

Swept-source optical coherence tomography angiography in diagnosing radiation retinopathy after choroidal melanoma plaque brachytherapy

Angiografia optycznej koherentnej tomografii typu swept-source w diagnostyce retinopatii popromiennej po brachyterapii czerniaka naczyniówki

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Słowa kluczowe: angiografia optycznej koherentnej tomografii, czerniak naczyniówki, retinopatia popromienna, płytкова brachyterapia.

Abstract

Radiation retinopathy is ischaemic damage to the retina and choroid following brachytherapy of intraocular tumours and head and neck tumours. It can lead to vision loss in patients treated with radiation due to choroidal melanoma. Patients following this type of treatment should be systematically monitored for tumour recurrence, metastases, and ischaemic radiation retinopathy. Follow-up should include a fundus examination and additional tests such as optical coherence tomography angiography (OCTA), fluorescein angiography (FA), and B-scan ultrasonography. OCTA proves to be a valuable diagnostic tool for early detection and treatment of radiation retinopathy, offering detailed vascular maps and effectively identifying radiation retinopathy features, complementing traditional methods like fluorescein angiography.

Streszczenie

Retinopatia popromienna jest niedokrwiennym uszkodzeniem siatkówki i naczyniówki w następstwie brachyterapii guzów wewnątrzgałkowych oraz guzów głowy i szyi. Może ona prowadzić do utraty wzroku u pacjentów naświetlanych z powodu czerniaka naczyniówki. Pacjenci po przebytym leczeniu tego typu powinni być systematycznie monitorowani w kierunku wznowy nowotworu, przerzutów i niedokrwiennnej retinopatii popromiennej. Kontrola powinna obejmować badanie dna oka oraz badania dodatkowe, takie jak angiografia optycznej koherentnej tomografii, angiografia fluoresceinowa oraz ultrasonografia B-skanów. OCTA okazuje się cennym narzędziem diagnostycznym do wczesnego wykrywania i leczenia retinopatii popromiennej. Oferuje szczegółowe mapy naczyń i skutecznie identyfikuje jej cechy, uzupełniając tradycyjne metody, takie jak angiografia fluoresceinowa.

Introduction

Uveal melanoma (UM) is the most common primary intraocular malignancy in adults. Ninety per cent of melanoma cases are localised in the choroid, while the remainder are located in the ciliary body (6%) and iris (4%) [1–3]. The Collaborative Ocular Melanoma Study (COMS) concluded that UM should be treated with sparing therapies rather than ocular enucleation to improve quality of life. These therapies include proton beam radiotherapy, plaque brachytherapy (PBT), stereotactic radiotherapy (SR), and radiosurgery [4].

Despite the above-mentioned treatment, 50% of patients with UM develop metastases, most commonly via haematogenous spread. In 90% of cases, metastases occur in the liver [3].

UM usually develops unilaterally, in patients between the ages of 50 and 70 years. Its incidence ranges from 2 to 8 per million in Europe and 5 people per million in the United States [5–7]. Patients with UM may have visual abnormalities such as blurred vision and visual field loss, but 30% have no symptoms, and the tumour is detected incidentally during fundus examination with slit lamp and indirect ophthalmoscopy



Figure 1. UM of the RE in a 58-year-old patient treated with 106 Ru brachytherapy in 2019. A partially amelanotic intraocular tumour, located peripherally in the inferior part of the fundus, was detected by accident (author's archive)



Figure 3. The USG B image of CM in a 58-year-old patient treated with 106 Ru brachytherapy in 2019 (tumour dimensions: base 10.01 mm, height 2.82 mm). Condition before brachytherapy (author's archive)

[7, 8]. Tests helpful in the diagnosis of UM are ultrabiomicroscopy (UBM), B-scan ultrasonography (B-scan ultrasound), and optical coherence tomography (OCT) [9].

The most popular current treatment for this condition is PBT. This method damages the DNA of cancer cells, which prevents them from dividing and growing [10–12]. This method can also damage the DNA of healthy cells, causing radiation retinopathy (RR). Various isotopes are used in PBT, such as iodine-125, ruthenium-106, palladium-103, and cesium-131 [12]. RR is diagnosed in about 25–28% of patients treated with PBT, and the incidence rises to 90% after 5 years of follow-up [13–15].

RR is a chronic and progressive disease of the retina and choroid of the eye. It is an ischaemic vasculopathy caused by PBT in the treatment of intraocular

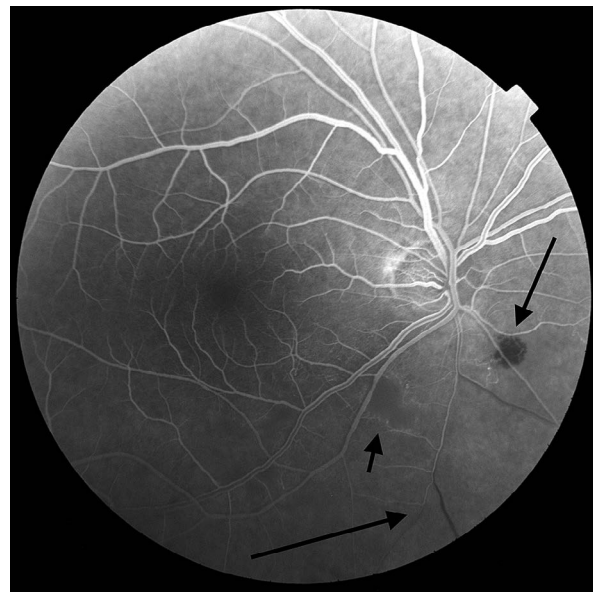


Figure 2. FA image of the central part of the fundus of the RE taken during the late phase of the examination in the same patient treated 3 years previously with radioactive ruthenium 106 Ru brachytherapy for peripherally located choroidal melanoma seen in the colour photo above. The smallest arrow indicates a small, hypofluorescent, ischaemic area corresponding to the cotton wool spot, the medium-length arrow indicates a small hypofluorescent area corresponding to the preretinal haemorrhage, and the longest arrow indicates a narrowing of the inferior temporal branches of the central retinal artery (author's archive)

tumours and external beam therapy in head and neck cancers [16]. PBT is now the standard treatment for small and medium-sized UMs (Figure 1) and some large melanomas. Enucleation is used to treat large intraocular tumours [17–19].

RR results from the effects of ionising radiation on the retina [20]. The ischaemic changes in RR are similar to rapidly progressive proliferative diabetic retinopathy (PDR), but the pathogenesis is different. Two mechanisms are likely to lead to RR: microvascular occlusion caused by direct irradiation, and diffuse neuroinflammation caused by cytokines and chemokines produced by irradiated UM cells [21–23]. Patients with RR notice a deterioration of visual acuity for distance and near and metamorphopsia in the visual field. The COMS study showed a decrease in visual acuity (less than 20/200) in UM patients 3 years after PBT of almost 50% [4].

Diagnosis and monitoring of RR

Diagnostic tools such as optical coherence tomography angiography (OCTA), fluorescein angiography (FA) (Figure 2), and B-scan ultrasound (Figure 3) of the eye help monitor and manage these patients [24]. Figures 1–8 show images of the right eye (RE) in a 58-year-old man treated with Ru 108 brachytherapy for UM localised to

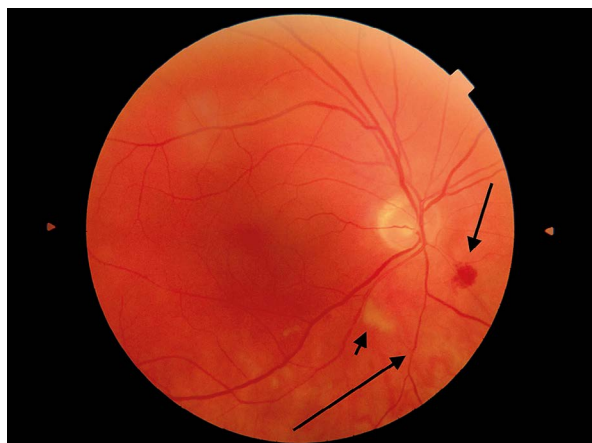


Figure 4. RR features in a patient treated 3 years previously (2019) with ^{106}Ru brachytherapy for peripherally located UM seen in the colour photo above (Figure 1). The smallest arrow indicates a cotton wool spot, the medium-length arrow indicates a preretinal haemorrhage, and the longest arrow indicates a narrowing of the inferior temporal branch of the central retinal artery (author's archive)

the peripheral lower fundus. The patient was managed in the Ophthalmology Clinic in Kielce in accordance with applicable regulations and legal requirements for the procedures performed [25]. Figures 1–8 demonstrate features of RR in the same eye found 3 years after treatment with ^{106}Ru brachytherapy. RR in this patient was treated with 3 consecutive monthly intravitreal injections of bevacizumab in the right eye (RE).

During PBT, a calculated radiation dose of a radioactive agent is used to damage tumour cells. However, this method of treatment can exhibit significant toxicity to healthy tissues around the tumour, such as the blood vessels of the retina and choroid. The risk of RR in the irradiated eye is increased in the elderly and in those with diabetes mellitus (DM) and hypertension. RR is also more common if irradiation has occurred near the macula or optic disc [18].

On fundus examination, features of the RR such as cotton wool spots, haemorrhages, microaneurysms, hard exudates, and retinal oedema are evident. Over time, new proliferating retinal vessels may develop [22, 26].

Advanced imaging techniques

FA is still the gold standard for the diagnosis of RR, imaging mainly retinal ischaemia. It is an invasive examination, requiring the administration of intravenous contrast. It is a time-consuming examination, which may cause additional side effects [27].

FA can reveal the RR features like hypofluorescent areas corresponding with ischaemic areas of the retina, oval hypofluorescent spots caused by preretinal haemorrhages, constricted or obliterated arterial branches of the central retinal artery, hypofluorescent dots at the site of microaneurysms with fluorescein dye leakage, and macular hyperfluorescence corresponding with macular oedema [27].

The underlying mechanism leading to the development of RR is the loss of vascular endothelial cells with subsequent vascular occlusion and retinal isch-

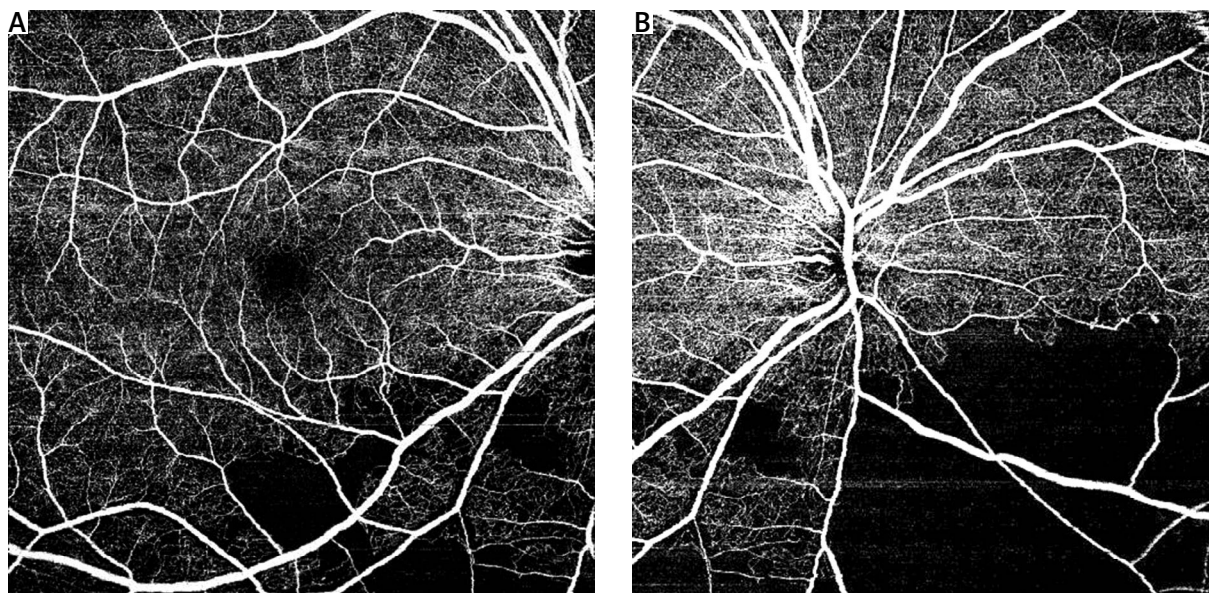


Figure 5. OCTA images of the macula (A) and nasal inferior part (B) in the RE in the same patient treated 3 years previously with radioactive ^{106}Ru brachytherapy for peripherally located choroidal melanoma seen in the colour photo above. The image A shows black, hyporeflective areas of the ischaemic retina located along the inferior branch of the central retinal artery. The image B shows black, hyporeflective areas of the ischaemic retina in the inferior nasal part of the posterior pole of the RE, near the optic disc (author's archive)

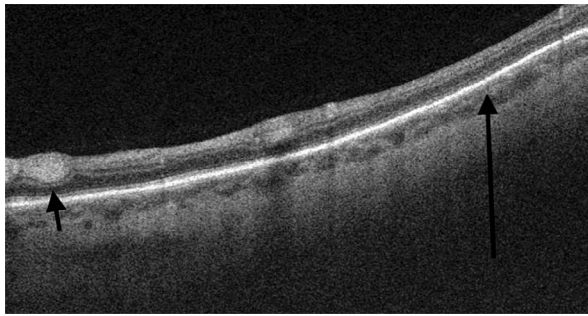


Figure 6. B-scan of OCT in the same patient treated 3 years earlier with radioactive ^{106}Ru brachytherapy for peripherally located choroidal melanoma seen in the colour image above. The shorter arrow indicates the hyperreflective inner part of the retina corresponding with a cotton wool spot, and the longer arrow indicates the thinner, ischaemic, nasal inferior part of the retina (author's archive)

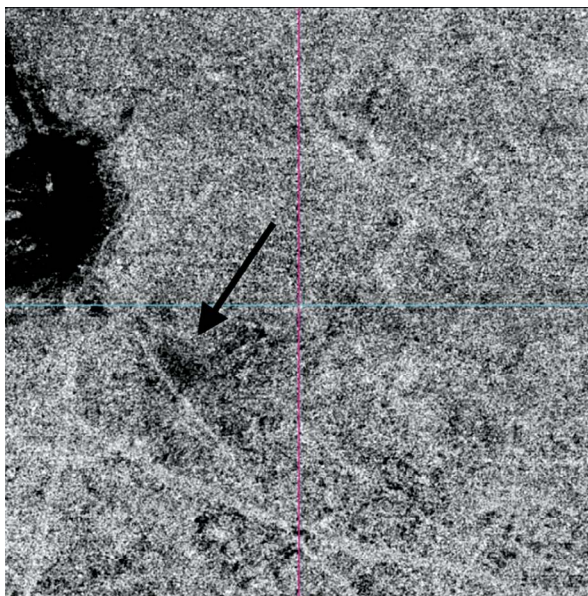


Figure 8. OCTA study shows dark areas in choriocapillaris without vessels in the same patient treated 3 years earlier with radioactive ^{106}Ru brachytherapy. The arrow indicates the "signal void" spot in the inferior nasal part of the posterior pole (author's archive)

aemia. RR can lead to vision loss [28]. It is therefore important to monitor patients with available diagnostic methods such as OCTA or FA and treat RR at an early stage to maintain good visual acuity. As in other ischaemic retinopathies, treatment includes the following methods: intravitreal antivascular endothelial growth factors (anti-VEGF) and/or intravitreal steroid agents or retinal lasers [29–31].

OCT is a modern, non-invasive examination method used for evaluation of various diseases affecting the eye [32]. It allows imaging of the structures of the eye through a cross-section of objects in real-time, without the use of histopathological procedures such as biopsy

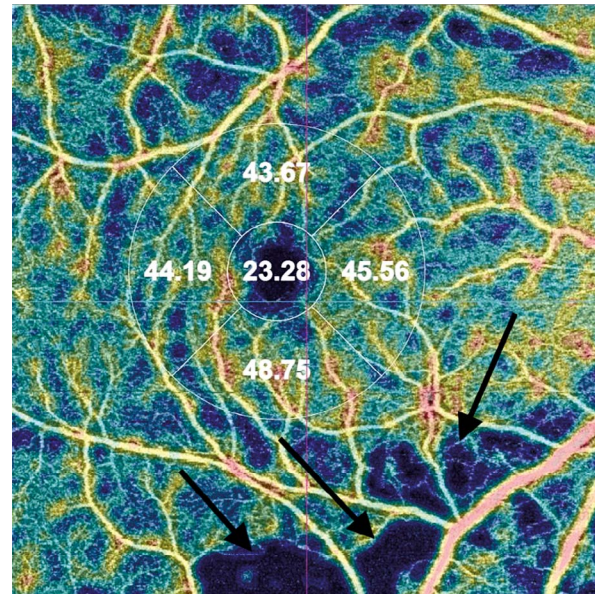


Figure 7. Vessel density (VD) map of the SCP in the macula in OCTA in the same patient treated 3 years earlier with radioactive ^{106}Ru brachytherapy for peripherally located choroidal melanoma seen in the colour image above. The arrows indicate dark, hyperreflective areas in the inferior part of the macula without retinal vessels (author's archive)

[31]. With this method, structures of the anterior and posterior segments of the eye can be diagnosed [33]. The more recent type of OCT tool is swept-source OCT (SS-OCT). The greatest advantage of this method is the high scanning speed of 370,000 scans A/s [34]. The technology allows the evaluation of even deeper layers of the eye such as the choroid. Penetration of light waves extends to the sclera. In the SS-OCT examination, the light wavelength is 1050 nm, axial resolution 2.6 μm , transverse resolution 14 μm , and scan width 12 mm [35, 36].

The B-scans of SS-OCT can show RR features like a thicker, hyperreflective part of the inner retina corresponding with cotton wool spots or macular oedema and thinner parts of the retina caused by ischaemia (Figure 6).

Research findings

The OCTA test is an ideal diagnostic tool for detecting RR features at an early stage, allowing rapid treatment implementation. The OCTA scan is based on a split-spectrum amplitude decorrelation algorithm that enhances the vascular signal and reduces background noise. This is related to the acquisition of consecutive B-scans of the same tissue section and allows the detection of erythrocyte movement. The movement of erythrocytes in the lumen of the vessel is visible as a known reflex in the cross-section under study. By analysing the movement of erythrocytes in all examined areas, the algorithm creates maps of the reti-

nal and choroidal vessels [37]. The analysed scans are 3×3 mm, 6×6 mm and 12×12 mm in size [38]. We can automatically assess OCTA parameters such as vessel density (VD) in the superficial capillary plexus (SCP), deep capillary plexus (DCP), and choriocapillaris (CC) using the Early Treatment of Diabetic Retinopathy Study (EDTRS) grid subfield. VD is analysed in the foveal (F), superior (S), inferior (I), nasal (N), and temporal (T) areas. We can also determine manually the size of the foveal avascular zone (FAZ) in SCP and DCP. The FAZ is the central area of the macula without clearly visible vessels in OCTA examination [39].

OCTA can reveal hyporeflective, ischaemic areas in the retina as a feature of RR and also areas in choriocapillaris without vessels (Figures 7, 8) [40]. Many investigators have found RR features on OCTA examination. Sellam *et al.* demonstrated many RR features using OCTA in patients with UM 36 months after treatment with PBT. In SCP, they observed microaneurysms, capillary loss, and dilated vessels. They found the DCP to be even more damaged than the SCP by 100% vascular loss, the presence of microaneurysms, and dilated vessels [41]. Another study showed changes in SCP and DCP in 112 irradiated eyes without clinical features of RR. These researchers highlighted the role of OCTA in detecting capillary ischaemia as a precursor to the clinically overt form of RR. However, the interpretation of OCTA results should also be approached critically given the technical artefacts if we compare this study with structural OCT. In addition, OCTA examination does not show vascular permeability, which enables FA. Thus, both OCTA and FA are complementary examinations [42].

Rose *et al.* studied 8 patients with a mean age of 55.75 years (SD = 12.58 years) who developed RR after 125-Iodine brachytherapy confirmed by FA testing. The mean interval between treatment and RR was 2.82 years (SD = 1.3 years). A second, healthy eye was used as a control. Visual acuity (logMAR scale) in the eye with RR was significantly lower compared to the other eye (0.63 ± 0.36 vs. 0.04 ± 0.06 , $p = 0.002$). Total retinal blood flow (TRBF) and retinal blood oxygen saturation were measured in both eyes with prototype methodologies of Doppler Spectral Domain OCT and a Hyperspectral Retinal Camera. The average TRBF in eyes with RR was significantly lower than in the healthy eyes ($p = 0.013$). They also observed higher arteriolar oxygen saturation (SaO_2) ($p = 0.008$) and venular oxygen saturation (SvO_2) ($p = 0.051$) in eyes with ischaemic retinopathy compared to fellow eyes.

These authors explain the above results by the reduced oxygen demand of the retina due to retinal cell death or degeneration secondary to radiation. Ultimately, there is a reduction in retinal blood flow. Furthermore, they believe that there is a radiation-induced activation of the coagulation cascade secondary to the loss of endothelial cells, causing vascular occlusion. This is followed by a thickening of the retinal vessel wall as

a consequence of the deposition of fibrillary or hyaline material. This process also leads to narrowing and subsequent constriction of the vascular lumen. Ultimately, the distribution of oxygen to the retina is significantly reduced. These researchers also observed a higher arteriolar SaO_2 . They explain this result by the fact that the reduced oxygen demand of the retina as a result of necrosis results in reduced oxygen consumption, which causes an increase in the oxygen concentration in its vessels [43]. Another mechanism explaining the above result may be a consequence of vascular collapse and closure due to loss of endothelial cells, while other vessels may dilate and appear telangiectatic [28, 44, 45]. It is thought that blood is rapidly perfused through these dilated capillaries avoiding the arterioles and venules of the retina, and the retina is thus deprived of oxygen and is ischaemic. This mechanism is compared to the retinal changes of diabetic retinopathy [46]. Higginson *et al.* also observed SaO_2 changes in retinal blood even before the onset of clinically apparent RR in head and neck cancer patients treated with external beam radiotherapy [47].

Conclusions

With available diagnostic methods such as OCTA and FA, it is possible to monitor the retinal status of patients after PBT for intraocular tumours and/or head and neck cancers. Observing the patient for metastases is important, but maintaining good visual acuity is equally important, because RR poses a risk of vision loss. Detection of RR in the preclinical period enables the introduction of treatment and preservation of eye function.

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Ethical approval

This project was approved by the Bioethics Committee of Collegium Medicum of Jan Kochanowski University in Kielce (study codes 54 approved 1 July 2021).

Conflict of interest

The authors declare no conflict of interest.

References

1. Jager MJ, Shields CL, Cebulla CM, Abdel-Rahman MH, Grossniklaus HE, Stern MH, Stern MH, Carvajal RD, Belfort RN, Jia R, Shields JA, Damato BE. Uveal melanoma. *Nat Rev Dis Primers*. 2020; 6: 24.
2. Piperno-Neumann S, Piulats J, Goebeler M, Galloway I, Lugowska I, Becker J, Vihinen P, Van Calster J, Hadjistilianou T, Proença R, Caminal JM, Rogasik M, Blay JY, Kapiteijn E. Uveal melanoma: a European network to face

- the many challenges of a rare cancer. *Cancers (Basel)*. 2019; 11: 817.
3. Finger P, Garg G, Kivelä T. Patients presenting with stage IV uveal melanoma: lessons learned. *Indian J Ophthalmol*. 2022; 70: 271.
 4. Kamrava M, Lamb J, McCannel TA. Ocular complications of radiotherapy. In: *Clinical Ophthalmic Oncology. Basic principles and diagnostic techniques*. Second edition, Springer Berlin, Heidelberg 2014; 99-111.
 5. Kaliki S, Shields C, Shields J. Uveal melanoma: estimating prognosis. *Indian J Ophthalmol*. 2015; 63: 93-102.
 6. Naseripour M, Azimi F, Mirshahi R, Khakpoor G, Poorhosseingholi A, Chaibakhsh S. Global incidence and trend of uveal melanoma from 1943-2015: a meta-analysis. *Asian Pac J Cancer Prev*. 2022; 23: 1791-1801.
 7. Kaliki S, Shields CL. Uveal melanoma: relatively rare but deadly cancer. *Eye*. 2017; 31: 241-257.
 8. Chattopadhyay C, Kim DW, Gombos DS, Oba J, Qin Y, Williams MD, Esmali B, Grimm EA, Wargo JA, Woodman SE, Patel SP. Uveal melanoma: from diagnosis to treatment and the science in between. *Cancer*. 2016; 122: 2299-2312.
 9. Foti PV, Travalì M, Farina R, Palmucci S, Spatola C, Raffaele L, Salamone V, Caltabiano R, Broggi G, Puzzo L, Russo A, Reibaldi M, Longo A, Vigneri P, Avitabile T, Ettore GC, Basile A. Diagnostic methods and therapeutic options of uveal melanoma with emphasis on MR imaging – Part I: MR imaging with pathologic correlation and technical considerations. *Insights Imaging*. 2021; 12: 66.
 10. Baskar R, Lee KA, Yeo R, Yeoh KW. Cancer and radiation therapy: current advances and future directions. *Int J Med Sci*. 2012; 9: 193-199.
 11. Reichstein DA, Brock AL. Radiation therapy for uveal melanoma: a review of treatment methods available in 2021. *Curr Opin Ophthalmol*. 2021; 32: 183-190.
 12. Rusňák Š, Hecová L, Kasl Z, Sobotová M, Hauer L. Therapy of uveal melanoma. A review. *Cesk Slov Oftalmol*. 2021; 77: 3-15.
 13. Sahoo NK, Ranjan R, Tyagi M, Agrawal H, Reddy S. Radiation retinopathy: detection and management strategies. *Clin Ophthalmol*. 2021; 15: 3797-3809.
 14. Abri Aghdam K, Soltan Sanjari M, Naseripour M, Manafi N, Sedaghat A, Bakhti S. The impacts of episcleral plaque brachytherapy on ocular motility. *J Binocul Vis Ocul Motil*. 2021; 71: 55-61.
 15. Akbaba S, Foerster R, Nicolay NH, Arians N, Bostel T, Debus J, Hauswald H. Linear accelerator-based stereotactic fractionated photon radiotherapy as an eye-conserving treatment for uveal melanoma. *Radiat Oncol*. 2018; 13: 140.
 16. Rose K, Krema H, Durairaj P, Dangboon W, Chavez Y, Kulasekara SI, Hudson C. Retinal perfusion changes in radiation retinopathy. *Acta Ophthalmol*. 2018; 96: e727-e731.
 17. Collaborative ocular melanoma study (COMS) randomized trial of I-125 brachytherapy for medium choroidal melanoma I. Visual acuity after 3 years COMS report no. 16. *Ophthalmology*. 2001; 108: 348-366.
 18. Krema H, Xu W, Payne D, Vasquez LM, Pavlin CJ, Simpson R. Factors predictive of radiation retinopathy post I-125Iodine brachytherapy for uveal melanoma. *Can J Ophthalmol*. 2011; 46: 158-163.
 19. Shields JA, Shields CL. Current management of posterior uveal melanoma. *Mayo Clin Proc*. 1993; 68: 1196-1200.
 20. Stallard HB. Radiant energy as (a) a pathogenic (b) a therapeutic agent in ophthalmic disorders. *Br J Ophthalmol Monograph Suppl*. 1933; 6: 1-126.
 21. Groenewald C, Konstantinidis L, Damato B. Effects of radiotherapy on uveal melanomas and adjacent tissue. *Eye*. 2013; 27: 163-171.
 22. Guyer DR, Mukai S, Egan KM, Seddon JM, Walsh SM, Gragoudas ES. Radiation maculopathy after proton beam irradiation for choroidal melanoma. *Ophthalmology*. 1992; 99: 1278-1285.
 23. Shields JA, Shields CL. Management of posterior uveal melanoma: past, present, and future: the 2014 Charles L. Schepens lecture. *Ophthalmology*. 2015; 122: 414-428.
 24. Płatkowska B, Kal M, Biskup M. Optical coherence tomography angiography – use in ophthalmological practice. *Med Stud*. 2020; 36: 195-205.
 25. Kocańda K. Awaiting consent to cure. *Med Stud*. 2022; 38: 14-21.
 26. Tseng VL, Coleman AL, Zhang ZF, McCannel TA. Complications from plaque versus proton beam therapy for choroidal melanoma: a qualitative systematic review. *J Cancer Ther*. 2016; 7: 169-185.
 27. Seregard S, Pelayes DE, Singh AD. Radiation therapy: posterior segment complications. *Dev Ophthalmol*. 2013; 52: 114-123.
 28. Atebara NH, Drouilhet JH, Brown GC. Duane's ophthalmology on CD-ROM. Wilkins, Philadelphia, PA 2006.
 29. Giuliani GP, Sadaka A, Hinkle DM, Simpson ER. Current treatments for radiation retinopathy. *Acta Oncol*. 2011; 50: 6-13.
 30. Reichstein D. Current treatments and preventive strategies for radiation retinopathy. *Curr Opin Ophthalmol*. 2015; 26: 157-166.
 31. Fujimoto JG, Brezinski ME, Tearney GJ, Boppart SA, Boma B, Hee MR, Southern JF, Swanson EA. Optical biopsy and imaging using optical coherence tomography. *Nat Med*. 1995; 1: 970-972.
 32. Kal M, Winiarczyk M, Zarębska-Michaluk D, Odrobińska D, Cieśla E, Płatkowska-Adamska B, Biskup M, Pabjan P, Głuszek S, Mackiewicz J. Long-term effect of SARS-CoV-2 infection on the retinal and choroidal microvasculature. *J Clin Med*. 2023; 12: 2528.
 33. Theodossias G. Optyczna koherentna tomografia choroby siatkówki – jaskra. Partner, Wrocław 2010.
 34. Huber R, Adler DC, Fujimoto JG. Buffered Fourier domain mode locking: Unidirectional swept laser sources for optical coherence tomography imaging at 370,000 lines/s. *Opt Lett*. 2006; 31: 2975-2977.
 35. Michalewska Z, Michalewski J, Nawrocki J. Swept-source OCT. *Retina Today*. 2013: 50-56.
 36. Waldstein SM, Faatz H, Szimacsek M, Glodan AM, Podkowinski D, Montuoro A, Simader C, Gerendas BS, Schmidt-Erfurth U. Comparison of penetration depth in choroidal imaging using swept source vs spectral domain optical coherence tomography. *Eye*. 2015; 29: 409-415.
 37. Jia Y, Tan O, Tokayer J, Potsaid B, Wang Y, Liu JJ, Kraus MF, Subhash H, Fujimoto JG, Hornegger J, Huang D. Split-spectrum amplitude-decorrelation angiography with optical coherence tomography. *Opt Express*. 2012; 20: 4710-4725.
 38. Spaide RF, Fujimoto JG, Waheed NK. Image artifacts in optical coherence tomography angiography. *Retina*. 2015; 35: 2163-2180.

39. Sawada O, Ichihara Y, Obata S, Ito Y, Kakinoki M, Sawada T, Saishin Y, Ohji M. Comparison between wide-angle OCT angiography and ultra-wide field fluorescein angiography for detecting non-perfusion areas and retinal neovascularization in eyes with diabetic retinopathy. *Arbeitsphysiologie*. 2018; 256: 1275-1280.
40. Cennamo G, Montorio D, Bernardo R, Farella A, Liuzzi R, Breve MA, Reibaldi M, Cennamo G. Retinal vascular changes in Radiation Maculopathy after intravitreal Ranebimab by optical coherence tomography angiography. *J Clin Med*. 2020; 9: 1618.
41. Sellam A, Coscas F, Lumbroso-Le Rouic L, Dendale R, Lupidi M, Coscas G, Desjardins L, Cassoux N. Optical coherence tomography angiography of macular features after proton beam radiotherapy for small choroidal melanoma. *Am J Ophthalmol*. 2017; 181: 12-19.
42. Say EAT, Samara WA, Khoo CTL, Magrath GN, Sharma P, Ferenczy S, Shields CL. Parafoveal capillary density after plaque radiotherapy for choroidal melanoma. *Retina*. 2016; 36: 1670-1678.
43. Rose K, Krema H, Durairaj P, Dangboon W, Hudson C. Retinal perfusion changes in radiation retinopathy. *Acta Ophthalmol*. 2018; 96: e727-e731.
44. Archer D, Amoaku W, Gardiner T. Radiation retinopathy – clinical, histopathological, ultrastructural and experimental correlations. *Eye*. 1991; 5: 239-251.
45. Irvine AR, Alvarado JA, Wara WM, Morris BW, Wood IS. Radiation retinopathy: an experimental model for the ischemic-proliferative retinopathies. *Trans Am Ophthalmol Soc*. 1981; 79: 103-122.
46. Rivilén S, Torp TL, Grauslund J. Retinal oximetry in patients with ischaemic retinal diseases. *Acta Ophthalmol*. 2017; 95: 119-127.
47. Higginson DS, Sahgal A, Lawrence MV, Moyer S, Stefanescu M, Willson AK, Qaqish B, Zanation A, Marks LB, Garg S, Chera BS. External beam radiotherapy for head and neck cancers is associated with increased variability in retinal vascular oxygenation. *PLoS One*. 2013; 8: e69657.

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