Saudi Journal of Medicine and Public Health

https://saudijmph.com/index.php/pub

Recent Advances and Innovations in Optical Coherence Tomography: Transforming Diagnosis and Management of Retinal Diseases

Salah Hamoud Almotairi*

Ministry of National Guard Health Affairs, Saudi Arabia

Abstract

Background: Optical coherence tomography (OCT) has revolutionized the field of ophthalmology since its introduction in 1991, providing high-resolution imaging of retinal and choroidal structures. This non-invasive imaging technique has become integral in diagnosing and managing various retinal diseases, including neovascular age-related macular degeneration (AMD) and central serous chorioretinopathy (CSCR).

Methods: This review synthesizes recent advancements in OCT technology and methodologies, categorizing them into clinical applications, scientific developments, and technological innovations. The review covers various OCT modalities, including time-domain OCT, spectral-domain OCT, swept-source OCT, visible light OCT, adaptive optics OCT, and polarization-sensitive OCT, as well as portable and intraoperative OCT devices.

Results: The findings demonstrate that advancements in OCT technologies have significantly enhanced the detection and monitoring of retinal diseases. Key developments include improved imaging resolution, speed, and the ability to visualize previously obscured choroidal structures. Innovations such as home-based OCT devices and intraoperative OCT (iOCT) have further improved patient care, allowing for real-time imaging during surgical procedures and facilitating daily monitoring for at-risk individuals.

Conclusion: The evolution of OCT technology continues to enhance our understanding of retinal pathologies and improve clinical outcomes. The integration of advanced imaging techniques promises to refine diagnostic accuracy and therapeutic interventions, heralding a new era in the management of retinal diseases. Future research should focus on the widespread implementation of these technologies in clinical settings to maximize their potential benefits.

Keywords: Optical Coherence Tomography, Retinal Diseases, Imaging Technology, Neovascular AMD, Intraoperative OCT

1. Introduction

Optical coherence tomography (OCT) is a scanning technique that has transformed ophthalmology. OCT, as a non-invasive imaging modality, employs light and light interference to provide high-resolution, cross-sectional tomographic data of biological tissues, including the retina and choroid, at the micron scale. This technique was first presented in 1991 and has been swiftly integrated into surgical procedures in retinal care [1]. Diagnostic assessments for retinal and choroidal illnesses are often performed using OCT, involving neovascular age-related macular degeneration (AMD), central serous chorioretinopathy (CSCR), vascular retinal disorders, and other vitreoretinal disorders [2-5]. OCT biomarkers have been crucial in enhancing the comprehension and surveillance of chorioretinal disease status; these biomarkers encompass central macular thickness, subretinal/intraretinal fluid, neurosensory detachment height, subfoveal choroidal thickness, choroidal vessel diameter, and choroidal vascularity index [6-8]. Recently, efforts to enhance the design of early interventional clinical trials for non-neovascular AMD have identified several structural OCT biomarkers, including intraretinal hyperreflective foci, subretinal drusenoid deposits, drusen with hyporeflective cores, and high central drusen volume, as indicators of elevated risk for progression to advanced stages of AMD [9-12].

Time-domain optical coherence tomography (TD-OCT) was the first OCT technology presented to the field of clinical ophthalmology [13,14]. In comparison to existing systems, TD-OCT exhibited a comparatively sluggish scanning velocity of 400 axial scans (A-scans) per second. Accelerated advancements enabled enhanced axial resolution and scanning velocity to improve the assessment of the retina and choroid. For instance, spectral-domain (SD) OCT and swept-source (SS) OCT were developed subsequent to TD-OCT, with acquisition rates varying from 27,000 A-scans per second to 100,000 A-scans per second. The axial resolution improved from around 10 µm with TD-OCT to 2 µm with both SD-OCT and SS-OCT [13].

Advancements in OCT imaging have enhanced the detection and diagnosis of retinal diseases, often resulting in early therapies and the preservation of vision. Optical coherence tomography (OCT) and optical coherence tomography angiography (OCTA) of the retina effectively visualize and measure the retinal structure and microvasculature [15-20]. Furthermore, improved penetration reveals features of the choroidal vasculature that were not observable with TD-OCT. Researchers have mapped the penetration locations of small posterior ciliary arteries, and in eyes with a thin choroid, particularly in cases

*Corresponding author e-mail: sh.almotairi@gmail.com.; (Salah Hamoud Almotairi).

Received date: 01 October 2024, Revised date: 15 November 2024 Accepted date: 25 Dec 2024

of extreme myopia, the scleral vessels, posterior episcleral tissue, along Tenon's layer may also be identified [15]. Their uses extend beyond the realm of the retina. OCT and OCTA imaging have significantly transformed glaucoma as well as neuro-ophthalmology by facilitating the early detection of neurodegenerative illnesses, such as Alzheimer's disease and perhaps preclinical Alzheimer's [21-24]. Consequently, advancements in OCT technology have promise in several domains of ophthalmology and neurology for the earlier identification of illnesses, which may enhance the formulation of preliminary intervention clinical studies [25,26]. The extensive applicability and developing nature of OCTA innovation, including all OCTA developments is beyond the scope of this article. This study reviews advancements in OCT technology and procedures, spanning wide-field OCT, visible light OCT, adaptive optics OCT, polarization-sensitive OCT, high-resolution OCT, intraoperative OCT, and portable OCT [27-30]. The recent improvements in this imaging technique will enhance various vital elements of retinal treatment, including imaging acquisition speeds, field of view, mobility, access, and intraoperative control [31,32].

2. Recent Developments in OCT Innovation and Methodologies

Numerous strategies assist in overcoming existing limitations of this therapeutically valuable imaging modality. We categorize these achievements into three groups: developing clinical applications, fundamental scientific and research developments, and recent technological innovations. As these advancements persist, these technologies are expected to become more prevalent and used in healthcare environments.

3. Visible Light Optical Coherence Tomography (Vis-OCT)

Visible light optical coherence tomography (vis-OCT) uses visible light for illumination instead of near-infrared (NIR) light to acquire pictures [33]. This approach enhances the resolution of retinal biological characteristics by using shorter illuminating wavelengths [33]. Zhang et al. recently documented the use of vis-OCT to measure subcellular reflectance components to the outermost ocular hyperreflective zones (Figure 1) [18]. Vis-OCT was first delineated by Povazay et al. [17]. This group used a sub-15 fs Ti:sapphire laser as well as photonic crystal fibers to exhibit light emission inside the 535 nm to 700 nm area of the electromagnetic spectrum, enhancing axial resolution to less than 2 microns. This was accomplished with a reduced bandwidth relative to contemporary OCT lighting techniques like NIR. Although the majority of OCT devices now use light in the near-infrared spectrum due to its tissue penetration capabilities and lower cost, there is a growing interest in the application of vis-OCT [17]. The primary applications of vis-OCT are now in blood vessel oximetry and the imaging of healthy eyes [34,35].

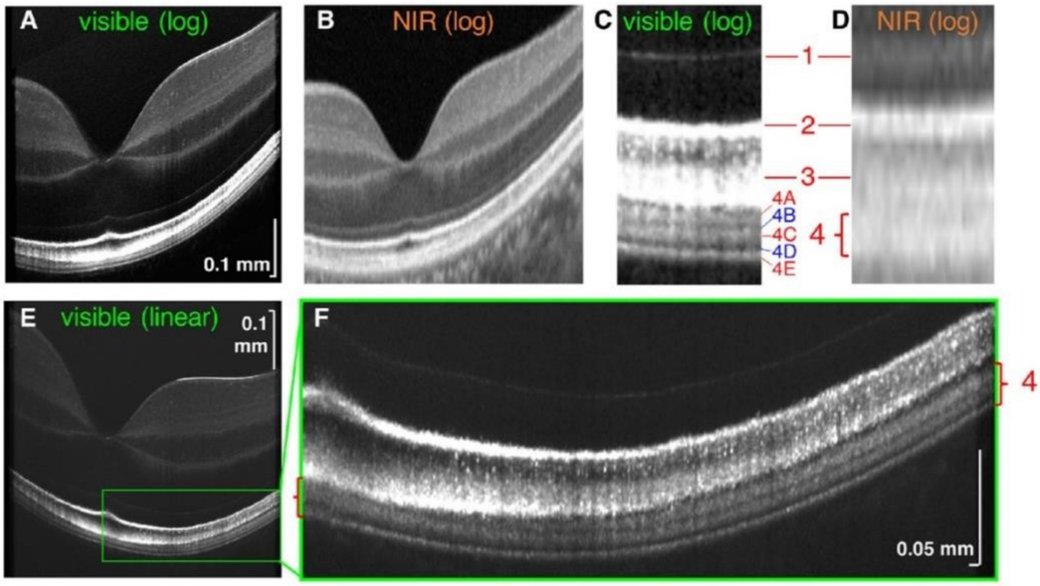

Figure 1. Visible light optical coherence tomography (vis-OCT) imaging. Comparative analysis of vis-OCT.

Vis-OCT devices primarily depend on supercontinuum lasers, which inherently produce relative intensity noise that limits their clinical use. Relative intensity noise may be mitigated by extending the camera's exposure period, which exposes patients to excessive light, thereby affecting their eye motions and impairing picture quality acquisition. Rubinoff et al. introduced a balanced-detection vis-OCT system using two spectrometers to mitigate relative intensity noise, which was evaluated in an artificial retina and in vivo in human subjects [36]. The study's results suggested less necessity of introducing patients to excessive light when using balanced detection. The study's findings are distinctive since their methodology exhibits greater degrees of perceived noise reduction compared to prior configurations.

Speckle noise, often resulting from the dispersion of light waves, may adversely affect picture interpretation in vis-OCT. Multi-volume picture restoration and modification of B-scans were proposed to mitigate speckle noise [37,38]. The consequent enhancement in vis-OCT picture quality improved the visibility of neurons across all layers of the rat retina. It enables vis-OCT to compete with the functionalities of NIR AO-OCT. Specifically, vis-OCT can now see structures like the inner plexiform layer, retinal pigment epithelium, and Bruch's membrane [39]. Vis-OCT is constrained by depth-dependent dispersion, which adversely affects picture quality. Zhang et al. established that water wavenumber standardization obviates supplementary resampling procedures and rectifies dispersion [40].

4. Adaptive Optics in Optical Coherence Tomography

Adaptive optics (AO) was first devised to mitigate dynamic wave-front aberrations in astronomical imaging [41]. It has subsequently been determined to measure and eradicate high-order monochromatic distortions from light traversing ocular tissues, including the cornea and lens. These aberrations result in suboptimal lateral resolution in ocular imaging, hence limiting the therapeutic uses of several ophthalmic imaging techniques [42,43]. Adaptive optics (AO) systems consist of a wavefront sensor, often a Shack-Hartmann wavefront sensor, which detects distortions; a wavefront corrector, usually a deformable mirror, that changes its configuration to mitigate aberrations; and a controller that integrates these components (Figure 2) [44,45].

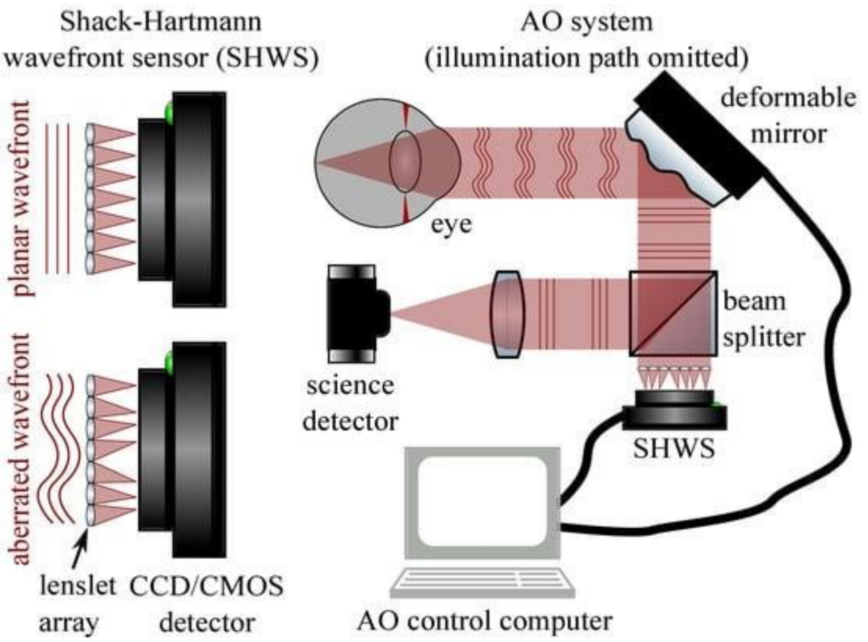

Figure 2. Schematic of an adaptive optics system using a Shack–Hartmann wavefront sensor (SHWS) as well as a deformable mirror. SHWS employs a diminutive lenslet array to sample a wavefront; displacements caused by aberrations may actuate a corrector.

The most significant aspect of AO in ophthalmology is its ability to image particular cells, including photoreceptors, in vivo [42,46,47]. AO achieves a lateral precision of 2 microns, representing a significant enhancement over the approximately 15-micron lateral precision of OCT [48]. Initially, adaptive optics (AO) was used with en-face imaging techniques to see individual rods and cones in two dimensions. When integrated with OCT, AO facilitates 3D scanning and the resolution of components like light receptors as well as the retinal pigment epithelium. Initiatives have been undertaken to enhance the field of view (FOV) of AO-OCT devices for imaging these cells, expanding the region from around 1 degree to 4 degrees by 4 degrees [49].

Computational adaptive optics (CAO) mitigates aberrations by altering the phase of optical coherence tomography (OCT) data in the spectrum domain and has been extensively researched in recent years. Although picture quality is sometimes compromised with CAO, it was developed to minimize the need for expensive hardware by rectifying distortions post-data acquisition [50,51]. The predominant CAO modality now is interferometric artificial aperture microscopy (ISAM), a computerized imaging method that improves depth-independent resolution [52]. ISAM requires little patient movement to provide excellent imaging quality. A stretched-pulse mode-locked laser illumination was evaluated to enhance the A-scan rate and mitigate the detrimental effects of ocular motion [53]. Boppart et al. developed the first model of computational adaptive optics (CAO) in polarization-sensitive optical coherence tomography (PS-OCT), which rectifies low-order abnormalities in ex vivo human tissues [54]. Proposed advancements have been made to enhance CAO distortion correction skills and picture quality [55]. CAO may optimize picture-collecting processes and facilitate cost reductions in the clinic but at the expense of image quality.

Sensorless Adaptive Optics (SAO) serves as an alternative to hardware-based Adaptive Optics Optical Coherence Tomography (AO-OCT), using the characteristics of pictures instead of a wavefront sensor to assess and rectify aberrations [56]. SAO optimization methods and approaches involve Zernike Mode Hill Climbing, stochastic parallel descent, and deep reinforcement learning, among others. SAO characteristics have been evaluated to a certain degree in CAO simulations as well [57-61]. Despite its introduction 15 years ago, AO-OCT is seldom used in ophthalmology hospitals owing to specific restrictions. Images obtained at high magnification are susceptible to blurred images and need continuous fixing [62]. This becomes progressively more challenging in eyes affected by AMD-related geographic atrophy and retinal dystrophies, such as cone dystrophy. Furthermore, inadequate mydriasis or the existence of any medium opacity substantially impacts picture quality [62]. Additional difficulties are to the exorbitant purchase cost, insufficient economic interest, the need for skilled personnel, and the necessity for substantial space to accommodate AO-OCT. Notwithstanding these constraints, researchers and clinicians may discern and expand the clinical applicability of AO-OCT in age-related macular degeneration, diabetic retinopathy, hereditary retinal dystrophies, and additional fields such as glaucoma.

5. Polarization-Sensitive Optical Coherence Tomography (PS-OCT)

Initially shown in 1992, PS-OCT operates by examining the polarization condition of backscattered light and quantifying refraction in the tissue specimen. Various tissues may alter the polarization status of the OCT light source [63]. Early PS-OCT methodologies relied on TD-OCT. Currently, PS is used in both SS-OCT and SD-OCT to visualize diverse ocular tissues, including the macula as well as peripheral retina [21,64,65]. A problem in the early detection of AMD is the identification of drusen; PS-OCT may segment the RPE and reveal drusen [66]. In several fiber-based PS-OCT configurations, the laser light is first polarized, after which the optical fiber is secured to maintain the polarization state. Subsequent alterations to the optical cable would impact the polarization state of the light source. A modified version of SS-based PS-OCT was evaluated, using a depolarizer as well as a polarizer to establish a model independent of input polarization, albeit this resulted in reduced sensitivity and significant loss of input light [67]. Another method reduces changes in the polarization state of the incoming light beam by employing a common-path interferometer alongside polarization-maintaining fibers to enhance the stability of the optical fiber [68].

PS-OCT adaptations including polarization-sensitive quantitative OCT (PS-QOCT). QOCT facilitates dispersion cancellation and determines the refraction coefficient of a medium, and when integrated with PS, enhances resolution relative to conventional techniques [69,70]. Sukharenko et al. recently shown the imaging and characterisation of a birefringent material with PS-QOCT, potentially applicable in the imaging of biological tissues [71].

PS-OCT has several prospective applications in both fundamental and medical ophthalmic research, especially in the automated division of retinal structures like the retinal pigment epithelium (RPE) [66]. Geographic atrophy, often seen in the dry variant of AMD, may be delineated using PS-OCT [21]. Fibrotic tissues, rich in collagen, exhibit significant birefringence, making them well-suited for imaging using PS-OCT. Schütze et al. showed that PS-OCT is effective for assessing RPE defects in choroidal neovascularization in eyes with neovascular AMD [72].

6. Home-Based Optical Coherence Tomography

Due to the characteristics of certain retinal disorders, regular monitoring via clinic visits and OCT imaging is essential for effective care [31]. Such trips may often be onerous, particularly for the senior demographic [73]. Notal Vision Home OCT, a home-based SD-OCT device, facilitates daily self-imaging for individuals susceptible to deteriorating retinal conditions. Research assessing this at-home, self-imaging OCT technique has shown strong concordance in retinal biomarkers with in-clinic OCT scans [31,32]. Liu et al. conducted a prospective, longitudinal research including 15 subjects using this technology, revealing an average everyday self-imaging rate of eighty percent [73]. Regular, almost daily observation of retinal as well as choroidal disorders may facilitate accurate treatment strategies. Artificial intelligence has been integrated with the Notal OCT Scanner to automate the detection of intra- as well as subretinal fluid [31,74]. Although this technique will persist in testing and research before general implementation, the capacity for near-daily OCT scans at home may aid in preventing vision loss for many individuals in the future.

7. Conclusions

OCT technology is advancing to overcome specific constraints identified in the existing standards of treatment for choroidal and retinal illnesses. Moreover, these advancements will facilitate fundamental scientific study and enhance our comprehension of the pathogenesis of chorioretinal disorders. Technologies like ultrawide-field OCT demonstrate the ability to diagnose and monitor retinal disorders using peripheral OCT capabilities. This discovery enables examination down to the individual axon of human retinal ganglion cells, as shown by full-field OCT. The advancements in optical coherence tomography (OCT), particularly intraoperative OCT, provide an enhanced understanding of the surgical treatment of chorioretinal diseases. At-home OCT facilitates the deployment of this advanced technology to the residences of at-risk patients, heralding a new era in retinal surveillance. Future research aims for the broader use of developing, clinically verified OCT technologies. These technologies signify a bright future in enhancing the comprehension, diagnosis, monitoring, and treatment of retinal illnesses.

References

1. Huang, D.; Swanson, E.A.; Lin, C.P.; Schuman, J.S.; Stinson, W.G.; Chang, W.; Hee, M.R.; Flotte, T.; Gregory, K.; Puliafito, C.A.; et al. Optical coherence tomography. Science 1991, 254, 1178–1181.
2. Stahl, A. The Diagnosis and Treatment of Age-Related Macular Degeneration. Dtsch Arztebl Int. 2020, 117, 513–520.
3. Semeraro, F.; Morescalchi, F.; Russo, A.; Gambicorti, E.; Pilotto, A.; Parmeggiani, F.; Bartollino, S.; Costagliola, C. Central Serous Chorioretinopathy: Pathogenesis and Management. Clin. Ophthalmol. 2019, 13, 2341–2352.
4. Boned-Murillo, A.; Albertos-Arranz, H.; Diaz-Barreda, M.D.; Orduna-Hospital, E.; Sánchez-Cano, A.; Ferreras, A.; Cuenca, N.; Pinilla, I. Optical Coherence Tomography Angiography in Diabetic Patients: A Systematic Review. Biomedicines 2021, 10, 88.
5. Majumdar, S.; Tripathy, K. Macular Hole. In StatPearls; StatPearls: Treasure Island, FL, USA, 2022.
6. Metrangolo, C.; Donati, S.; Mazzola, M.; Fontanel, L.; Messina, W.; D'Alterio, G.; Rubino, M.; Radice, P.; Premi, E.; Azzolini, C. OCT Biomarkers in Neovascular Age-Related Macular Degeneration: A Narrative Review. J. Ophthalmol. 2021, 2021, 9994098.
7. Dhurandhar, D.S.; Singh, S.R.; Sahoo, N.K.; Goud, A.; Lupidi, M.; Chhablani, J. Identifying central serous chorioretinopathy biomarkers in coexisting diabetic retinopathy: A multimodal imaging study. Br. J. Ophthalmol. 2020, 104, 904–909.
8. Sahoo, N.K.; Ong, J.; Selvam, A.; Maltsev, D.; Sacconi, R.; Venkatesh, R.; Reddy, N.G.; Madan, S.; Tombolini, B.; Lima, L.H.; et al. Longitudinal follow-up and outcome analysis in central serous chorioretinopathy. Eye 2022, 1–7.
9. Corradetti, G.; Corvi, F.; Nittala, M.G.; Nassisi, M.; Alagorie, A.R.; Scharf, J.; Lee, M.Y.; Sadda, S.R.; Sarraf, D. Natural history of incomplete retinal pigment epithelial and outer retinal atrophy

in age-related macular degeneration. Can. J. Ophthalmol. 2021, 56, 325–334.
10. Nassisi, M.; Fan, W.; Shi, Y.; Lei, J.; Borrelli, E.; Ip, M.; Sadda, S.R. Quantity of Intraretinal Hyperreflective Foci in Patients With Intermediate Age-Related Macular Degeneration Correlates With 1-Year Progression. Investig. Ophthalmol. Vis. Sci. 2018, 59, 3431–3439.
11. Lei, J.; Balasubramanian, S.; Abdelfattah, N.S.; Nittala, M.G.; Sadda, S.R. Proposal of a simple optical coherence tomography-based scoring system for progression of age-related macular degeneration. Graefes Arch. Clin. Exp. Ophthalmol. 2017, 255, 1551–1558.
12. Nassisi, M.; Lei, J.; Abdelfattah, N.S.; Karamat, A.; Balasubramanian, S.; Fan, W.; Uji, A.; Marion, K.M.; Baker, K.; Huang, X.; et al. OCT Risk Factors for Development of Late Age-Related Macular Degeneration in the Fellow Eyes of Patients Enrolled in the HARBOR Study. Ophthalmology 2019, 126, 1667–1674.
13. Gabriele, M.L.; Wollstein, G.; Ishikawa, H.; Kagemann, L.; Xu, J.; Folio, L.S.; Schuman, J.S. Optical coherence tomography: History, current status, and laboratory work. Investig. Ophthalmol. Vis. Sci. 2011, 52, 2425–2436.
14. Aumann, S.; Donner, S.; Fischer, J.; Muller, F. Optical Coherence Tomography (OCT): Principle and Technical Realization. In High Resolution Imaging in Microscopy and Ophthalmology: New Frontiers in Biomedical Optics; Bille, J.F., Ed.; Springer Nature: Cham, Switzerland, 2019; pp. 59–85.
15. Ohno-Matsui, K.; Fang, Y.; Morohoshi, K.; Jonas, J.B. Optical Coherence Tomographic Imaging of Posterior Episclera and Tenon's Capsule. Investig. Ophthalmol. Vis. Sci. 2017, 58, 3389–3394.
16. Zhang, Y.; Wang, Y.; Shi, C.; Shen, M.; Lu, F. Advances in retina imaging as potential biomarkers for early diagnosis of Alzheimer's disease. Transl. Neurodegener. 2021, 10, 6.
17. Povazay, B.; Bizheva, K.; Unterhuber, A.; Hermann, B.; Sattmann, H.; Fercher, A.F.; Drexler, W.; Apolonski, A.; Wadsworth, W.J.; Knight, J.C.; et al. Submicrometer axial resolution optical coherence tomography. Opt. Lett. 2002, 27, 1800–1802. [Google Scholar] [CrossRef]
18. Zhang, T.; Kho, A.M.; Yiu, G.; Srinivasan, V.J. Visible Light Optical Coherence Tomography (OCT) Quantifies Subcellular Contributions to Outer Retinal Band 4. Transl. Vis. Sci. Technol. 2021, 10, 30.
19. Miller, D.T.; Kocaoglu, O.P.; Wang, Q.; Lee, S. Adaptive optics and the eye (super resolution OCT). Eye 2011, 25, 321–330.
20. Zawadzki, R.J.; Jones, S.M.; Olivier, S.S.; Zhao, M.; Bower, B.A.; Izatt, J.A.; Choi, S.; Laut, S.; Werner, J.S. Adaptive-optics optical coherence tomography for high-resolution and high-speed 3D retinal in vivo imaging. Opt. Express 2005, 13, 8532–8546.
21. Sayegh, R.G.; Zotter, S.; Roberts, P.K.; Kandula, M.M.; Sacu, S.; Kreil, D.P.; Baumann, B.; Pircher, M.; Hitzenberger, C.K.; Schmidt-Erfurth, U. Polarization-Sensitive Optical Coherence Tomography and Conventional Retinal Imaging Strategies in Assessing Foveal Integrity in Geographic Atrophy. Investig. Ophthalmol. Vis. Sci. 2015, 56, 5246–5255.
22. De Boer, J.F.; Hitzenberger, C.K.; Yasuno, Y. Polarization sensitive optical coherence tomography—A review. Biomed. Opt. Express 2017, 8, 1838–1873.
23. Imaging that Enlightens. Deeper insights into retinal structures with High-Resolution OCT. Ophthalmologist. 2020.
24. Spaide, R.F.; Lally, D.R. High Resolution Spectral Domain Optical Coherence Tomography of Multiple Evanescent White Dot Syndrome. Retin. Cases Brief Rep. 2021.
25. Grieve, K.; Thouvenin, O.; Sengupta, A.; Borderie, V.M.; Paques, M. Appearance of the Retina With Full-Field Optical Coherence Tomography. Investig. Ophthalmol. Vis. Sci. 2016, 57, OCT96–OCT104.
26. Mece, P.; Scholler, J.; Groux, K.; Boccara, C. High-resolution in-vivo human retinal imaging using full-field OCT with optical stabilization of axial motion. Biomed. Opt. Express 2020, 11, 492–504.
27. Povazay, B.; Hermann, B.; Hofer, B.; Kajić, V.; Simpson, E.; Bridgford, T.; Drexler, W. Wide-field optical coherence tomography of the choroid in vivo. Investig. Ophthalmol. Vis. Sci. 2009, 50, 1856–1863.
28. Takahashi, H.; Tanaka, N.; Shinohara, K.; Yokoi, T.; Yoshida, T.; Uramoto, K.; Ohno-Matsui, K. Ultra-Widefield Optical Coherence Tomographic Imaging of Posterior Vitreous in Eyes With High Myopia. Am. J. Ophthalmol. 2019, 206, 102–112.
29. Ni, S.; Wei, X.; Ng, R.; Ostmo, S.; Chiang, M.F.; Huang, D.; Jia, Y.; Campbell, J.P.; Jian, Y. High-speed and widefield handheld swept-source OCT angiography with a VCSEL light source. Biomed. Opt. Express 2021, 12, 3553–3570.
30. Ehlers, J.P.; Tao, Y.K.; Srivastava, S.K. The value of intraoperative optical coherence tomography imaging in vitreoretinal surgery. Curr. Opin. Ophthalmol. 2014, 25, 221–227. [Google Scholar] [CrossRef]
31. Nahen, K.; Benyamini, G.; Loewenstein, A. Evaluation of a Self-Imaging SD-OCT System for Remote Monitoring of Patients with Neovascular Age Related Macular Degeneration. Klin. Mon. Für Augenheilkd. 2020, 237, 1410–1418.
32. Kim, J.E.; Tomkins-Netzer, O.; Elman, M.J.; Lally, D.R.; Goldstein, M.; Goldenberg, D.; Shulman, S.; Benyamini, G.; Loewenstein, A. Evaluation of a self-imaging SD-OCT system designed for remote home monitoring. BMC Ophthalmol. 2022, 22, 261. [Google Scholar] [CrossRef]
33. Shu, X.; Beckmann, L.; Zhang, H. Visible-light optical coherence tomography: A review. J. Biomed Opt. 2017, 22, 1–14.
34. Yi, J.; Wei, Q.; Liu, W.; Backman, V.; Zhang, H.F. Visibl.le-light optical coherence tomography for retinal oximetry. Opt. Lett. 2013, 38, 1796–1798.
35. Yi, J.; Liu, W.; Chen, S.; Backman, V.; Sheibani, N.; Sorenson, C.M.; Fawzi, A.A.; Linsenmeier, R.A.; Zhang, H.F. Visible light optical coherence tomography measures retinal oxygen metabolic

response to systemic oxygenation. Light Sci. Appl. 2015, 4, e334.
36. Rubinoff, I.; Miller, D.A.; Kuranov, R.; Wang, Y.; Fang, R.; Volpe, N.J.; Zhang, H.F. High-speed balanced-detection visible-light optical coherence tomography in the human retina using subpixel spectrometer calibration. IEEE Trans. Med. Imaging 2022.
37. Rubinoff, I.; Beckmann, L.; Wang, Y.; Fawzi, A.A.; Liu, X.; Tauber, J.; Jones, K.; Ishikawa, H.; Schuman, J.S.; Kuranov, R.; et al. Speckle reduction in visible-light optical coherence tomography using scan modulation. Neurophotonics 2019, 6, 041107.
38. Pi, S.; Hormel, T.T.; Wei, X.; Cepurna, W.; Morrison, J.C.; Jia, Y. Imaging retinal structures at cellular-level resolution by visible-light optical coherence tomography. Opt. Lett. 2020, 45, 2107–2110.
39. Zhang, T.; Kho, A.M.; Srinivasan, V.J. Morphometry of Inner Plexiform Layer (IPL) Stratification in the Human Retina With Visible Light Optical Coherence Tomography. Front. Cell Neuro Sci. 2021, 15, 655096.
40. Zhang, T.; Kho, A.M.; Srinivasan, V.J. Water wavenumber calibration for visible light optical coherence tomography. J. Biomed. Opt. 2020, 25, 090501. [Google Scholar] [CrossRef]
41. Babcock, H.W. The possibility of compensating astronomical seeing. In Publications of the Astronomical Society of the Pacific, 386th ed.; The Astronomical Society of the Pacific: San Francisco, WI, USA, 1953; Volume 65, pp. 229–236.
42. Liang, J.; Williams, D.R.; Miller, D.T. Supernormal vision and high-resolution retinal imaging through adaptive optics. J. Opt. Soc. Am. A Opt. Image Sci. Vis. 1997, 14, 2884–2892.
43. Roorda, A.; Romero-Borja, F.; Donnelly Iii, W.; Queener, H.; Hebert, T.; Campbell, M. Adaptive optics scanning laser ophthalmoscopy. Opt. Express 2002, 10, 405–412.
44. Akyol, E.; Hagag, A.M.; Sivaprasad, S.; Lotery, A.J. Adaptive optics: Principles and applications in ophthalmology. Eye 2021, 35, 244–264.
45. Jonnal, R.S.; Kocaoglu, O.P.; Zawadzki, R.J.; Liu, Z.; Miller, D.T.; Werner, J.S. A Review of Adaptive Optics Optical Coherence Tomography: Technical Advances, Scientific Applications, and the Future. Investig. Ophthalmol. Vis. Sci. 2016, 57, OCT51-68.
46. Roorda, A.; Williams, D.R. The arrangement of the three cone classes in the living human eye. Nature 1999, 397, 520–522.
47. Kadomoto, S.; Muraoka, Y.; Uji, A.; Ooto, S.; Kawai, K.; Ishikura, M.; Nishigori, N.; Akagi, T.; Tsujikawa, A. Human Foveal Cone and Müller Cells Examined by Adaptive Optics Optical Coherence Tomography. Transl. Vis. Sci. Technol. 2021, 10, 17.
48. Fernández, E.; Drexler, W. Influence of ocular chromatic aberration and pupil size on transverse resolution in ophthalmic adaptive optics optical coherence tomography. Opt. Express 2005, 13, 8184–8197.
49. Shirazi, M.F.; Brunner, E.; Laslandes, M.; Pollreisz, A.; Hitzenberger, C.K.; Pircher, M. Visualizing human photoreceptor and retinal pigment epithelium cell mosaics in a single volume scan over an extended field of view with adaptive optics optical coherence tomography. Biomed. Opt. Express 2020, 11, 4520–4535.
50. Liu, Z.; Kurokawa, K.; Zhang, F.; Lee, J.J.; Miller, D.T. Imaging and quantifying ganglion cells and other transparent neurons in the living human retina. Proc. Natl. Acad. Sci. USA 2017, 114, 12803–12808.
51. Adie, S.G.; Graf, B.W.; Ahmad, A.; Carney, P.S.; Boppart, S.A. Computational adaptive optics for broadband optical interferometric tomography of biological tissue. Proc. Natl. Acad. Sci. USA 2012, 109, 7175–7180. [Google Scholar] [CrossRef]
52. Ralston, T.S.; Marks, D.L.; Carney, P.S.; Boppart, S.A. Interferometric synthetic aperture microscopy. Nat. Phys. 2007, 3, 129–134.
53. Lee, B.; Lee, J.; Jeong, S.; Kang, W.; Oh, W.-Y. Video-rate computational adaptive optics optical coherence tomography with a stretched-pulse mode-locked laser. In European Conference on Biomedical Optics; Optical Society of America: Washington, DC, USA, 2021.
54. Wang, J.; Chaney, E.J.; Aksamitiene, E.; Marjanovic, M.; Boppart, S.A. Computational adaptive optics for polarization-sensitive optical coherence tomography. Opt. Lett. 2021, 46, 2071–2074.
55. Ruiz-Lopera, S.; Restrepo, R.; Cuartas-Vélez, C.; Bouma, B.E.; Uribe-Patarroyo, N. Computational adaptive optics in phase-unstable optical coherence tomography. Opt. Lett. 2020, 45, 5982–5985.
56. Liu, L.; Wu, Z.; Qi, M.; Li, Y.; Zhang, M.; Liao, D.; Gao, P. Application of Adaptive Optics in Ophthalmology. Photonics 2022, 9, 288.
57. Camino, A.; Ng, R.; Huang, J.; Guo, Y.; Ni, S.; Jia, Y.; Huang, D.; Jian, Y. Depth-resolved optimization of a real-time sensorless adaptive optics optical coherence tomography. Opt. Lett. 2020, 45, 2612–2615.
58. Zhu, D.; Wang, R.; Žurauskas, M.; Pande, P.; Bi, J.; Yuan, Q.; Wang, L.; Gao, Z.; Boppart, S.A. Automated fast computational adaptive optics for optical coherence tomography based on a stochastic parallel gradient descent algorithm. Opt. Express 2020, 28, 23306–23319.
59. Hofer, H.; Sredar, N.; Queener, H.; Li, C.; Porter, J. Wavefront sensorless adaptive optics ophthalmoscopy in the human eye. Opt. Express 2011, 19, 14160–14171.
60. Durech, E.; Newberry, W.; Franke, J.; Sarunic, M.V. Wavefront sensor-less adaptive optics using deep reinforcement learning. Biomed. Opt. Express 2021, 12, 5423–5438.
61. Iyer, R.R.; Sorrells, J.E.; Yang, L.; Chaney, E.J.; Spillman, D.R.; Tibble, B.E.; Renteria, C.A.; Tu, H.; Žurauskas, M.; Marjanovic, M.; et al. Label-free metabolic and structural profiling of dynamic biological samples using multimodal optical microscopy with sensorless adaptive optics. Sci. Rep. 2022, 12, 3438.

62. Pircher, M.; Zawadzki, R.J. Review of adaptive optics OCT (AO-OCT): Principles and applications for retinal imaging [Invited]. Biomed. Opt. Express 2017, 8, 2536–2562.
63. Hee, M.R.; Huang, D.; Swanson, E.A.; Fujimoto, J.G. Polarization-sensitive low-coherence reflectometer for birefringence characterization and ranging. JOSA B 1992, 9, 903–908.
64. Pircher, M.; Hitzenberger, C.K.; Schmidt-Erfurth, U. Polarization sensitive optical coherence tomography in the human eye. Prog. Retin. Eye Res. 2011, 30, 431–451.
65. Ueno, Y.; Mori, H.; Kikuchi, K.; Yamanari, M.; Oshika, T. Visualization of Anterior Chamber Angle Structures With Scattering- and Polarization-Sensitive Anterior Segment Optical Coherence Tomography. Transl. Vis. Sci. Technol. 2021, 10, 29.
66. Baumann, B.; Gotzinger, E.; Pircher, M.; Sattmann, H.; Schuutze, C.; Schlanitz, F.; Ahlers, C.; Schmidt-Erfurth, U.; Hitzenberger, C.K. Segmentation and quantification of retinal lesions in age-related macular degeneration using polarization-sensitive optical coherence tomography. J. Biomed. Opt. 2010, 15, 061704.
67. Sharma, S.; Hartl, G.; Naveed, S.K.; Blessing, K.; Sharma, G.; Singh, K. Input polarization-independent polarization-sensitive optical coherence tomography using a depolarizer. Rev. Sci. Instrum. 2020, 91, 043706.
68. Tang, P.; Wang, R. Stable fiber-based polarization-sensitive optical coherence tomography using polarization maintaining common-path interferometer. J. Biomed. Opt. 2020, 25, 116009.
69. Abouraddy, A.F.; Nasr, M.B.; Saleh, B.E.A.; Sergienko, A.V.; Teich, M.C. Quantum-Optical Coherence Tomography with Dispersion Cancellation; American Physical Society: College Park, MD, USA, 2002.
70. Booth, M.C.; Di Giuseppe, G.; Saleh, B.E.A.; Sergienko, A.V.; Teich, M.C. Polarization-sensitive quantum-optical coherence tomography. Phys. Rev. A 2004, 69, 043815.
71. Sukharenko, V.; Bikorimana, S.; Dorsinville, R. Birefringence and scattering characterization using polarization sensitive quantum optical coherence tomography. Opt. Lett. 2021, 46, 2799–2802.
72. Schutze, C.; Teleky, K.; Baumann, B.; Pircher, M.; Gotzinger, E.; Hitzenberger, C.K.; Schmidt-Erfurth, U. Polarisation-sensitive OCT is useful for evaluating retinal pigment epithelial lesions in patients with neovascular AMD. Br. J. Ophthalmol. 2016, 100, 371–377.
73. Liu, Y.; Holekamp, N.M.; Heier, J.S. Prospective, Longitudinal Study: Daily Self-Imaging with Home OCT for Neovascular Age-Related Macular Degeneration. Ophthalmol. Retin. 2022.
74. Chakravarthy, U.; Goldenberg, D.; Young, G.; Havilio, M.; Rafaeli, O.; Benyamini, G.; Loewenstein, A. Automated Identification of Lesion Activity in Neovascular Age-Related Macular Degeneration. Ophthalmology 2016, 123, 1731–1736.