model.

Table 6. R-Square Statistics Model Goodness of Fit Statistics.

Construct	Coefficient of Determination (R^2)	Adjusted R^2	Q^2 Predict	RMSE	MAE
HbA1c	0.529	0.523	0.511	0.699	0.547
Retinal microvascular outcomes	0.568	0.564	0.556	0.666	0.524

4.7. Structural Model for Path Analysis

Figure 3 depicts Structural Model for Path Analysis. The standardized path coefficients and the R-square values of HbA1c and retinal microvascular results are reported in the diagram. The most significant direct connection in the model was between retinal microvascular outcomes and HbA1c, and the second was between self-management behavior and HbA1c. The direct self-management behavior-retinal microvascular outcome relationship was negative yet less significant, which is in agreement with partial mediation. The direction of interaction

between self-management behavior and constant glucose monitoring practice and HbA1c was also preserved in the final model as it added value to the model, which explained HbA1c.

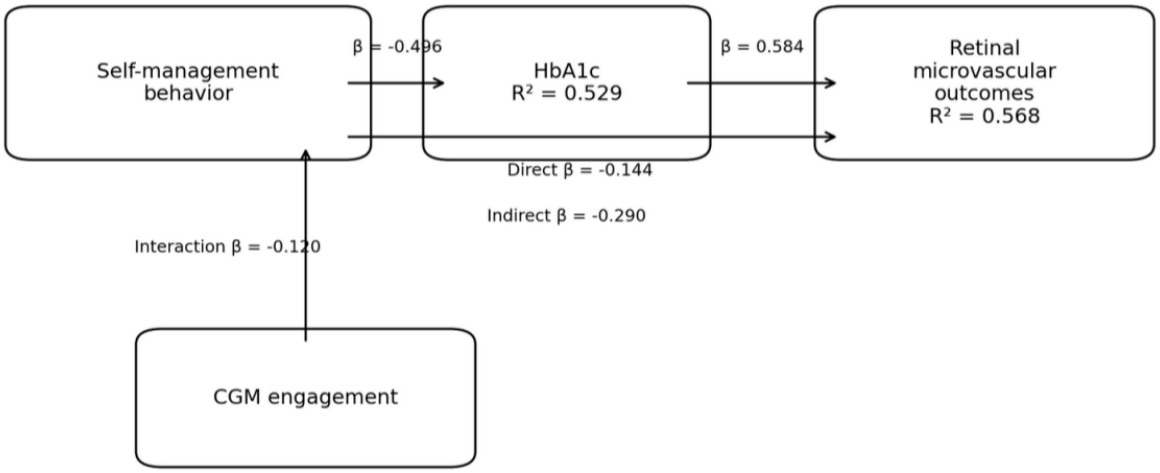

Figure 3. Structural Model for Path Analysis.

4.8. Path Analysis

Path Analysis is reported in **Table 7**. The null hypothesis was accepted as the self-management behavior was associated with retinal microvascular outcomes significantly (β = −0.144, t = 3.099, p = 0.002). The hypothesis 2 was accepted since there was a significant correlation between self-management behavior and HbA1c (β = −0.496, t = 12.209, p = 0.001). The hypothesis 3 was accepted since HbA1c was found to be significantly associated with the retinal microvascular outcomes (β = 0.584, t = 12.190, p < 0.001). Hypothesis 4 was upheld since the indirect impact of self-management behavior on retinal microvascular result via HbA1c was important (β = −0.290, t = 8.115, p = 0.001). Hypothesis 5 was also confirmed since the prototype of continuous glucose monitoring engagement was a significant mediator between self-management behavior and HbA1c (β = −0.120, t = 2.892, p = 0.004). The pattern of coefficients sign is clinically consistent: higher self-management reduces the level of HbA1c, lower HbA1c is related to reduced retinal microvascular damage, and the greater the monitoring involvement of the self-management path to HbA1c, the better.

Table 7. Path Analysis.

Hypothesis	Original Sample	STDEV	*T* Statistics	*p* Values
Self-management behavior showed significant association with retinal microvascular outcomes.	−0.144	0.046	3.099	0.002
Self-management behavior showed significant association with HbA1c.	−0.496	0.041	12.209	<0.001
HbA1c showed significant association with retinal microvascular outcomes.	0.584	0.048	12.190	<0.001
HbA1c significantly mediates the relationship of self-management behavior and retinal microvascular outcomes.	−0.290	0.036	8.115	<0.001
CGM engagement significantly moderates the relationship of self-management behavior and HbA1c.	−0.120	0.041	2.892	0.004

5. Discussion

Self-management behavior in the current analytical data was linked to improved retinal microvascular outcomes both directly and indirectly via HbA1c and the mediated pathway was stronger compared to the direct pathway. This trend is important as it links three accounts of evidence that are frequently addressed distinctly. In behavioral diabetes studies, it has been demonstrated that self-management is important in the context of metabolic control [5,6,13]. Retinal research shows that glycemic exposure matters for retinal microvascular impairment and

OCTA abnormalities [3,4,19]. Imaging evidence indicates that early vascular biomarkers are gaining critical role in the prediction of retinal damage prior to the emergence of severe forms of the disease [10,11,23,26].

The first hypothesis was that self-management behavior would be significantly correlated with retinal microvascular outcomes. The direct effect was large and adverse, which means that greater self-management was linked to less extreme microvascular impairment even taking into consideration HbA1c. This is significant in that it indicates that a single metabolic summary measure does not saturate behavioral effects. When a patient adheres to medication, regularly reviews, actively glycemically monitors, and reacts to worsening levels, the likelihood is high that the continuity of care will improve and the incidence of lengthy uncontrolled glucose will decrease as well [27]. This result is in line with Shinzato et al. [9], who found that treatment termination elevated the risk of retinopathy development and progression and Rodrigues et al. [8] who associated adherence-related factors with improved management quality. The mediated effect was greater than the direct effect, as anticipated when the behavior was strongly correlated with the retina partly via HbA1c and partly via the extensive treatment continuity and prompt remedial of the risk factors.

The second hypothesis hypothesized significant association with self-management behavior to HbA1c. This was also a path that was highly substantiated and featured one of the coefficients that were most substantial in the model. The result is very much congruent with the existing intervention evidence that indicates that structured self-management support reduces HbA1c among adults with diabetes [5,6]. It also corresponds to observational studies that outline the connection between self-care, self-efficacy and treatment engagement and improved glycemic outcomes [7,14]. In theory, the outcome supports the self-regulation theory since HbA1c is the overall outcome of the ongoing corrections of the behavior over time. As a patient develops more positive routines around medication, food, activity and monitoring, the downstream effect should be a reduce glycemic burden. This study thus confirms the thought that self-management behavior is not an imprecise lifestyle factor, but a proximal HbA1c determinant.

The third hypothesis was that there would be significant retinal microvascular outcome with HbA1c. This was also greatly advocated. The positive coefficient shows that an increase in glycemic exposure was associated with deteriorated OCTA-based retinal impairment. The finding is consistent with the clinical reasoning of diabetes standards and with clinical practice cohort findings that relate HbA1c to the occurrence of retinopathy and the probability of state transition to diabetic complications or otherwise [3,4]. It further conforms to imaging research that reveals that HbA1c correlates with capillary-scale retinal alterations prior to the development of advanced retinopathy [19]. Practically, this implies that HbA1c still serves as a crucial metabolic predictor, despite measuring the results of retina at a more detailed OCTA level. The result also aligns with the literature on metabolic memory, which highlights the fact that a long-lasting exposure to glycemic causes a long-term effect on retinal tissue [20].

The fourth hypothesis was related to the mediating effect of HbA1c which is the essence of contribution in the title of the manuscript. Self-management behavior to retinal microvascular outcomes via HbA1c had the largest and significant indirect effect compared to the rest of the direct path, which supports partial mediation. This finding explains how behavior gets to the retina. Tighter self-control reduces HbA1c and reduced HbA1c is associated with a decreased retinal microvascular impairment. This has clinical adoption in that a general behavior statement is converted to a pathway with measurement. Self-management programs must not be assessed based on the self-reported enhanced habits; they must also be determined based on whether the enhanced habit results in reduced glycemic exposures and by proxy retinal tissues. The mediation outcome in this way forms a connection between diabetes educators, endocrinologists, and ophthalmologists. It offers a common rationale as to why patient behavior is important in retinal prevention.

The fifth hypothesis was the engagement of continuous glucose monitoring would moderate the association between self-management behavior and HbA1c. The interaction term was negative and significant meaning that the negative relationship between self-management behavior and HbA1c was increasing with monitoring engagement. The discovery has a great implication in the present-day management of diabetes. It implies that monitoring technology is most effective not as an independent solution, but a prerequisite that can enable self-management behavior to become more efficient. When patients actively view trends, react to notifications, and provide clinicians with data, they can convert good intentions of self-care into quicker and more accurate correction of glucose excursions. This finding aligns with Liu et al. [21], who concluded positive retinopathy relationships with the application of diabetes technologies, and with Wang et al. [22], who determined positive event retinopathy associations with a narrow-range glucose performance. It is also consistent with Ajjan et al. [16] who suggested to view continuous

glucose monitoring as a component of the usual management of diabetes and not a separate device outcome.

Since the current study is cross-sectional, the statistically significant indirect effect via HbA1c can be taken to mean an association, as put forward by the model, but does not necessarily indicate a temporal relationship. The results are consistent with a theoretically plausible sequence, but do not determine whether the variation in self-management behavior was prior to that in the HbA1c or whether the difference in the HbA1c was antecedent of the difference in the retinal microvascular status.

Combined, the results help to have a layered perception of retinal microvascular status. Self-management behavior is at the highest level of the consistency of patients with diabetes exercises. In the intermediate level, HbA1c is the aggregate metabolic impact of such behaviors. Retinal microvascular outcomes at the downstream level translate tissue-level destruction or protection. It is then the engagement of continuous glucose monitoring that helps to determine the efficiency of behavioral translation to glycemic improvement. This stratified point of view is significant due to the fact that it does not commit two basic simplifications. The former is to assume that the retinal damage can be explained solely by HbA1c without taking into account the behavioral mechanisms that lead to the production of HbA1c. The second is that good self-management remains protective in nature automatically without demonstrating the metabolic pathway of protection. The current model does deal with both simplifications.

The implications of the discussion on the retinal imaging research are also discussed. Most recent research has focused on OCTA biomarkers as an indicator of retinal disease at an early stage, and such biomarkers are typically compared to demographic or biomedical predictors alone. The manuscript thus implies that retinal imaging can be utilized not just in the diagnosis but also in the study of behavioral complications by incorporating self-management behavior and HbA1c with the OCTA markers in the same model. Should comparable trends be corroborated by future primary data, the clinicians will be able to determine which patients have microvascular retinal risk persisting despite seemingly acceptable self-report or, vice versa, which patients with a good profile of self-management are already demonstrating retinal benefit. Such labor would contribute towards a more proactive and or combined model of diabetic eye care.

There are a number of limitations that must be taken into consideration when explaining these findings. To begin with, the cross-sectional study does not provide interventions by time or causation and the statistically significant indirect effect via HbA1c must be regarded as an association that is in line with the proposed model but not as evidence of time-mediated interventions. Second, many clinically relevant covariates, such as age, duration of diabetes, blood pressure, kidney functioning, lipid profile, treatment regimen, and initial severity of retinopathy, were not incorporated into the structural model, thus ruling out the presence of residual confounding. Third, the HbA1c and OCTA measures were indicated to reflect larger constructs of glycemic and retinal status. This decision adhered to the purpose of the study and was justified by the loading pattern, but there are other possible composite specifications that could be discussed in future research. Fourth, the results are based on adults diagnosed with type 2 diabetes and measured at one point in time and must not be assumed to be longitudinal progression.

Clinically speaking, the results suggest increasing the combination of diabetes education, metabolic monitoring, and OCTA-based retinal examination. Self-management behavior seems to have the greatest importance when it is converted to glycemic control and the moderation outcome indicates that active engagement in continuous glucose monitoring may help in translating this. In that regard, retinal safety must be thought of as a collective both in endocrinology, diabetes training, and ophthalmology, but long-term confirmation remains necessary.

In addition to hypothesis testing, wording and framing in the prevention of diabetic retinopathy are also highlighted in the discussion. Patients tend to listen to HbA1c being discussed as a statistic related to control but not necessarily to the eye in a specific sense. One approach to refer clinicians to communicate risk more effectively is a behavior-to-HbA1c-to-retina model: any medication choice, food preference, exercise regimen, and monitoring feedback could influence retinal outcomes by impacting cumulative glycemia. This change in communication can become a motivation on its own, in particular, in patients who are asymptomatic and who underestimate the retinal risk.

The current model, as well, implies that retinal prevention is an interdisciplinary result. Microvascular changes can be noticed by eye specialists, which are frequently planted in decisions at home, which diabetes education strengthens or weakens, and which glucose data sheds light on or clouds. The single pathway model will thus be able to facilitate enhanced service integration. Often patients do not get piecemeal advice when there is the same framework adopted by endocrinology, diabetes education, and ophthalmology teams. It is also one of the larger

conceptual values of the positioning of HbA1c as a mediating variable and retinal microvascular outcomes as an ultimate endpoint.

6. Conclusion

This research established that better self-management behavior was related to lower HbA1c and more desirable retinal microvascular status, whereas higher HbA1c was related to more adverse OCTA-based retinal microvascular status. An indirect statistically significant influence of HbA1c was also seen in the relationship between self-management behavior and retinal microvascular status, with an increased inverse relationship between self-management behavior and HbA1c with continuous glucose monitoring engagement. The findings advocate the usefulness of a combination of behavioral, metabolic, and retinal assessments in the pathophysiology of diabetic retinal disease. Since it was a cross-sectional design, the findings cannot be used as indicators of longitudinal development or causality.

Author Contributions

Conceptualization, Q.A. and M.H.B.N.; methodology, S.L.O.; software, M.H.B.N.; validation, Q.A., M.H.B.N. and S.L.O.; formal analysis, M.H.B.N.; investigation, S.L.O.; resources, M.H.B.N.; data curation, Q.A.; writing—original draft preparation, Q.A.; writing—review and editing, M.H.B.N.; visualization, Q.A. and M.H.B.N.; supervision, M.H.B.N. and S.L.O.; project administration, Q.A. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Human Research Ethics Committee of Universiti Sultan Zainal Abidin, Malaysia (protocol code UniSZA/UHREC/2024/049) and dated 6 March 2024.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data that support the findings of this study are openly available in Figshare at 10.6084/m9.figshare.32231913.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used OpenAI's ChatGPT 5.3 for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

References

1. Wang, W.; Lo, A.C.Y. Diabetic retinopathy: Pathophysiology and treatments. *Int. J. Mol. Sci.* **2018**, *19*, 1816.

2. Jan, Y.-K.; Kelhofer, N.; Tu, T.; et al. Diagnosis, pathophysiology and management of microvascular dysfunction in diabetes mellitus. *Diagnostics* **2024**, *14*, 2830.
3. Hernández-Teixidó, C.; Barrot de la Puente, J.; Miravet Jiménez, S.; et al. Incidence of diabetic retinopathy in individuals with type 2 diabetes: A study using real-world data. *J. Clin. Med.* **2024**, *13*, 7083.
4. Seshasai, S.; He, F.; Lam, B.; et al. Transition probabilities of diabetic retinopathy and death in an Asian population with diabetes. *Asia-Pac. J. Ophthalmol.* **2024**, *13*, 100070.
5. Chowdhury, H.A.; Harrison, C.L.; Siddiquea, B.N.; et al. The effectiveness of diabetes self-management education intervention on glycaemic control and cardiometabolic risk in adults with type 2 diabetes in low- and middle-income countries: A systematic review and meta-analysis. *PLoS One* **2024**, *19*, e0297328.
6. Yuksel, M.; Bektas, H.; Canli Ozer, Z. The effect of nurse-led diabetes self-management programmes on glycosylated haemoglobin levels in individuals with type 2 diabetes: A systematic review. *Int. J. Nurs. Pract.* **2023**, *29*, e13175.
7. Li, D.; Pan, E.; Sun, Z.; et al. Associations between perceived care quality, self-care behaviors, and glycemic control in Chinese adults with type 2 diabetes under the national essential public health services program. *BMC Public Health* **2024**, *24*, 1964.
8. Rodrigues, S.; Patrício, A.I.; Cristina, C.; et al. Health literacy and adherence to therapy in type 2 diabetes: A cross-sectional study in Portugal. *HLRP Health Lit. Res. Pract.* **2024**, *8*, e194–e203.
9. Shinzato, Y.; Nakayama, Y.; Okamoto, S.; et al. Impact of treatment cessation on incidence and progression of retinopathy in Japanese patients with type 2 diabetes mellitus: A retrospective cohort study. *Diabetol. Int.* **2024**, *15*, 535–543.
10. Crincoli, E.; Sacconi, R.; Querques, L.; et al. OCT angiography 2023 update: Focus on diabetic retinopathy. *Acta Diabetol.* **2024**, *61*, 533–541.
11. Parravano, M.; Cennamo, G.; Di Antonio, L.; et al. Multimodal imaging in diabetic retinopathy and macular edema: An update about biomarkers. *Surv. Ophthalmol.* **2024**, *69*, 893–904.
12. Yang, F.; Zou, W.; Li, Z.; et al. Optical coherence tomography angiography for detection of microvascular changes in early diabetes: A systematic review and meta-analysis. *Diabetes Metab. Res. Rev.* **2024**, *40*, e3812.
13. Okati-Aliabad, H.; Nazri-Panjaki, A.; Mohammadi, M.; et al. Determinants of diabetes self-care activities in patients with type 2 diabetes based on self-determination theory. *Acta Diabetol.* **2024**, *61*, 297–307.
14. Ong-Artborirak, P.; Seangpraw, K.; Boonyathee, S.; et al. Health literacy, self-efficacy, self-care behaviors, and glycemic control among older adults with type 2 diabetes mellitus: A cross-sectional study in Thai communities. *BMC Geriatr.* **2023**, *23*, 297.
15. Tarricone, R.; Petracca, F.; Svae, L.; et al. Which behaviour change techniques work best for diabetes self-management mobile apps? Results from a systematic review and meta-analysis of randomised controlled trials. *EBioMedicine* **2024**, *103*, 105091.
16. Ajjan, R.A.; Battelino, T.; Cos, X.; et al. Continuous glucose monitoring for the routine care of type 2 diabetes mellitus. *Nat. Rev. Endocrinol.* **2024**, *20*, 426–440.
17. Rudraraju, M.; Narayanan, S.P.; Somanath, P.R. Regulation of blood-retinal barrier cell-junctions in diabetic retinopathy. *Pharmacol. Res.* **2020**, *161*, 105115.
18. Kunutsor, S.K.; Zaccardi, F.; Balasubramanian, V.G.; et al. Glycaemic control and macrovascular and microvascular outcomes in type 2 diabetes: Systematic review and meta-analysis of cardiovascular outcome trials of novel glucose-lowering agents. *Diabetes Obes. Metab.* **2024**, *26*, 1837–1849.
19. Lee, K.; Lee, G.H.; Lee, S.E.; et al. Glycemic control and retinal microvascular changes in type 2 diabetes mellitus patients without clinical retinopathy. *Diabetes Metab. J.* **2024**, *48*, 983–992.
20. Sheemar, A.; Bellala, K.; Sharma, S.V.; et al. Metabolic memory and diabetic retinopathy: Legacy of glycemia and possible steps into future. *Indian J. Ophthalmol.* **2024**, *72*, 796–808.
21. Liu, T.Y.A.; Shpigel, J.; Khan, F.; et al. Use of diabetes technologies and retinopathy in adults with type 1 diabetes. *JAMA Netw. Open* **2024**, *7*, e240728.
22. Wang, Y.; Lu, J.; Yu, J.; et al. Association between time in tight range and incident diabetic retinopathy in adults with type 2 diabetes. *Diabetes Obes. Metab.* **2025**, *27*, 1415–1422.
23. Tan, T.E.; Jampol, L.M.; Ferris, F.L.; et al. Imaging modalities for assessing the vascular component of diabetic retinal disease: Review and consensus for an updated staging system. *Ophthalmol. Sci.* **2023**, *4*, 100449.
24. Oliveira, D.; Costa, A.; Henriques, A.; et al. Validation of the Portuguese version of the diabetes self-management questionnaire-revised (DSMQ-R) in people with type 2 diabetes mellitus. *BMC Psychol.* **2024**, *12*, 405.
25. Innab, A.; Kerari, A. Validation of the Arabic version of the diabetes self-management questionnaire in pa-

tients with type 2 diabetes mellitus: A cross-sectional study. *BMC Prim. Care* **2024**, *25*, 274.
26. Zhang, Z.; Deng, C.; Paulus, Y.M. Advances in structural and functional retinal imaging and biomarkers for early detection of diabetic retinopathy. *Biomedicines* **2024**, *12*, 1405.
27. American Diabetes Association Professional Practice Committee. 12. Retinopathy, Neuropathy, and Foot Care: Standards of Care in Diabetes—2025. *Diabetes Care* **2025**, *48*, S252–S265.