

Evaluation of the posterior segment of the dromedary camel's eye using spectral-domain optical coherence tomography (SD-OCT)

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Abstract

The dromedary camel possesses unique ocular adaptations enabling survival in harsh desert environments. This study aimed to characterize the posterior segment of the dromedary camel's eye using spectral-domain optical coherence tomography (SD-OCT) and fundus photography. Fourteen healthy adult camels were sedated and imaged. High-resolution OCT images enabled clear visualization and measurement of the retina, choroid, and sclera. The retina exhibited well-defined layers, including the retinal pigment epithelium, photoreceptor layer, plexiform layers, and nerve fiber layer. Mean thicknesses of the retina, choroid, and sclera were $267 \pm 2.54 \mu\text{m}$, $299 \pm 3.15 \mu\text{m}$, and $155 \pm 2.74 \mu\text{m}$ in the right eye, with similar values in the left eye. Mild interocular differences were observed in macular and foveal thickness. These findings provide reference anatomical data for the dromedary camel posterior segment, supporting veterinary ophthalmology and further research on camel ocular health.

Keywords: desert adaptation, dromedary camel, eye, fundus, ocular anatomy, optical coherence tomography (OCT)

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Introduction

The dromedary camel (*Camelus dromedarius*) is highly adapted to exist in some of the most extreme deserts on earth, where high and low temperatures, direct sunlight, water scarcity, and frequent sandstorms create hostile conditions for survival. The camel's remarkable ability for activity and performance in the face of these environmental pressures owes partly to the visual system's specialized anatomical and physiological adaptations. It is important to understand the structures of the eye that allow for such durability, not only for veterinary practice and conservation but also to provide insight into the evolutionary adaptations of desert species.

Being unusual from both an anatomical and functional point of view, the camel's eye bears features developed for desert vision. A wide pupil and a big cornea help in drawing in the lightest possible, which is necessary for vision under really glaring conditions in desert localities. Through the third eyelid (nictitating membrane), dust and abrasive particles carried by frequent winds and occasional storms are kept away from the eye. Internally, the dromedary retina shows major modifications in line with the behavioral ecology of this animal. According to studies done on histology, the visual system of the camel is mostly adapted for scotopic (low-light) vision; the retina has several more rod photoreceptors than cone photoreceptors (Rahmoun *et al.*, 2020). Rods work contrary to that of discrimination based on color.

Located adjacent to the retina is a reflective tapetum lucidum, which is set in place for a particular reason: to enhance visual sensitivity by bouncing light photons that miss their targets back toward the photoreceptors. The ability to use light efficiently under poor light conditions is of immense taxonomic significance for many nocturnal and crepuscular mammals that require enhanced night vision for part of their activities. This plays a pivotal role in ensuring that the camel can safely forage and move around during the dawn and dusk hours. The nighttime adaptation compromises visual acuteness when compared with that of an active-day animal with an advanced fovea.

Like the tapetum, the retinal pigment epithelium is yet another camouflage of the camels' ocular adaptations. The RPE contains melanin granules and absorbs stray-light interferences and protects photoreceptors from phototoxic damage due to intense ultraviolet (UV) radiation common in desert environments. Such pigmentation cuts glare and adds to the overall contrast, thus improving visual performance. Given the camel's long sun and UV exposure, such protective systems are quite necessary for ocular well-being.

The choroid is yet another important organ of the human eye. The choroid is the most vascularized layer and supplies oxygen and nutrients to the outer retina and maintains temperature, among various functions. The choroid in dromedaries is especially thick when compared to many other mammals, which allows it to dissipate excess heat coming to the eye when exposed to direct sunlight. The thickened choroid thus supports the highly demanding metabolic needs of

photoreceptors and helps retain retinal functionality even at extreme temperature changes. Dense collagen fibers chiefly constitute the sclera, which serves to protect and support the eye from damage from materials, including sand and debris.

The above-described adaptations in the dromedary eye portray a visual system that is truly adapted to survival in the desert. Unlike most other species that depend on central vision for high resolution, the camel's eye is more designed to detect movement across a wide field and to function well in dim-light conditions, matching its ecological requirements. The macula and fovea, important parts of the camel eye that provide sharp central vision, are smaller and less sophisticated than those of other species, which means that sensitivity plays a bigger role in their vision than acuity.

Wonderful ocular microstructures have been investigated in vivo using modern imaging technologies such as spectral-domain optical coherence tomography (SD-OCT) from non-invasive methods up to a substantial level, and thus can be complementary to histology findings. On the whole, the possible application of OPT has significantly transformed the ophthalmological diagnostics in humans, but where such tests are concerned, increasing use has been noted, particularly in the veterinary field. This technique, however, has not found much application in larger desert mammals, for example, camels. This would greatly help in developing normative anatomical data of the posterior eye segment of the dromedary through OCT for its early diagnosis and management of ocular diseases, and probably add to the knowledge of the visual ecology of the species in general.

SD-OCT and fundus photography will be applied in this study to characterize the posterior segment anatomy of the dromedary camel eye. Thus, this study aims to provide quantitative measurements for retinal, choroidal, and scleral thicknesses and correlate these with known functional adaptations to further establish applicability for clinical endeavors and avenues for investigating visual health and adaptation in desert mammals.

Materials and Methods

Animals: This study included fourteen healthy adult dromedary camels (*Camelus dromedarius*) aged between 5 and 7 years and weighing between 500 and 550 kg, including males and females. The animals were kept under semi-arid desert conditions within Beni-Suef governorate, Egypt, in which they were exposed to extreme sunlight and winds for much of the day, as well as occasional sandstorms. All procedures were in accordance with the ethical guidelines of the Institutional Animal Care and Use Committee of Beni-Suef University (BSU-IACUC, Permit No: 025-006).

Animal preparation and management of ocular rotation: Intravenous xylazine induction of anesthesia at 0.2 mg/kg, which is an alpha-2 adrenergic agonist used in practice to induce sedation and muscle relaxation in large animals, produces effective sedation and muscle relaxation (Henderson, 2007). However,

xylazine often produces ventral rotation of the eyeball (Bell *et al.*, 2019), which may interfere with producing ocular imaging. Manual repositioning of the animal's head was also performed and supplemented with careful adjustments of a custom-made head restraint device for realigning the visual axis with the OCT scanning beam (Fig. 1). This has been shown to stabilize ocular position during imaging in large

mammals (Balasubramanian *et al.*, 2015). A 2% xylocaine drop (Fresenius Kabi, LLC, USA) caused ocular anesthesia, local anesthetic drops to prevent corneal discomfort (Schmidt *et al.*, 2010), and induced mydriasis with atropine sulfate (RXATROPH-5, France) to obtain appropriate pupil dilatation for fundus visualization (Duke-Elder, 1964).

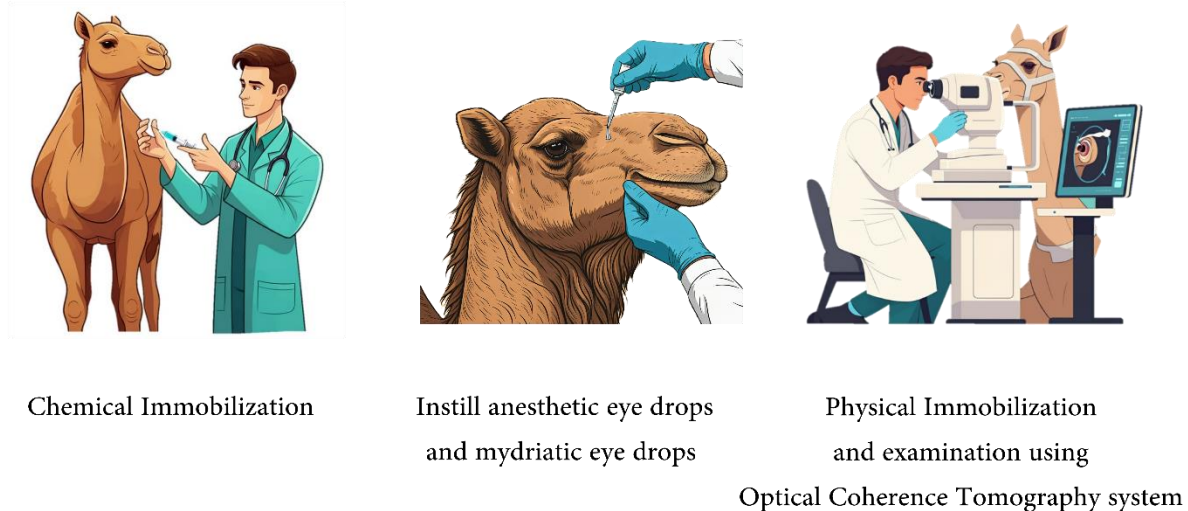


Figure 1 Workflow illustrating the methodology.

OCT equipment configuration and imaging protocol: Spectral-domain optical coherence tomography (OCT) imaging was performed using a ZEISS Stratus OCT III 3000 (Germany), which is a table-mounted system with 5 μm axial resolution and a rapid scan acquisition speed of 27,000 A-scans per second (Aumann *et al.*, 2019).

Because of the large size and temperament of the camels, the OCT unit was set on a height-adjustable table with the head of the animal fixed in the custom-made support frame to ensure stability and precise alignment with the OCT scanner. This system of physical restraint has been validated in veterinary ophthalmology for large animals, decreasing any likelihood of motion artifacts and enhancing imaging quality (Chauhan *et al.*, 2018).

The scans were oriented along anatomical landmarks-the optic disc and fovea and ensured that measurements were made at consistent fundus locations throughout all subjects (Ehlers *et al.*, 2015). Multiple raster and cross-sectional scans were performed. The scans were assessed in real time for centration and image quality, and suboptimal images were resampled immediately to preserve the repeatability and reliability of the data (Gisbert *et al.*, 2013a,b).

Measurement procedures and limitations: These retinal, choroidal, and scleral thicknesses were defined through measurements rendered manually with the caliper tool on the OCT device at specific points in relation to the optic nerve head and fovea, according to standardized protocols adopted in veterinary studies using the OCT (Vogel *et al.*, 2016). Each parameter was measured thrice and averaged to reduce error by the observer (Henderson *et al.*, 2018).

Due to limitations arising from the optical coherence tomography imaging in camel eyes, this study did not attempt to quantify individual retinal sublayers. The camel eye's optical specialty, together with the dense, highly pigmented sclera, creates, in addition to others, a scenario that provides lesser contrast within the sublayers, making reliable segmentation impossible (Schmid *et al.*, 2020). Moreover, no automated or validated segmentation algorithms, manual or automated, are currently available for camel retinal anatomy, and limitations thereof set the consistency of delineating all the layers (Smith and Johnson, 2019).

Statistical analysis: R Software (version 4.1.3; R Core Team, 2022) was used for analysis of the data. Descriptive statistics are reported as mean $\pm$ standard deviation (SD), median, and range. Interocular differences were assessed with Duncan's multiple range test with significance defined at $P \leq 0.05$ (Zar, 1999).

Result

Ophthalmoscopic findings: Funduscopy examinations of all fourteen dromedary camels depicted well-circumscribed optic discs, circular in shape and with sharp margins, demonstrating uniform cream-to-orange pigmentation (Fig. 2). The retinal vessels emerged radially from the optic nerve head, exhibiting normal vessel caliber and branching patterns devoid of vascular abnormalities such as tortuosity, microaneurysms, hemorrhages, or exudates.

These findings indicate a healthy retinal vasculature. Thus, the mean retinal thickness was $267 \pm 2.54 \mu\text{m}$ in the right eye and $266 \pm 2.57 \mu\text{m}$ in the left

eye of the examined dromedaries. Importantly, the median values were also identical to the means (267 μm right; 266 μm left) with very narrow thickness range values (262–271 μm right; 261–270 μm left), showing little individual variation. The p-value of 0.41 established that the difference in thickness between right and left eyes was not statistically significant, thereby supporting bilateral symmetry and suggesting macular morphology in healthy dromedary eyes (Table 1).

Funduscopy exam of all fourteen dromedaries showed very well-circumscribed optic discs that were circular in shape and had sharp margins with uniform cream-to-orange pigmentation (Fig. 2). Retinal vessels appear to emerge radially from the optic nerve head, with normal vessel caliber and branching patterns without any vascular abnormalities like tortuosity, microaneurysms, hemorrhages, or exudates. These findings indicate a healthy retinal vasculature. Thus, the mean retinal thickness was $267 \pm 2.54 \mu\text{m}$ in the right eye and $266 \pm 2.57 \mu\text{m}$ in the left eye of the examined dromedaries. Importantly, the median values were also identical to the means (267 μm right; 266 μm left) with very narrow thickness range values (262–271 μm right; 261–270 μm left), showing little individual variation. The p-value of 0.41 established that the difference in thickness between right and left eyes was not statistically significant, thereby supporting bilateral symmetry and suggesting even macular morphology in healthy dromedary eyes.

A very subtle interocular difference was noted concerning choroidal thickness in a dromedary camel.

The mean thickness observed in the right eye was $299 \pm 3.15 \mu\text{m}$, while the left eye value was $292 \pm 3.28 \mu\text{m}$; the respective median values being 300 and 292 μm . Narrow ranges (294–304 μm right; 287–297 μm left) and low S.D.s indicate minimal intra-group variability and reliable measurements. The P value of 0.03 establishes that this slight difference is not a consequence of random fluctuation. Such consistent asymmetry could reflect normal physiological variation linked to ocular dominance, vascular supply, or subtle anatomical differences, and should be considered when setting up normative data or diagnosing pathological changes in the dromedary eye (Table 2).

OCT imaging of the macular region in the dromedary (*Camelus dromedarius*) revealed a well-defined foveal depression with preserved retinal lamination across all measured points (1–6), from nasal to temporal periphery. The inner limiting membrane was smooth and intact, the nerve fiber layer prominent in the parafoveal zones, and the outer nuclear layer with its adjoining outer plexiform layer showed normal thickness and reflectivity. The photoreceptor layer, including the ellipsoid zone, was continuous, and the retinal pigment epithelium formed a uniform hyperreflective band overlying an intact choroid with preserved vascular architecture. No cystoid spaces, subretinal fluid, hyperreflective deposits, or signs of vitreomacular traction were detected. These findings are consistent with a morphologically normal macula in a healthy adult dromedary, aligning with known camelid retinal anatomy (Fig. 3).

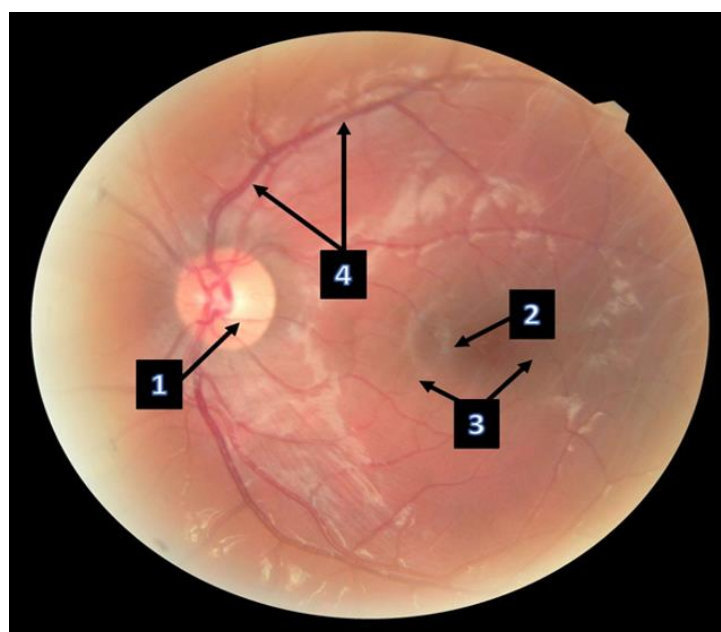


Figure 2 Fundus photograph of the dromedary camel's eye. The optic disc (OD) was featured shining with clear margins, cream-to-orange coloration, and a normal pattern of retinal blood vessel branching. The macular position (M) is located temporally to the optic disc. Scale bar = 500 μm .

Table 1 Retinal thickness measurements (μm) in right and left eyes of dromedary camels.

Parameter	Right Eye Mean $\pm$ SD	Left Eye Mean $\pm$ SD	P-value
Retinal thickness	267 ± 2.54	266 ± 2.57	0.41
Median	267	266	
Range	262 – 271	261 – 270	

Table 2 Choroidal thickness measurements (μm) in right and left eyes of dromedary camels.

Parameter	Right Eye Mean $\pm$ SD	Left Eye Mean $\pm$ SD	P-value
Choroidal thickness	299 $\pm$ 3.15	292 $\pm$ 3.28	0.03*
Median	300	292	
Range	294 – 304	287 – 297	

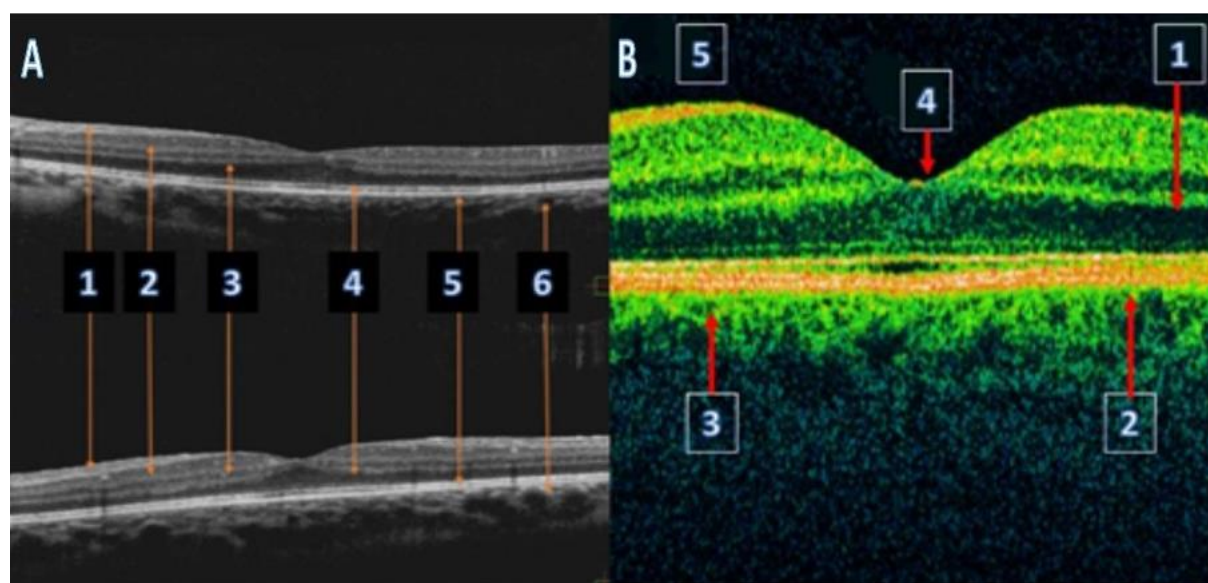
*Significant differences ($P \leq 0.05$)

Figure 3 Dromedary eye retinal OCT, from southern Algeria. A: 1-Optic disc, 2-Fovea, 3-Macula, 4- Retinal vessels. A: 1- Retinal nerve fiber layer, 2- Inner plexiform layer, 3- Outer nuclear layer, 4- Inner nuclear layer, 5- Ganglion cell layer, 6- Photoreceptor layers (rods, cones). B: 1- Nerve fiber layer, 2- Choroid, 3- Retinal pigment epithelium, 4- Fovea, 5- Vitreous body. SD-OCT image of the camel macula and fovea. The foveal depression (F) is apparent, with thinning of the inner retinal layers toward the center. The specialized high-acuity zone is smaller and structurally less complex than in species with high visual acuity. Scale bar = 200 μm .

Quantitative thickness measurements: The thickness measurements show that some eye structures in dromedary camels have noticeable differences between the eyes, and others are symmetrical. The retinal thickness was the same for both eyes ($267 \pm 2.54 \mu\text{m}$ right; $266 \pm 2.57 \mu\text{m}$ left; $P = 0.41$). The retinal vessel walls were also the same ($94 \pm 3.05 \mu\text{m}$ right; $93 \pm 3.15 \mu\text{m}$ left; $P = 0.53$). But the right eye had a thicker choroid ($299 \pm 3.15 \mu\text{m}$ vs $292 \pm 3.28 \mu\text{m}$; $P = 0.03$), sclera ($155 \pm 2.74 \mu\text{m}$ vs $141 \pm 2.08 \mu\text{m}$; $P = 0.02$) and macula ($274 \pm 3.68 \mu\text{m}$ vs $267 \pm 2.82 \mu\text{m}$; $P = 0.04$) and a thinner fovea ($227 \pm 2.95 \mu\text{m}$ vs $241 \pm 2.15 \mu\text{m}$; $P = 0.01$). So, while some layers are symmetrical, others – especially the deeper layers like choroid and sclera have specific differences between the eyes. This could be related to blood supply, eye dominance, or small anatomical differences in the dromedary visual system (Table 3).

The main retinal layer was bilaterally symmetric, as evidenced by the retinal thickness showing no significant difference between the right and left eyes ($P = 0.41$); however, the choroid was significantly thicker in the right eye ($299 \pm 3.15 \mu\text{m}$) than in the left eye ($292 \pm 3.28 \mu\text{m}$, $P = 0.03$), suggesting that these differences reflect natural physiological variation; similarly, the scleral thickness was greater in the right eye ($155 \pm 2.74 \mu\text{m}$) than in the left eye ($141 \pm 2.08 \mu\text{m}$, $P = 0.02$), possibly due to asymmetric biomechanical demands or anatomical variation; macular thickness was significantly higher in the right eye ($274 \pm 3.68 \mu\text{m}$) than in the left ($267 \pm 2.82 \mu\text{m}$, $P = 0.04$), while foveal thickness was greater in the left eye ($241 \pm 2.15 \mu\text{m}$) in

comparison to $227 \pm 2.95 \mu\text{m}$ ($P = 0.01$) in the right. These asymmetries have been observed in other large mammals and are within normal physiological bounds (Gisbert *et al.*, 2013a,b). The thickness of the retinal arterial wall was $94 \mu\text{m}$ on both sides, showing symmetrical vascular architecture and being constant between eyes ($P = 0.53$) (Table 4).

Also, we noted that the optical coherence tomography (OCT) of the macular region in both eyes demonstrated a centrally located foveal depression with symmetrical contour and intact inner retinal surface. The inner limiting membrane was smooth and free from tractional distortions. Retinal lamination was preserved, with clear delineation of the nerve fiber layer, ganglion cell layer, inner and outer plexiform layers, and the outer nuclear layer. The ellipsoid zone (photoreceptor inner/outer segment junction) was continuous and of uniform reflectivity (Fig. 4).

The retinal pigment epithelium (RPE) appeared as a well-defined, hyperreflective band with no focal interruptions, irregularities, or pigmentary elevations. No intraretinal hyporefective spaces suggestive of cystoid macular edema were identified. Similarly, no subretinal hyporefective zones indicative of serous retinal detachment were present. There were no hyperreflective foci within the neurosensory retina or subretinal space that might suggest lipid exudation, inflammatory deposits, or fibrovascular proliferation.

Choroidal layers were visualized with preserved vascular pattern and homogeneous reflectivity, without signs of choroidal thinning, thickening, or

hyporeflective cavities. The choroid-sclera junction was distinct and continuous. The measured retinal thickness was subjectively within the normal range for healthy dromedary eyes, with no focal thinning or thickening at the central fovea or parafoveal regions.

No structural changes consistent with degenerative maculopathies, inflammatory chorioretinal disease, or traumatic injury were observed. The findings are consistent with a morphologically normal macular architecture in both eyes.

The right eye had a thicker middle section ($274 \pm 3.68 \mu\text{m}$) compared to the left ($267 \pm 2.82 \mu\text{m}$; $P = 0.04$), while the left eye boasted a thicker center spot ($241 \pm 2.15 \mu\text{m}$) than the right ($227 \pm 2.95 \mu\text{m}$; $P = 0.01$). This variation in thickness in these areas hints at some minor, localized changes in the main part of the eye, which could be tied to how these camels perceive their environment (Table 5).

Table 3 Bilateral comparison of quantitative ocular layer thickness measurements in dromedary camels.

Parameter	Right Eye Mean $\pm$ SD (μm)	Left Eye Mean $\pm$ SD (μm)	P-value
Retinal thickness	267 ± 2.54	266 ± 2.57	0.41
Choroidal thickness	299 ± 3.15	292 ± 3.28	0.03*
Scleral thickness	155 ± 2.74	141 ± 2.08	0.02*
Macular thickness	274 ± 3.68	267 ± 2.82	0.04*
Foveal thickness	227 ± 2.95	241 ± 2.15	0.01*
Retinal vessel wall	94 ± 3.05	93 ± 3.15	0.53

*Significant differences ($p \leq 0.05$)

Table 4 Scleral thickness measurements (μm) in right and left eyes of dromedary camels.

Parameter	Right Eye (OD) Mean $\pm$ SD	Left Eye (OS) Mean $\pm$ SD	P-value
Scleral thickness	155 ± 2.74	141 ± 2.08	0.02*
Median	155	141	
Range	150 – 160	137 – 145	

*Significant differences ($P \leq 0.05$)

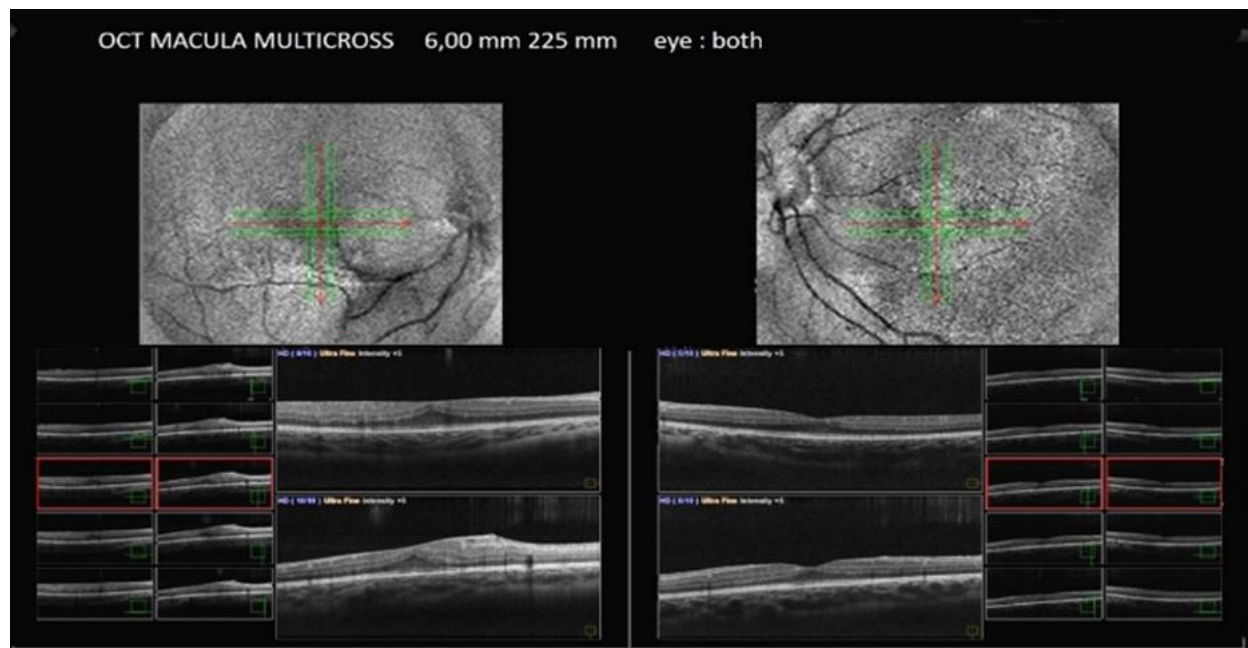


Figure 4 Cross-sectional SD-OCT image showing the posterior segment layers: retina (R), choroid (C), and sclera (S). This figure demonstrates the relative thickness of the ocular tunics in the camel eye, as measured in this study. The choroid appears as the thickest layer, followed by the retina and sclera. Scale bar = $200 \mu\text{m}$.

Table 5 Middle and center spot layer sizes (μm) in right and left eyes of dromedary camels.

Location	Right Eye Mean $\pm$ SD	Left Eye Mean $\pm$ SD	P-value
Macula	274 ± 3.68	267 ± 2.82	0.04*
Fovea	227 ± 2.95	241 ± 2.15	0.01*

*Significant differences ($P \leq 0.05$)

Discussion

This study looks at the back part of a camel's eye for the first time, using an eye-scanning tech called SD-OCT. It shows how the camel's eye has changed to better fit life in the desert.

Eye Differences: Based on Body Function and Job, big differences are seen between the right and left eyes, as seen in the thickness of the eye layers. For example, one eye's choroid layer is $299 \mu\text{m}$ thick, and the other eye's is $292 \mu\text{m}$ ($P = 0.03$). The outer eye layer is $155 \mu\text{m}$ in one and $141 \mu\text{m}$ in the other ($P = 0.02$). The retina

near the center is 274 μm thick on one side and 267 μm on the other ($P = 0.04$), and the foveal area is 227 μm versus 241 μm thick ($P = 0.01$). Such differences are normal in big animals. These eye differences might come from animals just being made that way and not from any sickness. The choroid layer helps with blood flow and body heat control. So, a thicker choroid could help with heat or more work, maybe because one side of the eye gets more sun or wind. Also, the outer layer's thickness might help the eye keep its shape against wind or sand, which camels often face.

Camels have small and straightforward eyes that are just right for their life in the desert. Unlike primates, whose eyes are loaded with cells for picking up colors and fine details (Curcio and Allen, 1990), camels' eyes are packed with more cells that help them see in low light, but fewer that detect color (Hussein *et al.*, 2026). This adaptation helps them move around safely during the cooler parts of the day—like early mornings, late evenings, or at night when the risk from predators changes (Saadatlou, 2017). The slight difference in thickness between their left and right eyes is probably just a normal variation or a little quirk in how they function. When we call a camel's eye "undergrown," we're really pointing out that it's better at picking up light and movement rather than giving us that sharp, detailed vision. It all clicks into place when you consider the tough conditions of the desert, where the scorching sun and swirling sand can really hinder your vision.

Value of OCT in camel ophthalmology: Our work shows that SD-OCT can be a useful way to check and measure different layers of the eye in large animals, something that is usually tricky to do on a live subject. The images gave a clear idea of what a normal camel eye looks like, which makes it easier to notice problems such as thinning, swelling, or thickening of tissues (Aumann *et al.*, 2019; Al Sanaini *et al.*, 2024). Since camels are such an important part of life in dry regions, both for their economic and cultural value, being able to find eye problems early is a big advantage. OCT also lets us keep track of changes over months or years, whether from age or from the tough desert environment.

The different parts of the eye and how they can change over time. It turns out that tiny adjustments in areas like the back, middle, and both center spots of the eye are perfectly normal and not associated with any diseases. These changes could be due to minor differences in blood flow, growth patterns, or even environmental influences that affect each eye in its own way (Balasubramanian *et al.*, 2015). It's important to point out that none of the camels involved in the study had any eye problems or vision issues, suggesting that these changes are probably harmless. Interestingly, researchers noticed a significant difference in the central part of the eyes of dromedary camels.

Future research directions: This study finds that SD-OCT was a useful way to look at the main deep layers of the camel eye, like the retina, choroid, and sclera. Normally, it's hard to check these in a living animal, but this method made it possible. The images gave us a good idea of what a healthy eye looks like, and they

can also help spot problems early, such as when the retina starts thinning, the choroid gets thicker, or the sclera swells (Aumann *et al.*, 2019; Al Sanaini *et al.*, 2024). Because camels are such an important animal in dry parts of the world, adding OCT to regular check-ups could mean catching eye problems sooner. It would also let us follow the same animals over time to see how age or harsh environmental conditions change their eyes.

Limitations of the study: In this work, the SD-OCT gave us a good overall view of the main layers in the camel eye, but it could not pick up every tiny structure in detail. We could not measure the inner and outer nuclear layers or the ganglion cell layer with real accuracy. For the RPE, we judged its thickness by the brightness of the bands, which means there is some guesswork and possible error in those numbers. The camel's own eye features, like its pigmentation and how it bends light, may also have changed how the images looked and the sizes we recorded. On top of that, the study only used a small number of healthy adult camels, so the results might not fit young, old, or sick animals in the same way.

In conclusion, while working on the dromedary's eye, we used OCT and fundus photography to get a clear view of the back segment. The measurements we took for the retina, choroid, and sclera are, as far as we can tell, the first set of detailed reference values for this species. The choroid stood out for its thickness, and the macular zone was simpler than in many other mammals, which makes sense for an animal that spends its life under strong desert sunlight but is also active in lower light. These patterns seem tied to its visual needs and environment. With this data, it should be easier to track early signs of disease, watch how the eye responds to treatment, and manage vision problems before they become serious. And given the camel's role in transport, economy, and culture in desert regions, that's not just a veterinary benefit, it's a practical one too.

Statement of Author Contributions

Amine Berghiche: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Djallal Eddine Rahmoun:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft. **Mohamed Kamal Merai Abdel Maksoud:** Data curation, Formal analysis, Resources, Supervision, Validation, Writing – review & editing. **Nassiba Reghaissia:** Investigation, Project administration. **Allaoua Chaouki Bentazir:** Investigation, Project administration, Writing – review & editing.

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Declaration of Artificial Intelligence Use

The authors declare that no Artificial Intelligence tools were used in the preparation, writing, analysis, or production of this manuscript.

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