• Bibliometric Research •

Artificial intelligence in ophthalmic optical coherence tomography angiography: a bibliometric analysis

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Abstract
● **AIM:** To analyze research landscapes, hotspots, and trends in artificial intelligence (AI) applied to ophthalmic optical coherence tomography angiography (OCTA) from 2015 to 2024, aiming to reveal global collaborations and guide future research.
● **METHODS:** We retrieved publications from Web of Science Core Collection using AI and OCTA-related search terms. After screening, 237 articles were analyzed with CiteSpace (version 6.3.R1) for co-citation, collaboration, and keyword burst analysis.
● **RESULTS:** Annual publications grew rapidly since 2017. China (94 publications) and the US (86 publications) were the most productive and influential countries. Research focused on: deep learning algorithms and vessel segmentation, ocular disease diagnosis including diabetic retinopathy and glaucoma, and automated vascular quantification and multimodal imaging. Key limitations included small sample sizes and limited algorithm generalizability.
● **CONCLUSION:** The integration of AI with OCTA has significantly advanced the automation and precise quantitative analysis of ophthalmic vascular imaging, demonstrating substantial potential for diagnosing various retinal and choroidal diseases. Future efforts should focus on developing more robust and interpretable AI models, conducting large-scale, multi-center clinical validation, and establishing standardized imaging and analysis protocols to ultimately realize the widespread adoption of AI-OCTA technology in routine clinical practice.
● **KEYWORDS:** artificial intelligence; optical coherence tomography angiography; bibliometric analysis; trends
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INTRODUCTION

Optical coherence tomography angiography (OCTA) is a relatively new technology built upon optical coherence tomography (OCT) that has undergone rapid development in recent years[1], finding extensive application across multiple fields, particularly in ophthalmology. OCTA enables three-dimensional (3D) imaging of the retinal and choroidal circulation[2]. In contrast to fundus fluorescein angiography (FFA) and indocyanine green angiography (ICGA), it can non-invasively generate depth-resolved images of retinal and choroidal blood flow[3]. This capability allows for its use in the screening and diagnosis of various ocular diseases, including macular diseases such as age-related macular degeneration[4], retinal diseases such as diabetic retinopathy (DR)[5], as well as optic nerve diseases and glaucoma[6]. However, the image processing time can be protracted during scanning and analysis. Furthermore, OCTA cannot directly depict vascular functional status, and segmentation errors may occur in the visualized vasculature under certain ocular pathological conditions[7]. Consequently, there remains significant scope for improvement in ophthalmic OCT technology.

Artificial intelligence (AI) is a discipline that utilizes computer science to investigate and develop theories, methods, techniques, and applications for simulating and extending human intelligence[8]. In recent years, AI has been widely applied in medical fields, including ophthalmology. Machine learning (ML) and deep learning (DL) have been employed for ophthalmic medical image analysis, yielding significant results[9]. The development of ophthalmic AI is rapid. Traditional ML[10] and DL[11] techniques have been applied to OCTA for tasks such as image recognition and classification, assisted assessment of vascular density and morphology, anomaly detection and screening, and image quality enhancement. The recent emergence of large models offers new directions for diagnosing ophthalmic diseases. For instance, a novel approach combining ChatGPT and Vertex AI for diagnosing DR could potentially enable physicians lacking specialized coding expertise to preprocess images, analyze data, and train ML models[12]. The deep integration of AI—encompassing traditional ML, DL, and large models—with ophthalmic OCTA holds promise for transforming existing disease diagnostic systems and generating substantial clinical impact within ophthalmic healthcare services[13].

This study aims to conduct a bibliometric analysis of the most recent literature concerning the application of AI in ophthalmic OCTA imaging, based on articles retrieved from the Web of Science Core Collection (WoSCC) database. By synthesizing data including general publication metrics, country/region and institutional contributions, research categories, and keywords, alongside an analysis of the top 10 most influential publications in the field, this research evaluates the global landscape of AI-OCTA applications in ophthalmology. A key objective is to develop a reproducible and unbiased strategy for analyzing research hotspots and trends, thereby exploring the dynamic knowledge frontiers within this research domain. Specifically, this investigation examines the active areas, prospective developments, and potential obstacles in the application of AI to ophthalmic OCTA imaging. It intends to offer guidance and recommendations for AI specialists, ophthalmologists, and medical imaging researchers.

MATERIALS AND METHODS

Citation data for publications from January 1, 2015, to December 31, 2024, was obtained from the WoSCC and independently verified. The search query was: TS=("artificial intelligence" OR "AI" OR "machine learning" OR "deep learning" OR "transfer learning" OR "neural network" OR "robot*" OR "supervised learning" OR "unsupervised learning" OR "computer vision system" OR "computational intelligence" OR "evolutionary computation" OR "ensemble learning" OR "reinforcement learning" OR "large language model" OR "LLM") AND TS=("optical coherence tomography angiography" OR "OCTA" OR "OCT Angiography"). The search was limited to English-language articles, excluding early access publications, meeting abstracts, book chapters, data papers, and retracted publications.

To ensure analytical accuracy, manual screening of titles and abstracts was performed. Exclusion criteria were: 1) non-ophthalmic research focus; 2) studies not utilizing OCTA; 3) research methods not involving AI. The filtration process is detailed in Figure 1. Consequently, the final dataset exclusively pertains to the application of AI in ophthalmic OCTA.

Bibliometric analysis was conducted using the analytical features of WoS and CiteSpace (version 6.3.R1). This analysis encompassed general publication data, country/regional and institutional contributions, subject categories, and keywords. A comprehensive examination of highly influential publications was also undertaken. All relevant citation metrics are included in this study (Figure 1).

RESULTS

Distribution of Articles by Publication Year A total of 237 studies on the application of AI in ophthalmic OCTA, published from January 1, 2015—marking the initial integration of AI with OCTA—to December 31, 2024, were analyzed. Data collected and tallied from the WoSCC were deduplicated using the duplicate removal function in CiteSpace. The annual publication count grew rapidly between 2017 and 2021 and has remained stable at over 30 articles per year for the past 5y. The annual number of publications is presented in Figure 2.

Countries or Regions Employing the default settings of CiteSpace, the number of publications from each country was quantified, and collaborative networks between countries and regions were analyzed. The collected citations encompassed 38 countries and regions. In Figure 3, the size of each yellow node corresponds to the total citation count. The three largest nodes, representing China, the United States, and Japan, have publication counts of 94, 86, and 19, respectively. The connecting lines between nodes signify collaborative relationships. Countries with a greater number of connections demonstrate higher influence within the research network. The H-index serves as an accurate metric for assessing a country's academic output and impact. The three countries with the highest H-index values are the United States, China, and Japan (Table 1). In summary, China and the United States not only lead in the volume of publications in this field but also produce research with the highest reference value.

Institutions Table 2 lists the top 10 institutions most active in researching AI for OCTA applications, based on the selected publications. Oregon Health & Science University (United States) leads in both the number of publications and ranks first in H-index. Institutions from China and the United States comprise the majority of those listed. Oregon Health & Science University significantly leads other institutions, with 38 publications and an H-index of 22.

Keywords To gain a comprehensive understanding of AI applications in ophthalmic OCTA over the past decade, a keyword co-occurrence network analysis was conducted. The results are presented in Figure 4. Burst detection analysis identifies terms that have undergone significant changes in citation frequency within a specific period, thereby revealing

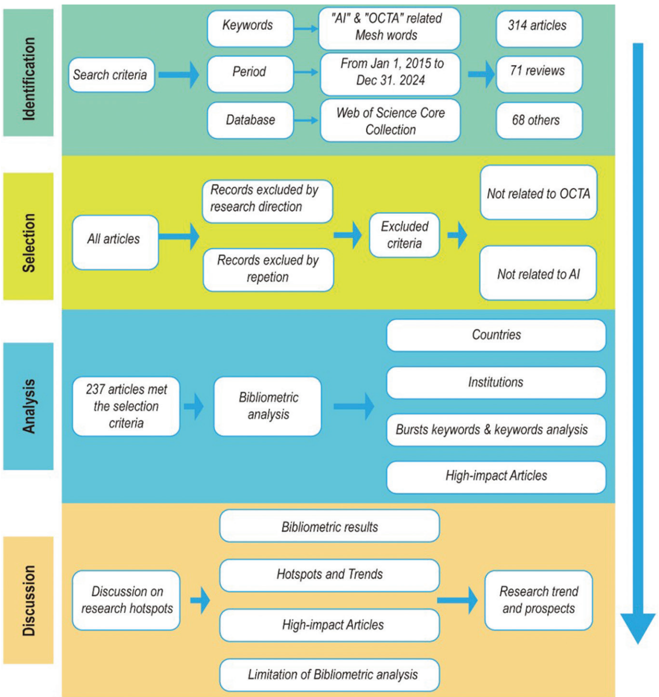

Figure 1 Frame flow diagram AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

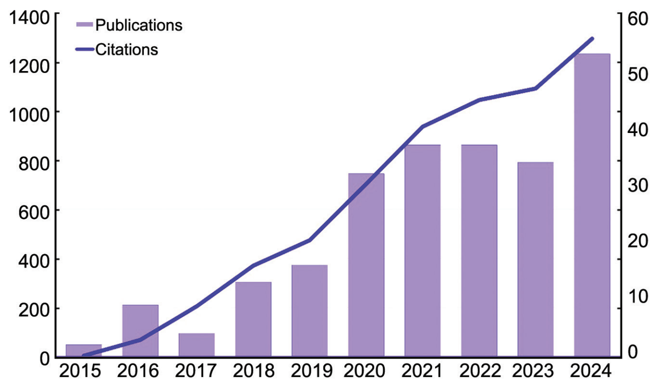

Figure 2 The annual number of publications and citations on AI application in ophthalmic OCTA between 2015 and 2024 AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

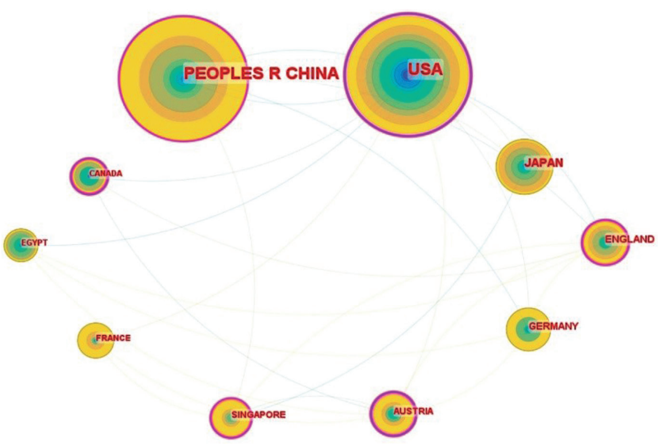

Figure 3 Collaboration of countries or regions that contributed to publications on AI application in ophthalmic OCTA between 2015 and 2024 AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

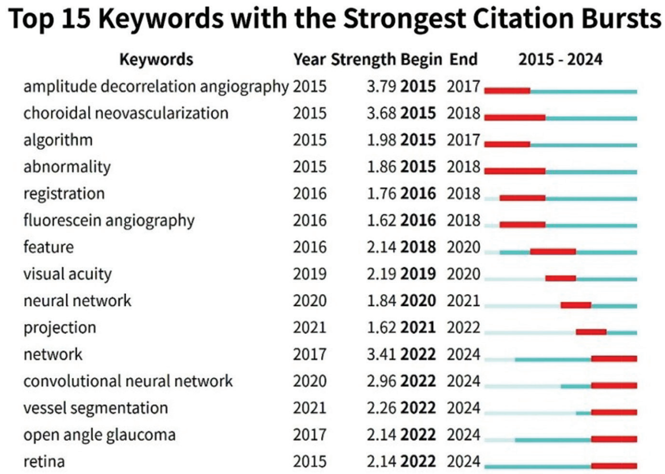

Figure 4 Keywords with the strongest citation bursts for publications on AI application in ophthalmic OCTA between 2015 and 2024 AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

Table 1 Top 10 countries with the highest publication volume in the field of AI ophthalmic OCTA from 2015 to 2024

Rank	Countries/regions	Counts	H-index
1	China	94	21
2	USA	86	33
3	Japan	19	10
4	England	13	9
5	Germany	12	7
6	Austria	10	7
7	Singapore	10	4
8	France	8	4
9	Canada	7	6
10	Egypt	7	5

AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

the emergence or decline of research foci. Keywords exhibiting such bursts during the investigation timeline are indicated by red squares in Figure 4.

High-Impact Articles Table 3[2,4,14-21] details the top 10 most-cited articles on the application of AI in ophthalmic OCTA, providing critical insights into the foundational research shaping this field.

DISCUSSION

Principal Results The findings demonstrate a rapid increase in publications focused on AI applications in ophthalmic OCTA since its formal clinical adoption. This trend underscores the significant potential of integrating OCTA with AI, particularly in ophthalmology. As an imaging technology combining OCT with AI, OCTA has evolved into a prominent research focus in the medical field.

Numerous studies confirm that ML and DL algorithms exhibit high sensitivity and specificity in detecting and classifying ocular diseases using OCTA images, establishing this as a highly promising research area[22].

Table 2 Top 10 institutions with the highest publication volume in the field of AI ophthalmic OCTA from 2015 to 2024

Rank	Institution	Counts	H-index	Countries/regions
1	Oregon Health Science University	38	22	USA
2	Sun Yat-sen University	13	7	China
3	University of California System	10	6	USA
4	Chinese Academy of Sciences	10	5	China
5	Medical University of Vienna	9	6	Vienna
6	Shanghai Jiao Tong University	9	4	China
7	University of Illinois Chicago	8	7	USA
8	Egyptian Knowledge Bank Ekb	7	5	Egypt
9	Nanyang Technological University	7	4	Singapore
10	Ningbo Institude of Materials Technology and Engineering, CAS	7	4	China

AI: Artificial intelligence; OCTA: Optical coherence tomography angiography.

Regarding national output, China and the United States are the two leading contributors, ranking first and second in both publication volume and influence, with a substantial gap over third-ranked Japan. While the United States trails slightly in publication count, it leads in influence, reflecting its dominant role in this domain. Japan and the England also hold notable centrality and impact. Among institutions, the top-ranked organization by publication volume is from the United States, while seven of the top ten institutions are from China, highlighting the latter's strong engagement and activity in this field. In terms of institutional H-index, Oregon Health & Science University demonstrates the most exceptional influence.

The emergence of AI has continued to drive advancements in ophthalmology, particularly through its applications in disease screening and diagnostic grading[23]. Current research efforts prioritize enhancing traditional ML and DL algorithms, as well as exploring specific applications of large models[24].

Hotspots and Trends OCTA, an emerging ophthalmic vascular imaging technology, differs fundamentally from conventional OCT in functionality. Characterized by its speed and non-invasiveness, OCTA provides volumetric data with the clinical capability for specific localization and delineation of pathology, simultaneously displaying structural and flow information[25]. It is specifically designed for the identification and analysis of vascular disorders by detecting motion contrast from flowing red blood cells, whereas OCT primarily focuses on imaging static retinal structural layers by measuring backscattered light[26]. This functional distinction leads to different application modes for AI. AI applications based on traditional OCT often focus on layer segmentation, lesion identification (*e.g.*, drusen, intraretinal fluid), and structural parameter measurement. In contrast, AI models for OCTA are tailored to its vascular imaging capabilities. These models are developed to analyze blood flow information, quantify vascular morphology, and detect perfusion abnormalities, which are crucial for diagnosing and managing vascular-related retinal diseases[27]. A key advantage of OCTA over traditional angiography is its dye-free nature, eliminating the risk of adverse patient reactions to contrast agents. Additionally, OCTA acquisition time can be as brief as seconds, compared to the 5–10min required for traditional angiography[28].

The AI research related to OCTA is primarily conducted through three main approaches: segmentation, classification, and quantification. Segmentation models, often based on U-Net or similar DL architectures, are the most common. Their main task is to accurately delineate vascular networks, segment the foveal avascular zone (FAZ), or identify areas of capillary nonperfusion[19]. Classification models, are employed for disease diagnosis and grading. These models learn features from OCTA images to distinguish between healthy and diseased eyes (*e.g.*, DR *vs* normal) or to classify disease severity[29]. Quantification studies represent a more advanced application, where AI algorithms automatically extract and calculate key vascular biomarkers from segmented images. These parameters include vessel density, vessel diameter, fractal dimension, and FAZ area, providing objective and reproducible data for monitoring disease progression and treatment response[30]. These diverse research models collectively advance the clinical utility of OCTA.

In current clinical practice, interpreting OCTA results and corresponding vascular biomarkers predominantly relies on experienced clinicians[31]. With continuous advancements in AI, models with enhanced computational power can utilize OCTA angiographic outcomes more comprehensively and efficiently, thereby improving the diagnostic accuracy for vascular diseases[32]. Based on burst term data from the bibliometric analysis, research hotspots in AI applications for OCTA primarily focus on the following areas.

1) Technological and methodological advancements

Amplitude decorrelation angiography (ADA): As the core imaging technique of OCTA, ADA showed a significant burst in 2015 (Strength: 3.79). This technology improves the signal-

Table 3 Top 10 most-cited articles on computational methodologies in ophthalmic OCTA from 2015 to 2024

Rank	Title of citing documents	DOI	Times cited	Interpretation of the findings	Research limitations
1	Detailed vascular anatomy of the human retina by projection-resolved optical coherence tomography angiography[2]	10.1038/srep42201	656	A new algorithm has been developed to improve the blood flow projection artifact issue in traditional OCTA technology, along with a proposed nomenclature standard for retinal vascular complexes	The effectiveness of this algorithm may be compromised when applied to certain specific retinal pathologies
2	Quantifying microvascular density and morphology in diabetic retinopathy using spectral-domain optical coherence tomography angiography[14]	10.1167/iovs.15-18904	412	Researchers have discovered that a specific algorithm, under certain conditions, can qualitatively highlight subtle changes in retinal vessels, facilitating the early diagnosis of DR	1) The study evaluated only the macula and its surrounding areas, which is insufficient for a comprehensive assessment of microvascular changes across the entire retina. 2) The interference of image artifacts affects both the quality and accuracy of the images. 3) In 2D imaging, the overlap of vessels reduces the sensitivity to subtle changes in retinal vasculature
3	Automated quantification of capillary nonperfusion using optical coherence tomography angiography in diabetic retinopathy[15]	10.1001/ jamaophthalmol.2015.5658	302	Researchers have developed a novel algorithm that can automatically identify and measure capillary non-perfusion areas from OCTA images, aiding in the diagnosis, treatment, and monitoring of DR	1) The results may be influenced by motion artifacts and low blood flow velocities. 2) The sample size is relatively small, and the study focuses on a specific disease
4	Projection-resolved optical coherence tomographic angiography[16]	10.1364/BOE.7.000816	282	Researchers have proposed a novel algorithm that effectively suppresses projection artifacts while preserving true vascular signals as much as possible	1) The algorithm exhibits errors when processing certain ocular structures. 2) In some cases, significant algorithms are required to assist in the removal of projection artifacts. 4o mini
5	A novel strategy for quantifying choriocapillaris flow voids using swept-source OCT angiography[17]	10.1167/iovs.17-22953	243	Researchers have proposed a novel algorithm that compensates for signal attenuation caused by the RPE and Bruch's membrane complex in SS-OCTA, allowing for more accurate quantification of choroidal capillary flow voids	1) The lack of an established gold standard for *in vivo* flow void segmentation prevents assurance of the method's absolute accuracy. 2) The study only involved healthy subjects and those with epiretinal membranes, without including a broader range of eye disease patients. 3) The proposed algorithm may be ineffective under conditions of high reflectivity from the RPE/Bruch's membrane complex, potentially impacting image reproducibility and accuracy. 4) For more severe conditions involving larger RPE elevations and macular fluid accumulation, signal attenuation may be greater, which could reduce image reproducibility
6	Projection-resolved optical coherence tomography angiography of macular retinal circulation in glaucoma[18]	10.1016/j.ophtha.2017.06.002	228	Researchers employed a novel algorithm that can remove blood flow projection artifacts, allowing for a more accurate analysis of the retinal three-layer vascular complex	Artifacts in certain locations cannot be completely removed
7	ROSE: a retinal oct-angiography vessel segmentation dataset and new model[19]	10.1109/TMI.2020.3042802	204	Researchers have presented a high-quality retinal OCTA vascular segmentation dataset and developed a vascular segmentation model that outperforms contemporaneous algorithms on this dataset	1) The study was attempted on a single dataset, with no mention of clinical validation, leaving external generalizability unknown. 2) The dataset size was not specified, which may limit the model's generalization capability
8	Visualization of 3 distinct retinal plexuses by projection-resolved optical coherence tomography angiography in diabetic retinopathy[20]	10.1001/ jamaophthalmol.2016.4272	152	Researchers have proposed a novel technique that differentiates blood flow signals from projection artifacts, enabling earlier detection of microvascular changes in DR	1) The control group did not account for age-matched controls. 2) No prospective follow-up was conducted, necessitating validation of the generalizability and applicability of the results
9	Advanced image processing for optical coherence tomographic angiography of macular diseases[21]	10.1364/BOE.6.004661	126	Researchers developed an algorithm to automatically quantify the area of choroidal neovascularization and retinal non-perfusion regions, enhancing the accuracy and efficiency of OCTA in diagnosing macular lesions. Additionally, they proposed an innovative method for visualizing OCT angiography data. 4o mini	In a few cases, algorithm segmentation still requires manual correction
10	Multimodal deep learning with feature level fusion for identification of choroidal neovascularization activity in age-related macular degeneration[4]	10.1111/aos.14928	124	The study proposes a feature-level fusion multimodal deep learning framework (UFNet and BFNet) that addresses the limitation of traditional classification-level fusion in neglecting inter-modal correlations, thereby enhancing the performance of multimodal medical diagnosis	1) The sample size of this study is limited. 2) The study lacks an FFA reference group

DR: Diabetic retinopathy; OCT: Optical coherence tomography; OCTA: Optical coherence tomography angiography; SS-OCTA: Spectral-domain optical coherence tomography angiography; RPE: Retinal pigment epithelium; FFA: Fundus fluorescein angiography.

to-noise ratio (SNR) for blood flow detection by splitting the OCT spectrum into several narrower bands. The SSADA algorithm significantly enhanced the SNR for flow detection and the connectivity of the microvascular network in images of the living human macula and optic nerve head, underscoring its critical role in OCTA.

Algorithm: Keywords related to algorithms began bursting in 2015 (Strength: 1.98), forming the foundation for OCTA image analysis and processing. DL algorithms are widely employed for various functions, including artery-vein classification, image quality assessment, and generating retinal flow maps from structural OCT. Frequently co-occurring keywords, such as motion correction, image registration (2016, Strength: 1.76), and automated segmentation, reflect continuous technological refinements that effectively improve OCTA image quality and analytical efficiency.

Convolutional neural network (CNN): Burst detection analysis indicates a significant rise in CNN-related keywords in 2020 (Strength: 2.96). In recent years, methods based on complex CNN architectures have demonstrated exceptional performance in OCTA angiographic analysis. Techniques like multi-scale retinal vessel segmentation, which integrates vascular connectivity modules within CNNs, enable more precise analysis[33].

Vessel segmentation: Vessel segmentation technology reached its burst period in 2022 (Strength: 2.26), aimed at precisely extracting vascular information from OCTA images. As a non-invasive imaging modality, OCTA reveals high-resolution retinal vasculature. Accurate and efficient retinal vessel segmentation is achieved by applying improved recursive ConvNeXt blocks to full-resolution convolutional networks. This technology holds significant clinical value for quantifying retinal vascular changes in various retinal and systemic diseases[19,34].

2) In-depth exploration of ocular vascular diseases

Choroidal neovascularization (CNV): CNV experienced its first major burst in 2015 (Strength: 3.68), establishing itself as a key disease area in OCTA research. OCTA can reliably diagnose myopic CNV in clinically suspected patients, whereas spectral-domain optical coherence tomography (SD-OCT) may not reliably establish a positive diagnosis of CNV[35]. Recent research, like the CNV-Net study involving 130 OCTA images from 101 treatment-naïve CNV patients, has developed AI-based algorithms to assess CNV activity[36].

Open angle glaucoma: Open-angle glaucoma gained attention starting in 2017 (Strength: 2.14), with evidence in 2022 (peak strength) solidifying OCTA's important role in glaucoma management. A close relationship exists between AI-assisted OCTA-derived FAZ parameters and the progression of visual field defects in open-angle glaucoma.

Macular degeneration: Research on macular degeneration continues to evolve. A 2023 update highlighted the application of OCTA in age-related macular degeneration studies, significantly enhancing our understanding of ocular microcirculation and its associated diseases[37].

3) Expansion of diagnostic and assessment capabilities

Visual acuity: A burst in visual acuity assessment occurred in 2019 (Strength: 2.19). AI enables the identification and grading of pathologies through OCTA image analysis, which is crucial for monitoring disease progression and treatment efficacy.

Abnormality detection: Abnormality detection began developing in 2015 (Strength: 1.86). AI facilitates the detection of retinal and choroidal anomalies *via* OCTA image analysis, playing a vital role in early diagnosis and treatment[38].

4) Comparison and integration of imaging technologies

Fluorescein angiography (FA) *vs* OCTA: While FA is still considered the gold standard for *in vivo* retinal vascular imaging, OCTA is a non-invasive, relatively rapid imaging modality that can be performed alongside conventional OCT[39]. Deep vascular plexus OCTA better identifies microaneurysms compared to superficial OCTA or FA, whereas the FAZ area appears larger on FA than on OCTA images of both vascular plexuses[40].

Studies indicate good agreement between FFA and OCTA in diagnosing retinal vascular diseases, with extensive research exploring OCTA's potential as an effective, non-invasive alternative to FFA. Ultra-widefield FA (UWFFA) allows assessment of peripheral retinal perfusion, while OCTA is non-invasive, rapidly acquired, and provides more detailed information on capillary perfusion[41].

Trend analysis: OCTA technology is evolving towards specialized vascular imaging, functionally complementing traditional OCT. Since 2015, DL techniques have iterated rapidly, significantly advancing capabilities in vessel segmentation, disease classification, and quantitative analysis. Clinical applications have expanded beyond pure technological development to the diagnosis of various fundus vascular diseases, including CNV, DR, glaucoma, and macular degeneration[42-43]. Concurrently, multi-modal integration has enhanced comprehensive analysis and monitoring performance. Future standardization within the field will be pivotal for the widespread clinical adoption of AI algorithms[28].

High-Impact Articles Numerous high-impact studies have emerged in this field, utilizing 3D OCTA angiography to provide crucial tools for the early diagnosis of diseases such as DR, glaucoma, and age-related macular degeneration. Early high-impact research on AI applications in OCTA primarily focused on technical optimization. Through algorithmic improvements, these efforts aimed to enhance vascular clarity, increase image resolution, and effectively remove projection artifacts. As the technology advanced, research emphasis gradually shifted from image quality enhancement to clinical applications. While demonstrating technological breakthroughs, these studies also reveal key challenges and limitations in current AI-OCTA applications.

1) Projection artifact removal algorithms: breakthroughs and challenges

Technical highlights: The projection-resolved OCTA algorithm developed by Campbell *et al*[2] distinguishes true flow signals from projection artifacts by identifying voxels with in-situ blood flow, significantly improving the depth resolution of retinal vascular layers. Zhang *et al*[44] further refined the PR algorithm, demonstrating its efficacy in suppressing projection artifacts from superficial vessels in deeper layers.

Limitations: However, these algorithms face significant technical challenges. The PR algorithm has high computational complexity, demands strict image quality and acquisition conditions, and performs unstably in images with low SNR or severe motion artifacts. Although Campbell *et al*'s[2] study showed excellent results in normal volunteers, its robustness under pathological conditions requires further validation. Furthermore, optimizing algorithm parameters often requires adjustments for specific devices and scanning protocols, hindering standardization for widespread clinical adoption.

Future directions: Future efforts should focus on developing more robust artifact removal algorithms adaptable to various imaging conditions and pathological states. Adaptive algorithms incorporating DL hold promise for overcoming the limitations of current rule-based approaches.

2) Automated vascular analysis: enhanced accuracy and the clinical validation gap

Technical highlights: The microvascular density and morphology quantification method developed by Kim *et al*[14] objectively assesses vascular changes in DR using multidimensional parameters, demonstrating good reproducibility. The automated quantification algorithm by Hwang *et al*[15] achieved 100% sensitivity and specificity in distinguishing DR patients from normal controls.

Limitations: A major limitation of these studies is their relatively small sample sizes and lack of multi-center validation. Kim *et al*'s[14] study included only 84 DR eyes and 14 healthy eyes, while Hwang *et al*'s[15] sample was even more limited (12 cases each). Results from such small-scale studies are often at risk of overfitting, and their excellent performance metrics may not be replicable in large-scale clinical applications. Additionally, algorithm performance is highly dependent on image quality; variations commonly encountered in real-world clinical settings can significantly impact their efficacy.

Future directions: Large-scale, multi-center validation studies are needed to evaluate algorithm performance in real clinical environments. Simultaneously, more robust algorithms capable of handling low-quality images and providing uncertainty quantification should be developed.

3) Choroidal imaging technology: innovative methods and standardization challenges

Technical highlights: The choroidal capillary flow void quantification strategy proposed by Zhang *et al*[17] significantly improved measurement accuracy through signal compensation. This method provides a new technical means for the quantitative assessment of choroidal diseases.

Limitations: Choroidal imaging technology faces major challenges, including significant variations between devices, a lack of unified standardization protocols, pronounced individual differences in choroidal structure making normal value ranges difficult to define, and increased data processing complexity from signal compensation algorithms which may introduce new systematic errors. Furthermore, validation of this study was primarily focused on healthy populations; its performance under pathological conditions requires further investigation.

Future directions: Establishing standardized choroidal OCTA imaging and analysis protocols, developing universal algorithms applicable to different devices, and creating normal value databases based on large samples are essential future steps.

4) Multimodal DL: superior performance and insufficient interpretability

Technical highlights: The feature-level fusion multimodal DL model developed by Jin *et al*[4] achieved 95.5% accuracy in identifying CNV activity. The OCTA-Net model by Ma *et al*[19] outperformed traditional methods in vessel segmentation tasks.

Limitations: The main issues with DL models include: 1) Poor interpretability: The model decision-making process lacks transparency, hindering trust among clinicians; 2) Strong data dependence: They require large amounts of high-quality annotated data, which is costly to obtain for medical images; 3) Limited generalization ability: Performance often degrades significantly outside the training data distribution; 4) High technical barrier: Clinical application requires specialized AI technical support.

Although the ROSE dataset constructed by Ma *et al*[19] filled a gap in the field, its scale of 229 images remains limited for DL model requirements. While the multimodal model by Jin *et al*[4] demonstrates excellent performance, its complex architecture increases the difficulty of deployment and maintenance.

Present Limitations and Future Opportunities Through bibliometric methods, we explored the hotspots, trends, and technological advances within high-impact articles in this field. Concurrently, these studies reveal current research shortcomings and highlight potential future directions.

While bibliometric analysis offers significant advantages in revealing disciplinary structures and research trends, its limitations cannot be overlooked. This study was based on English-language articles indexed in the Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) under the Ophthalmology category in the WoSCC. This selection criterion may have excluded important studies on AI applications in OCTA, particularly those published in non-English journals or conference papers, preprints, and clinical reports not covered by SCIE/SSCI. Such literature often contains significant advancements in algorithm innovation, technical validation, or clinical application, and its absence may affect the representativeness and comprehensiveness of the research clustering results.

Furthermore, bibliometric methods focus on quantitative indicators, such as citation frequency and publication count, making it difficult to fully capture the qualitative impact of AI in OCTA applications—for instance, algorithm reliability, clinical applicability, and actual changes to diagnostic and treatment paradigms. Notably, the "citation lag" phenomenon particularly affects emerging and rapidly evolving research directions like AI-OCTA. Many innovative studies, such as those on AI-based vascular quantification, automated lesion detection (*e.g.*, for DR or glaucoma), and hemodynamic parameter prediction, possess significant academic and clinical potential. However, their true impact is not yet fully reflected in citation data due to their recent publication dates[45].

It is especially important to note that the application of AI in OCTA image analysis is in a phase of rapid development. Novel model architectures (*e.g.*, transformer), the application of Generative Adversarial Networks (GANs) for image enhancement, and multimodal fusion diagnostics are continuously emerging, demonstrating potential value in areas such as image quality enhancement, data augmentation, and diagnostic generalizability. Due to their recent inception, these cutting-edge contributions are likely underestimated in the current bibliometric analysis.

Limitations This study is subject to several limitations. First, it specifically focused on articles published between 2015, marking the clinical introduction of AI in ophthalmic OCTA, and 2024. This scope necessarily excludes ongoing, unpublished research, which may limit the breadth and implications of our findings. Second, our analysis was restricted to English-language articles within the WoSCC academic database. Consequently, relevant studies published in other languages or databases might have been overlooked, considering the practical difficulties in merging and analyzing literature from disparate sources[46]. Finally, despite a careful review and analysis of all 237 articles included in this study, the possibility of inherent researcher bias during the investigation process cannot be entirely eliminated.

Systemic Challenges and Future Development Trends

The current research field of AI applications in OCTA faces multiple systemic challenges: low standardization hinders the comparability and generalizability of results across studies; most research remains at the technical validation stage, lacking large-scale prospective clinical trial validation; the cost-effectiveness of implementing AI-OCTA systems in clinical practice has not been fully assessed; and regulatory approval standards and processes for AI medical devices are still evolving.

Addressing these challenges, future development is expected to follow these trends: integrated AI analysis platforms for multimodal imaging (OCT, OCTA, fundus photography, FA) will become mainstream; the application of federated learning techniques will address medical data privacy concerns, enabling multi-center collaborative model training[47]; the development of lightweight models will support edge computing deployment, adapting to resource-constrained clinical environments; personalized medicine integrating multi-dimensional data such as genomics and clinical history will be gradually realized[19]; real-time AI monitoring systems capable of continuously tracking disease progression and treatment response will be developed; and advances in explainable AI will improve the clinical acceptance of DL models.

Despite significant current progress, an important gap remains between research findings and clinical practice. Deep collaboration between industry, academia, research institutions, and medical professionals is required to establish robust standardized systems and validation frameworks[48] to fully realize the clinical value of AI-OCTA technology[49].

This study systematically reviewed 237 publications retrieved from the WoSCC, revealing a rapid growth in research output since the initial integration of AI with OCTA in 2015, with annual publications stabilizing at over 30 articles in recent years. China and the United States are the leading contributors in terms of publication volume and academic influence, as reflected by H-index values. Key institutions such as Oregon Health Science University (United States) and Sun Yat-sen University (China) have played pivotal roles in advancing this field.

The keyword analysis and burst detection identified several evolving research themes, including advances in algorithms (*e.g.*, CNN-based models, vessel segmentation), application in retinal and choroidal diseases (*e.g.*, DR, glaucoma, CNV), and the integration of multimodal imaging. The analysis of highly cited articles further highlighted both the technical advances—such as projection-resolved OCTA, automated quantification of capillary non-perfusion, and multimodal DL—and persistent challenges including limited sample sizes, algorithm generalizability, interpretability of AI models, and the need for standardized imaging and evaluation protocols.

In conclusion, the convergence of AI and OCTA has significantly enhanced the capability for non-invasive, depth-resolved visualization and quantification of retinal and choroidal vasculature, offering substantial potential for improving the diagnosis and management of major ocular diseases. However, future efforts should focus on developing more robust and interpretable AI models, validating algorithms in large multi-center clinical settings, establishing standardized imaging and analysis protocols, and promoting collaborative research across disciplines and regions to facilitate the translation of AI-OCTA technologies into routine clinical practice.

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