Optical coherence tomography imaging of the peripheral retina

Niveditha Pattathil[1,2], Netan Choudhry[1,2,3]

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Abstract:

This review critically assesses the applicability of retinal periphery imaging technology, scrutinizing its practical limitations and potential advancements within ophthalmology. It underscores the significant costs and the need to evaluate the clinical utility of optical coherence tomography (OCT) and OCT angiography devices. It emphasizes how clinicians should consider their practice-specific use-cases while investing in devices with capabilities like ultra-widefield OCT, autofluorescence imaging, and angiography. The paper also highlights the challenges associated with image acquisition, such as artifact management and patient cooperation for extended fixation periods. This review outlines the utility of these modalities in various retinal pathologies, as well as their contribution to telemedicine and personalized care, facilitated by artificial intelligence for improved image processing, quantification, and interpretation. These techniques potentially offer a more comprehensive understanding of peripheral retinal conditions and associated pathologies, thus influencing clinical decision-making, particularly in remote regions with limited specialist access.

Keywords:

Imaging, ocular imaging, ophthalmology, optical coherence tomography, peripheral retina, periphery, retina, retinal imaging

[1]Vitreous Retina Macula Specialists of Toronto, [2]Octane Imaging Lab, [3]Department of Ophthalmology and Vision Sciences, University of Toronto, Toronto, Ontario, Canada

Address for correspondence:
Dr. Netan Choudhry, Vitreous Retina Macula Specialists of Toronto, 3280, Bloor Street West, Suite 310, Toronto M8X 3X3, Ontario, Canada.
E-mail: netan.choudhry@vrmto.com

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Introduction

Optical coherence tomography (OCT) has revolutionized ophthalmology since its inception in the early 1990s. It has become an indispensable tool for diagnosing, monitoring, and managing a wide range of retinal conditions. While the macula has traditionally been the primary focus of OCT imaging, advancements in imaging technology have led to increasing interest in the peripheral retina. Through continued advancements, OCT technology has given rise to widefield (WF) and ultra-WF (UWF) imaging techniques, which are capable of capturing an expansive field of view up to 220°. The capacity to image the peripheral retina has broadened the clinical applications of OCT significantly.

In 2019, the International WF Imaging Study Group outlined that WF imaging encapsulates a view range of roughly 60°–100°, capturing the retina's midperiphery to the posterior boundary of the vortex vein ampulla.[1] UWF imaging involves capturing images of the retina's far periphery, extending from the anterior edge of the vortex vein ampulla and beyond, resulting in a field of view of 110°–220°. These definitions are depicted in Figure 1.

It was a formidable challenge to image the far periphery of the retina with OCT until recently. The introduction of UWF imaging capabilities by the Heidelberg Spectralis HRA-OCT (from Heidelberg Engineering USA) using a steering technique, the Silverstone (by Optos PLC Edinburgh), the Plex Elite 9000 (from Zeiss, Oberkochen, Germany), and the Xephilio OCT-S1 (by Canon Medical Systems, Japan) has made this possible. In addition, Toward Pi has developed a swept-source OCT machine that provides an 81° ×68° field of view and an A-scan speed of 400 kHz.[2] In this review, we discuss the application of OCT for various conditions in the retinal periphery.

Retinal Detachment

OCT holds significant potential in diagnosing, monitoring, and managing retinal detachments in the far retinal periphery. Important microstructural retinal details, such as photoreceptor integrity

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and subretinal fluid resolution, are challenging to discern through clinical examination or UWF fundus photography. In contrast, UWF-OCT garners vital data both pre- and postretinal detachment treatment. In a study by Drs. Lee and Muni, longitudinal findings obtained by the Optos Silverstone offered insights into the retinal response to treatments, including laser retinopexy and cryopexy.[3] A novel observation of choroid and sclera separation was detected in the 1st week postcryopexy using OCT, a phenomenon not previously described.[3] OCT also reaffirmed observations made in past histological analyses, which included coagulative necrosis and retinal splitting postlaser retinopexy, along with destruction of retinal layers and RPE separation postcryopexy. An additional *post hoc* analysis of the PIVOT trial, which compared outcomes of vitrectomy and pneumatic retinopexy in treating retinal detachment, examined postoperative outer retinal folds using OCT.[4] The analysis discovered that these outer retinal folds were linked with poorer visual outcomes after a year, and that patients undergoing vitrectomy were more likely to have postoperative outer retinal folds.[4] Despite these observations being restricted to OCT imaging of the posterior pole, they suggest that UWF-OCT could offer supplemental information on retinal healing postretinal detachment repair in the mid-far periphery, where retinal breaks typically occur.

UWF-OCT serves a critical role in distinguishing between retinal detachments and degenerative retinoschisis or schisis detachments, particularly in instances where clinical indicators may be unclear [Figure 2].[5-7] Clinically diagnosed retinoschisis cases have occasionally demonstrated retinal detachment when observed through OCT, and vice versa.[8,9] In 2014, Stehouwer *et al*. at the University of Amsterdam's Academic Medical Centre identified that out of 18 presumptive retinoschisis cases, three displayed retinal detachment upon peripheral OCT examination; another study reported a similar finding in six out of 53 eyes.[6,9] This differentiation is paramount since the treatment approaches for these two conditions vary considerably. Retinoschisis is often a harmless condition that may not necessitate intervention, but retinal holes, an indication for intervention in retinoschisis, can also be detected on peripheral OCT.[10] These preliminary studies provide support that UWF-OCT can provide valuable insights for diagnosing and managing retinal detachment in the far periphery.

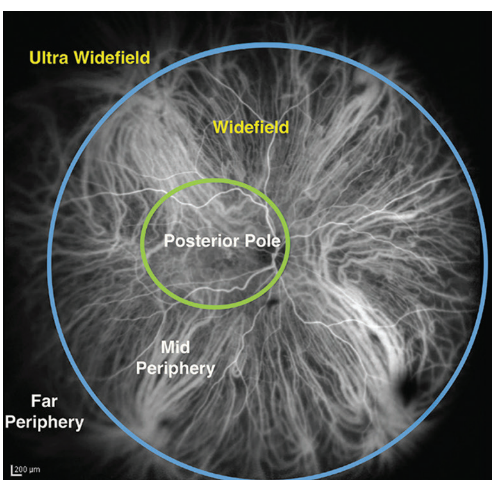

Figure 1: An illustrative representation from the International Widefield Imaging Study Group that delineates the definitions of widefield and ultra-widefield in relation to the vortex vein ampullae. The figure explicitly marks the boundaries for the posterior pole, the mid-periphery, and the far periphery

Pathologic Myopia

OCT has been instrumental in exploring and characterizing features of high myopia, such as posterior staphylomas, dome-shaped macula (DSM), and choroidal thickness, contributing valuable knowledge to the classification and pathophysiology of these conditions. Despite DSM initially being classified as a type of staphyloma, UWF-OCT has revealed distinct pathophysiological characteristics unique to the condition.[11] DSM is defined by an inward bulge of at least 50 μm, involving both the retinal pigment epithelium and Bruch's membrane [Figure 3]. UWF-OCT findings also indicate that DSM correlates with an anomalous curvature of the posterior sclera.[11]

UWF-OCT has proven helpful in differentiating between wide and narrow staphylomas, offering a quantitative evaluation of these staphylomas.[12,13] Dr. Nakao *et al*. from Tokyo discovered a correlation between higher axial lengths and sharper staphyloma edges in eyes with narrow staphylomas. This correlation was not observed in wide staphylomas, thereby distinguishing these two categories of staphylomas.[12] In a different study, Dr. Shinohara *et al*. from Tokyo suggested that UWF-OCT could be more efficient in detecting staphylomas

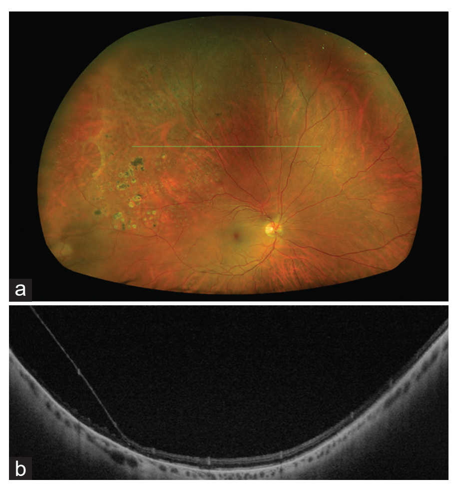

Figure 2: Degenerative retinoschisis captured with the Silverstone optical coherence tomography (OCT) device (Optos, Edinburgh). (a) The pseudocolor image shows an area of retinoschisis in the superotemporal quadrant, indicated by the transparency of the inner retinal layers and a reticular pattern of schisis cavities. Visible laser scars encircle the area of schisis. (b) The swept source-OCT structural B-scan showcases the peripheral retina over the area of retinoschisis, demonstrating a distinct separation between the inner and outer retina, indicative of retinoschisis

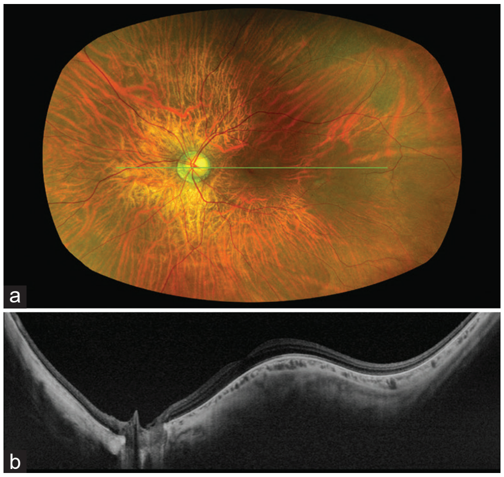

Figure 3: Image of dome-shaped macula in the left eye taken by the Silverstone optical coherence tomography (OCT) (Optos, Edinburgh). (a) Pseudocolor depiction. (b) A 24-mm swept source-OCT structural B-scan traversing the optic nerve and fovea, illustrating the inward protrusion of the dome-shaped macula

than 3D-MRI, although their results did not reach statistical significance.[14] The detection and monitoring of staphylomas facilitated by UWF-OCT can provide crucial information about their progression and the risk of potential complications for patients.

Peripheral Retinal Degeneration

UWF-OCT can facilitate clear characterization and documentation of peripheral pathologies, such as lattice degeneration, retinal tufts, retinal tears, retinal holes, and paving-stone degeneration. The practicality of obtaining clinically valuable OCT of these pathologies has been demonstrated in multiple studies.[5,15-17] In 2016, Dr. Choudhry *et al*. utilized a steering technique to capture UWF spectral-domain OCT (SD-OCT) of the peripheral retina, describing the structural characteristics of these peripheral pathologies.[17] In this project, nineteen peripheral retinal features were identified through near-infrared scanning laser ophthalmoscopy images and SD-OCT, which were then matched to UWF color photographs.[17] This included vortex vein, congenital hypertrophy of the retinalpigment epithelium, pars plana, ora serrata pearl, typical cystoid degeneration, cystic retinal tuft, meridional fold, lattice and cobblestone degeneration, retinal hole, retinal tear, rhegmatogenous retinal detachment, typical degenerative senile retinoschisis, peripheral laser coagulation scars, ora tooth, cryopexy scars, bone spicules, white without pressure, and peripheral drusen.[17] The results revealed that SD-OCT could distinguish structural aspects of all peripheral findings.[17] For example, dilated hyporeflective tubular structures within the choroid were seen in the vortex vein, and hyporeflective intraretinal spaces were visible in multiple entities like cystic retinal tufts and retinal holes.[17] Furthermore, the vitreoretinal interface, often consisting of lamellae-like structures of the condensed cortical vitreous near or adherent to the neural retina, was clearly visible in most peripheral findings, affirming its correlation with many low-risk and vision-threatening pathologies.[17]

High-quality and clinically relevant SS-OCT images of the mid and far periphery can also be acquired without the need for montage or steering, as demonstrated using a novel scanning laser ophthalmoscope-UWF imaging device with integrated full-field OCT capabilities (Optos Silverstone; Optos PLC; Dunfermline, UK).[5] Dr. Kovacs *et al*. from New York reported that UWF-OCT imaging contributed meaningful clinical information that influenced management in 38% of the eyes imaged.[15] Dr. Stanga *et al*. utilized a novel UWF-OCT device in a retrospective study to visualize peripheral retinal pathology, correlating the findings with histological photomicrographs depicting the retina and vitreous attachments.[16] They discovered that, aside from microstructural details in the peripheral retina, OCT can also provide essential data regarding the vitreoretinal interface and the presence or absence of traction. Such distinctions in pathology and related characteristics can help prevent invasive management by excluding tears and holes in cases of vitreoretinal tufts, or by ruling out vitreoretinal traction in instances of lattice degeneration.[16]

Choroidal Pathology

OCT can be instrumental in distinguishing and diagnosing peripheral choroidal melanoma and choroidal nevi.[5] A key risk factor for the transformation of nevi into melanoma is the presence of subretinal fluid, which can be detected by OCT.[18] In cases of peripheral lesions, UWF-OCT enables both the detection of subretinal fluid and the estimation of lesion size.

Peripheral exudative hemorrhagic chorioretinopathy (PEHCR) lesions can mimic the appearance of choroidal melanoma, making proper characterization critical. Since these lesions are predominantly found in the retinal periphery (89% situated between the equator and ora serrata), peripheral OCT proves highly valuable.[19] Features like retinal exudation and RPE atrophy can help distinguish PEHCR from choroidal melanoma.[19] A retrospective study of 50 eyes with PEHCR lesions identified the presence of subretinal fluid on OCT as a risk factor for future macular involvement, intravitreal bleeding, and vision loss.[19] Lesions extending beyond three clock hours were also indicative of high-risk eyes.[19] A subgroup analysis from this study suggested that treating these high-risk eyes could help prevent macular involvement.[19] Further investigations using peripheral OCT can help to refine treatment recommendations for patients.

Dr. Xuan *et al*. explored a series of choroidal osteomas using a novel SS-OCT and OCT angiography (OCTA) technology by Toward Pi. This technology provides an ultra-high-resolution 120° field of view, capturing the entire tumor.[2] The system was able to detect choroidal neovascularization, which can be challenging with traditional imaging methods due to the dense nature of the mass and RPE changes.[2]

Applications of Ultra-widefield-optical Coherence Tomography in Pediatric Populations

Imaging in pediatric ophthalmology poses its unique set of challenges, particularly concerning patient positioning and fixation. Much like in adults, detecting subtle anatomical alterations with OCT imaging can prove invaluable in numerous conditions. Handheld OCT devices are one way to address these difficulties. Dr. Nguyen *et al*. demonstrated the effectiveness of a handheld SS-OCT device in nonsedated pediatric patients in neonatal ICUs, as well as in sedated patients in operating rooms.[20,21] Their WF prototype device boasts a 105° field of view and offers real-time en-face OCT images.[20,21]

For pediatric conditions such as retinopathy of prematurity (ROP), this technology could be pivotal in screening, monitoring, and even offering new pathophysiological insights.[20] WF-OCT allows physicians to determine the area of vascularized retina and the border between vascular and avascular zones.[20] The device enables accurate detection and characterization of neovascularization, particularly extraretinal neovascularization, which plays a significant role in ROP classification.[20] OCT findings like changes in the vitreoretinal interface can also inform management decisions in various pathologies. In cases of pediatric retinal detachments, OCT can differentiate between tractional and exudative detachments.[21] OCT can also help track subtle changes over time.

WF-OCT also proves useful in retinoblastoma cases as it can detect tumors and even subclinical-sized tumors in the retinal periphery.[21,22] The efficacy of OCT in identifying subclinical retinoblastoma tumors smaller than 400 µm, undetectable by ophthalmoscopy, is well-established.[22-24] Dr. Gaillard *et al*. from the University of Lausanne, Switzerland, shared a case series of 16 subclinical recurrent tumors detected using a commercial handheld OCT device.[23] Even without WF capabilities, this device underscored the value of OCT in monitoring patients with retinoblastoma. This could enable earlier detection of recurrences, potentially significantly impacting survival and visual outcomes. Beyond early detection, OCT can offer crucial clinical details about the tumor, thus guiding management decisions. The future development of pediatric WF-OCTA could be incredibly beneficial in detecting and managing intraocular tumors.

UW-optical Coherence Tomography Angiography

The evolution of OCT has paved the way for noncontrast angiography capabilities [Figure 4]. While OCTA is not yet in widespread use, it can serve as a noninvasive, safe, and easily repeatable alternative to dye-based angiography techniques involving fluorescein or indocyanine green.[25] One of the key advantages of OCTA is its ability to generate high-resolution, depth-resolved angiographic images that can be associated with flow overlay B scans.[25] Early OCTA technology was hampered by its restricted field of view, but advancements have enabled wider field OCTA.[26] The International WF Imaging Study Group proposed definitions for WF and UWF OCTA in 2019, comparable to OCT imaging standards. According to these standards, WF OCTA should capture all four quadrants of the retina, including the posterior edge of the vortex veins, while UWF OCTA should extend imaging beyond the anterior edge of the vortex veins. If all four quadrants are not captured, the imaging should be labeled as asymmetric WF or asymmetric UWF OCTA.[1]

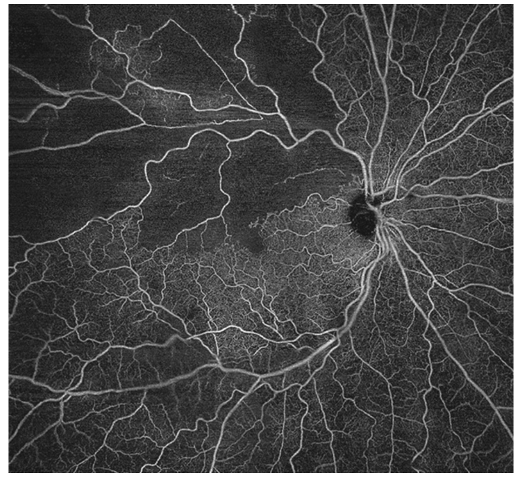

Figure 4: A branch retinal vein occlusion in the right eye was documented using the Plex Elite 9000 system (Zeiss, Oberkochen, Germany). The en face swept source-optical coherence tomography angiography montage, with a dimension of 24 mm × 24 mm, showcases regions of non-perfusion and disruption in the foveal avascular zone

Studies have discovered significant clinical value in the use of WF OCTA for assessing retinal vein occlusions. In two distinct studies involving 43 and 26 patients respectively, it was observed that the detection and quantification of retinal nonperfusion areas with OCTA align closely with FA results.[27,28] Given that the peripheral retina often displays larger areas of nonperfusion, WF OCTA could provide a more precise estimation of the extent of nonperfusion.[28] In the first of these studies, Dr. Glacet-Bernard *et al*. in France demonstrated that using a 60° field of view, as opposed to a 12× 12 40° field of view, disclosed nonperfusion in an additional 30% of eyes.[27]

Another study led by Dr. Huemer *et al*. at Moorfields used OCTA to identify distinct neovascularization patterns in RVO: a sea-fan type and a nodular type.[29] They observed a propensity for nodular neovascularization to be misdiagnosed as retinal hemorrhage in clinical exams, underscoring the vital role of OCTA in these patients.[29]

In a retrospective study involving 54 patients, Dr. Tang *et al*. from Shanghai found that the depth-resolved nature of OCTA enables the evaluation of the periarterial capillary-free zone (paCFZ), an avascular area surrounding retinal arteries, in the superficial capillary plexus.[30] This has been explored as a potential biomarker in RVO and has been demonstrated to be larger in eyes affected by branch RVO.[30] The researchers examined this measure pre- and post-antivascular endothelial growth factor (VEGF) therapy and noticed an improvement in paCFZ with treatment.[30] Furthermore, Dr. Tang *et al*.'s group found that a lower ratio of paCFZ to artery area tends to predict better visual outcomes at 12 months following anti-VEGF injections.[30]

Despite not being broadly used at present, UWF-OCT has been shown to hold considerable value in the detection of pathologies such as subclinical retinoblastoma and the diagnosis of clinically ambiguous presentations like retinoschisis. It can also play a role in monitoring disease progression, such as myopic staphylomas, and aid in making treatment decisions by providing clear information about structural anatomy, like the vitreoretinal interface.

Conclusion

Despite the significant advancements in technology, there are numerous constraints to the practical application of technology for imaging of the retinal periphery. A primary restriction is the substantial cost for devices with WF or UWF capabilities. Given the considerable investment needed, it is crucial to consider the clinical utility of OCT and OCTA, along with the other functionalities of these machines. For instance, some devices offer UWF OCT capabilities but can also capture UWF pseudocolor photography, autofluorescence imaging, and fluorescein and indocyanine green angiography. Each clinician must assess the usefulness of these modalities in their specific practice. Further, image acquisition presents certain challenges, such as managing the numerous artifacts associated with wider field imaging, including eyelid, inversion, and motion artifacts.

Most scans rely on the patient's ability to maintain fixation for extended periods, particularly with OCTA, as it requires the collection of more information. As technology evolves, the speed of data capture increases, making it more practical in ophthalmology. Many commercial devices, including the Optos Silverstone, the Plex Elite 9000, and the Xephilio OCT-S1, offer an acquisition speed of 100 kHz or higher. However, the newer Toward Pi device and the prototype pediatric handheld device both boast an acquisition speed of 400 kHz.[2,5,16,20,27]

Looking forward, as platforms capable of imaging the periphery become more widely accessible, these imaging modalities have the potential to significantly contribute to the expanding field of telemedicine. Moreover, the rapidly developing field of artificial intelligence applied to OCT and OCTA image processing, quantification, and interpretation could enhance clinical management and prognosis for patients with central and peripheral retinal diseases, heralding a new era of personalized medicine.

In conclusion, OCT imaging of the retinal periphery is feasible with current commercially available devices and provides detailed anatomical data of the peripheral retina, including benign and pathologic entities, that have not been previously imaged. This imaging technique may enhance our structural comprehension of these entities and their potential associated macular and systemic pathologies, and could influence decision-making in clinical practice, especially in areas with tele-ophthalmological capabilities but limited access to retinal specialists.

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Conflicts of interest

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