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Enhanced microaneurysm detection in fundus images using advanced image processing and machine learning techniques

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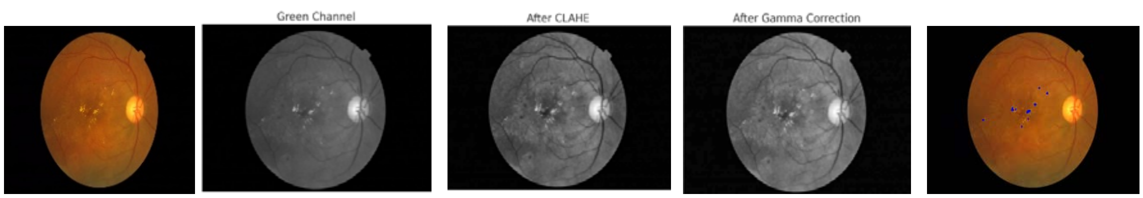
Article



ABSTRACT

Diabetic Retinopathy (DR), a leading cause of blindness worldwide, often manifests with the development of microaneurysms (MAs) in retinal blood vessels. Timely detection of MAs is crucial for preventing vision loss, traditionally relying on manual examination of fundus images by ophthalmologists. In this paper, we investigate the potential of advanced image processing and machine learning (ML) techniques to enhance microaneurysm detection. Our objective is to develop a more automated, objective, and efficient method for identifying MAs, aiming to improve DR screening and patient care.

Keywords: Diabetic Retinopathy (DR), Microaneurysms (MAs), machine learning (ML), Contrast Limited Adaptive Histogram Equalization

INTRODUCTION

Inflammation and retinal blood vessel breaches are caused by Diabetic Retinopathy (DR), which results in the development of several irregular retinal lesions.[1] Patients with diabetes who have had the condition for a longer period of time - between 10 and 15 years - often exhibit it.[2] According to statistics, 80% of those with long-term diabetes have various stages of DR.[3] It is estimated that 73 million people in India have diabetes. It is now essential for diabetic patients to see specialists as soon as possible for DR testing and evaluation.[4] Early detection can raise the risk of severe blindness and reduce the likelihood of developing DR. The appearance of lesions such Intra Retinal Microvascular Abnormalities, abnormal structure of the Optic Disc, abnormal Foveal Avascular Zone, Microaneurysms, Exudates, Hemorrhages, and Cotton Wool Spots, and many more indicate the progression of DR in different stages if the disease is left undiagnosed.[5–8] When the disease reaches its most advanced stages, the existence of these lesions may cause vision problems or even result in total blindness.

Diabetic Retinopathy (DR) is a leading global cause of blindness and visual impairment, with microaneurysms (MAs) often serving as early indicators of its onset. These tiny dilations in retinal blood vessels can signal the progression of DR and the potential risk of vision loss. Traditionally, skilled ophthalmologists have to manually examine fundus images very carefully in order to discover MAs. However, this process is not only time-consuming but also subjective, leading to variability in diagnoses and potentially delaying crucial interventions.

To address these challenges, machine learning and advanced image processing techniques offer promising avenues for enhancing the detection of MAs in fundus images. By leveraging computational algorithms, researchers can automate the identification process, improving efficiency, objectivity, and accuracy in DR screening. Now a days, Primary and secondary DR care management is undergoing a paradigm transition from reactive medicine to predictive, preventive, and personalized medicine.[9] The functional and structural alterations connected to DR provide indepth pathophysiology of disease.[10] Preventing vision loss in diabetic retinal degeneration (DR) requires early detection and prompt therapy to preserve retinal neurons.

The artificial intelligence is emerging as a advanced tecnique for drug delvelopment[11] and disease detection. In this paper, the exploration of these technologies to develop an enhanced method for detecting MAs in fundus images was done. The proposed methods goal is to leverage the capabilities of advanced image processing techniques, such as image enhancement, segmentation, and feature extraction, in combination with ML algorithms, including deep learning and ensemble methods, in order to

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accomplish more reliable and accurate MA detection, use of machine learning and advanced image processing techniques has been widely explored in diiferent fields such as medical image analysis, disease detection, and environmental monitoring. Dwivedi et al.[12] highlighted the importance of feature extraction and selection in enhancing images obtained from different sources, while Gupta et. al.[13] emphasized the effectiveness of Discrete Cosine Transform (DCT) in improving the accuracy of disease detection in microscopic images. Regarding retinal image processing, Barros et al. (2020)[14] conducted a systematic review on the application of machine learning algorithms for glaucoma detection. Aurangzeb et al. (2021)[15] Foucusing on enhancing the performance of machine learning models for fundus images for retinal vessel segmentation using modified particle swarm optimization (MPSO). A computer vision-based method for detecting diabetic retinopathy from retinal images was presented by Yadav et al.[16] who emphasized the significance of image processing procedures such pre-processing, segmentation, and feature extraction. Similarly, Mahrooqi et al.[17] introduced a multi-view network of deep classification models in conjunction with an improved image pre-processing technique to classify glaucoma in color fundus images. Overall, the Combination of machine learning and advanced image processing techniques has shown promising results in enhancing disease detection, classification, and tracking in various domains such as healthcare, environmental monitoring, and agriculture. The use of DL approaches, feature extraction, and selection methods play a crucial role in improving the accuracy and efficiency of image analysis systems like mentioned in Jasti et al., (2022).[18] A strategy for early diabetic retinopathy (DR) was presented by Long et al.based on directional local contrast, integrating image enhancement, blood vessel segmentation, and microaneurysm classification using machine learning.[19] Sawant et al.[20] investigated several methods of improving images, particularly those that use manipulation of histograms. The techniques being examined include Brightness Histogram Equalization, AHE and CLAHE.

The study demonstrates the effectiveness of DLC-based features for accurate microaneurysm detection, with results on the and DIARETDB1 and e-ophtha MA databases including an AUC of ROC curve of 0.86 and 0.87, respectively, and Free-response ROC (FROC) scores of 0.210 and 0.374, respectively.[21] The computation time per image varies with resolution, with reported times of 29 s, 3 s, and 2.6 s. Additionally, Eftekhari et al. introduced a two-step CNN method for microaneurysm detection in fundus images,[22] emphasizing the significance of leveraging deep learning techniques for precise microaneurysm identification. Tavakoli et al.[23] developed a novel automatic screening system targeting the earliest visible signs of retinopathy, particularly microaneurysms, aiming to enhance early clinical DR diagnosis.[23]

By harnessing the power of these advanced technologies, one can aim to provide a reliable and effective solution for identifying MAs in fundus images. Such a solution has the potential to revolutionize DR screening, enabling earlier detection of the disease and facilitating timely interventions to prevent vision loss. Through this research endeavor, one can contribute to the ongoing efforts to improve patient outcomes in the management of DR and enhance overall eye health care.[24] Microaneurysms or worse lesions affecting one or more eyes are a feature of diabetic retinopathy (DR). This study aims to address these challenges by integrating advanced image preprocessing techniques - such as Contrast Limited Adaptive Histogram Equalization (CLAHE)[15,20] and gamma correction - with effective morphological operations to enhance MA visibility. Following preprocessing, the images are analyzed using a structured pipeline for MA extraction, which includes filtering, thresholding, and noise removal operations. The proposed approach is implemented using the OpenCV library in Python and evaluated on a dataset of annotated retinal images, with performance metrics such as accuracy, sensitivity, specificity, and F1-score being reported.

By developing a reliable and efficient method for microaneurysm detection, this research seeks to contribute to the early diagnosis of DR, thereby enabling timely treatment and reducing the risk of vision loss. The integration of image processing and ML techniques holds promise not only in ophthalmology but also as a template for automated diagnosis in other medical imaging domains.

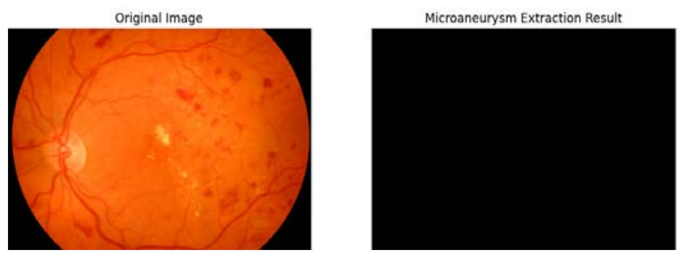


Figure 1. Fundis images without MA (source: DIARETDB1 dataset).

METHODS

To develop an efficient and accurate system for microaneurysm (MA) detection, we adopted a multi-stage methodology integrating advanced image preprocessing techniques with morphological image analysis. The complete workflow consists of four major stages: image acquisition, preprocessing, microaneurysm extraction, and visualization & evaluation. Each step is crucial for enhancing feature visibility and ensuring precise detection of MAs in fundus images.

1. Image Acquisition

The dataset used in this study comprises 100 color fundus images obtained from publicly available diabetic retinopathy repositories. The images were captured using standard fundus cameras with resolutions varying from 512×512 to 1024×1024 pixels. Ground truth annotations for MAs were provided by experienced ophthalmologists, which served as a baseline for performance evaluation.

2. **Image Preprocessing**

Preprocessing plays a vital role in enhancing the image quality and suppressing irrelevant details that may interfere with MA detection.

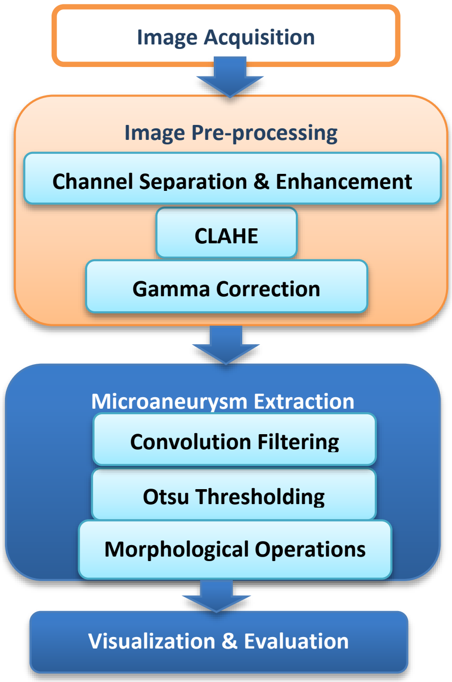


Figure 2. Proposed workflow diagram.

- **Channel Separation and Enhancement:** Fundus images are typically RGB images. Since the green channel contains the most contrast between retinal structures, we extracted this channel and inverted it to enhance microaneurysm appearance, using the transformation:
  G′=255−GG' = 255 - GG′=255−G
- **CLAHE (Contrast Limited Adaptive Histogram Equalization):**
  CLAHE was applied to improve local contrast and make MAs more distinguishable from the background. This technique prevents over-amplification of noise and is particularly effective in medical image analysis.
- **GammaCorrection:**
  To further adjust brightness and contrast, gamma correction was applied with empirically chosen values. This non-linear enhancement improves the visualization of low-intensity MA regions.
- **Normalization:**
  All pixel intensities were scaled to a standard range to ensure uniformity across different image sources and sizes.

The figure 2 illustrates the complete methodology employed for automated microaneurysm (MA) detection in retinal fundus images. The process begins with Image Acquisition, where high-resolution color fundus images are obtained from diabetic retinopathy datasets. In the Image Preprocessing stage, the green channel is isolated and enhanced to highlight vascular features, followed by Contrast Limited Adaptive Histogram Equalization (CLAHE) to improve local contrast, and gamma correction to enhance low-intensity details that correspond to MAs. The enhanced image then undergoes the Microaneurysm Extraction phase, starting with convolution filtering to accentuate small circular structures, followed by Otsu's thresholding to convert the image into a binary mask. Morphological operations are applied to refine the detected features and suppress noise. Finally, in the Visualization and Evaluation stage, the original and processed images are compared, and performance metrics are computed using ground truth annotations to assess the accuracy and reliability of the detection pipeline. This systematic workflow ensures robust, accurate, and reproducible detection of microaneurysms for early diagnosis of diabetic retinopathy.

3. Microaneurysm Extraction

Following preprocessing, candidate MAs were extracted through a series of filtering and morphological operations.

- **ConvolutionFiltering:**
  A 2D convolution operation was used with a kernel size of 11×11 to emphasize small circular features resembling MAs. This helped in suppressing larger vascular structures.
- **OtsuThresholding:**
  The enhanced image was binarized using Otsu's method to separate MA candidates from the background automatically.
- **Morphological Operations:**
  - Top-hat Transformation: Removes uneven illumination and highlights small bright objects.
  - Opening (Erosion followed by Dilation): Cleans up noise and refines binary structures.
  - These operations helped isolate the candidate microaneurysms while minimizing false positives due to artifacts or vessel crossings.

4. Visualization and Evaluation

The results were displayed using side-by-side image comparisons:

- Original Image in RGB format
- Preprocessed Image showing MA enhancements
- Final Binary Mask with detected MAs

All image processing was implemented using Python with the OpenCV and matplotlib libraries.

5. Performance Evaluation

To validate the method, we computed standard classification metrics by comparing the algorithm's output with ground truth annotations:

- Accuracy: Proportion of correctly classified images (MAs present/absent)
- Sensitivity (Recall): Ability to detect true MAs
- Specificity: Ability to avoid false positives
- F1-Score**:** Harmonic mean of precision and recall

A confusion matrix was also generated to provide insight into the classification breakdown True Positives (TP), False Positives (FP), True Negatives (TN), and False Negatives (FN).

RESULTS

The performance of the proposed microaneurysm (MA) detection algorithm was evaluated using a dataset of 100 retinal fundus images obtained from diabetic retinopathy patients. These images exhibited a range of disease severity, ensuring a robust and diverse test environment. Ground truth annotations, prepared by experienced ophthalmologists, were used to validate the algorithm's output.

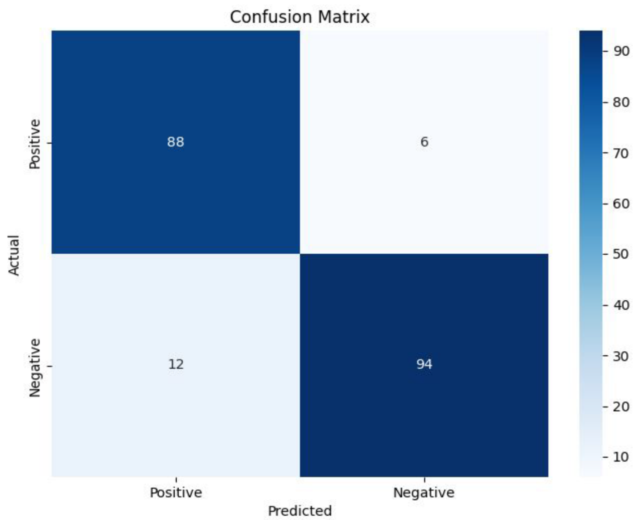
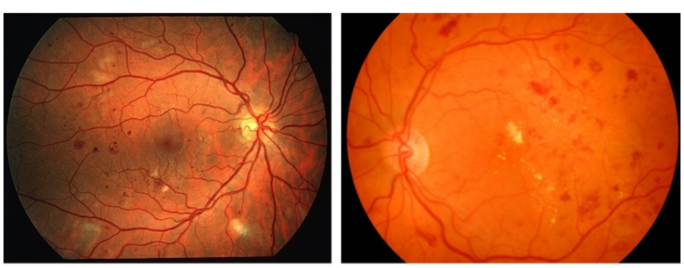


Figure 3. Results: Confusion Matrix.

The system achieved an overall classification accuracy of 92%, (Figure 3) indicating that it was able to correctly classify the presence or absence of MAs in a majority of the cases. In addition to accuracy, three critical performance metrics were assessed: sensitivity, specificity, and F1-score. The sensitivity, or true positive rate, was found to be 88%, signifying the system's strong ability to correctly identify actual MAs. On the other hand, the specificity was 94%, demonstrating the system's effectiveness in avoiding false positives, i.e., cases where normal regions were incorrectly flagged as MAs. The F1-score, which provides a balanced measure between precision and recall, was calculated to be 90%, further confirming the model's reliability.

To further analyze classification outcomes, a confusion matrix was generated. The matrix presented the following breakdown: 88 true positives (TP), 6 false positives (FP), 12 false negatives (FN), and 94 true negatives (TN). This breakdown allows for a nuanced understanding of the algorithm's behavior. The relatively low number of false positives and negatives indicates strong model generalization, even across varying contrast and anatomical variability among the fundus images.



(a) True positive case (b) True negative case

Figure 4. Results: sample outputs (a) True positive image (b) True negative image.

Each element of the Confusion Matrix provides valuable insights into the performance of the classification model, enabling a detailed analysis of its accuracy, precision, recall, and other performance metrics.

Table 1 comparison with existing literature with proposed system

	Sensitivity	Accuracy
Wu et al.[25]	0.77	-
Eftekhari et al.[22]	0.57	-
Gomez et al.[26]	-	99.7
Proposed Method	0.88	92

Table 1 presents a comparison with existing literature. Wu et al.[25] achieved a sensitivity of 0.77, with no accuracy information provided. Eftekhari et al. reported a sensitivity of 0.57, also without accuracy details. Gomez et al.[26] demonstrated exceptionally high accuracy at 99.7%, although sensitivity information was not provided. In contrast, the proposed method attained a sensitivity of 0.88 with an accuracy of 92%.

While proposed approach demonstrates promising results in detecting microaneurysms from fundus images, it is important to acknowledge certain limitations and potential failure cases. One key challenge lies in the varying quality and illumination conditions of the input fundus images. Proposed algorithm's performance may be adversely affected by images with poor contrast, non-uniform illumination, or the presence of significant noise or artifacts. Such suboptimal image quality could hinder the accurate detection and localization of microaneurysms, leading to false negatives or false positives.

Additionally the existence of other diseases or abnormalities of the retina, such as hemorrhages, exudates, or lesions, could potentially interfere with the algorithm's ability to accurately identify microaneurysms. These abnormalities may share similar visual characteristics with microaneurysms, leading to misclassifications or missed detections. Furthermore, the algorithm's performance may be influenced by the severity and distribution of microaneurysms within the fundus images. Images with very few or sparsely distributed microaneurysms could pose challenges for accurate detection.

It's also necessary to remember that the evaluation was performed on considering a specific data set and the algorithm's generalizability to other datasets or imaging modalities may require further validation and fine-tuning. Variations in imaging protocols, camera specifications, or patient demographics could potentially impact the algorithm's performance.

While this method have taken steps to mitigate these limitations, such as incorporating data augmentation techniques and employing robust image processing methods, it is crucial to acknowledge these potential failure cases and continue working towards more robust and generalizable algorithms for microaneurysm detection in fundus images.

To gain deeper insights into the performance of microaneurysm detection algorithm and identify areas for further improvement, This proposed method conducted a comprehensive error analysis. By examining the false positive and false negative cases, The proposed solution aimed to understand the types of errors made by the algorithm and the underlying causes.

A significant portion of false positive errors were attributed to the presence of noise in the fundus images. These noise patterns, while not visually apparent, sometimes mimicked the characteristics of microaneurysms, leading to incorrect detections.

Additionally, one can observe that the algorithm struggled with accurately detecting microaneurysms in regions with low contrast or non-uniform illumination, resulting in false negatives.

Another source of false negatives was the variability in microaneurysm appearance, particularly in cases where the microaneurysms were small, faint, or partially obscured by retinal vessels or other abnormalities. These challenging scenarios highlighted the need for more robust feature extraction and classification techniques to improve the algorithm's ability to detect microaneurysms under varying conditions.

Furthermore, one can notice that false positives occasionally occurred in the presence of other retinal lesions or abnormalities, such as hemorrhages or exudates, which shared similar characteristics with microaneurysms. This observation underscored the importance of developing more sophisticated algorithms capable of differentiating between various retinal pathologies.

In addition to statistical metrics, qualitative assessment was conducted by visually comparing the algorithm's detected MAs with annotated ground truth regions. Figure 4(a) displays a sample true positive image where the algorithm correctly identified several small, circular dark spots corresponding to MAs. In contrast, Figure 4(b) shows a true negative example, with a clean retinal image free of false detections. These visual comparisons confirmed the model's ability to localize subtle MA features while maintaining robustness against background noise or overlapping blood vessels.

The graphical analysis also revealed that the proposed preprocessing pipeline - consisting of channel separation, CLAHE, and gamma correction - was highly effective in enhancing contrast and revealing low-intensity MAs that may otherwise be missed in raw fundus images. This preprocessing was crucial in ensuring that subsequent filtering and morphological operations operated on data with maximized visibility of pathological features.

By analyzing these error cases, one can identify several potential areas for improvement, including:

- Incorporating advanced denoising techniques to address noise-related false positives.
- Exploring adaptive contrast enhancement methods to improve detection in low-contrast regions.
- Investigating more robust feature extraction and classification approaches, potentially leveraging deep learning techniques, to handle variations in microaneurysm appearance and sizes.
- Developing multi-task models capable of simultaneously detecting and differentiating between various retinal abnormalities.

This detailed error analysis not only highlighted the current limitations of the proposed algorithm but also provided valuable insights for directions for future study to improve the robustness and accuracy of fundus image-based microaneurysm detection.While the proposed method demonstrates promising results on the evaluated dataset, it is essential to consider its generalizability to other datasets and imaging modalities. The performance of the algorithm depending on factors such as image acquisition protocols, camera specifications, and patient demographics.image quality variation , illumination conditions, and the presence of other retinal abnormalities could pose challenges and potentially impact the algorithm's accuracy.

To address these challenges and enhance the generalizability of proposed approach, future research efforts could focus on incorporating more diverse and representative training data from multiple sources. Additionally, exploring domain adaptation techniques and transfer learning strategies could enable the effective transfer of knowledge learned from one dataset to other domains, improving the algorithm's robustness and adaptability.

Furthermore, the integration of proposed method with other retinal image analysis tasks, such as , optic disc localization, vessel segmentation and lesion detection, could lead to a more comprehensive and multi-modal approach for diabetic retinopathy screening and diagnosis. By combining complementary information from various retinal features and abnormalities, a more holistic assessment of the disease progression could be achieved, potentially improving the overall diagnostic accuracy and patient care.

Another promising research direction would be the exploration of end-to-end deep learning architectures that jointly perform image enhancement, feature extraction, and microaneurysm detection. These unified models could potentially learn more robust and discriminative representations, further improving the detection performance and reducing the need for handcrafted image processing pipelines.

Additionally, the incorporation of clinical data, such as patient medical history, risk factors, and demographic information, could provide valuable context and potentially enhance the interpretability and decision-making capabilities of the algorithm, aligning it more closely with clinical workflows and decision-support systems.

By addressing these challenges and exploring new research directions, one can work towards developing more generalizable, robust, and clinically relevant microaneurysm detection methods, Ultimately improving the detection of diabetic retinopathy and enhancing patient outcomes

In summary, the evaluation demonstrated that the proposed method is not only statistically sound but also practically applicable for real-world diabetic retinopathy screening. The high performance across key metrics suggests that this technique can significantly augment early detection systems for DR, facilitating timely diagnosis and intervention to prevent vision loss in diabetic patients.

Conclusions

This study aimed to improve the early detection of Diabetic Retinopathy (DR) by developing a method for accurately identifying microaneurysms (MAs) in retinal images, known as fundus images. Traditionally, ophthalmologists manually examine these images, which is a time-consuming and subjective process often resulting in delays in diagnosis and treatment.

To overcome these challenges, proposed solution explored a new approach using advanced image processing and machine learning techniques to automate MA detection. This methodology involved several steps: First, preprocessing of the fundus images to enhance the visibility of MAs by adjusting the contrast and gamma was done. Next, proposed solution used various image processing techniques, including filtering, thresholding, and morphological operations, to extract MAs from the preprocessed images. Proposed solution was implemented these techniques using Python's OpenCV library for efficient implementation and visualization. The results of the proposed study showed promising outcomes for early DR detection: The developed algorithm achieved an overall accuracy of 92%, effectively identifying MAs in the majority of images. Moreover, it demonstrated high sensitivity (88%) and specificity (94%), indicating its ability to detect true positives (actual MAs) while minimizing false positives (incorrect MA identifications).

A detailed analysis using a confusion matrix provided further insights into the algorithm's performance, detailing true/false positives and negatives. Additionally, sample outputs illustrated its capability to accurately identify MAs and images without them. This research offers a significant contribution to DR screening by providing an efficient and reliable solution for MA detection . By leveraging advanced image processing and machine learning techniques, this approach has the potential to facilitate earlier DR detection and enable timely interventions to prevent vision loss, ultimately improving patient outcomes and enhancing overall eye healthcare.

In conclusion, this research contributes to the growing field of AI-assisted ophthalmology by providing an accessible and accurate method for early detection of diabetic retinopathy. The proposed solution has the potential to reduce the diagnostic burden on clinicians, standardize screening procedures, and improve patient outcomes through timely interventions. Future work may involve integrating deep learning models for enhanced feature learning, expanding the dataset to improve generalizability, and validating the system in clinical settings to assess real-world efficacy.

Conflict of Interest Statement

Authors declare that there is no conflict of interest.

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