







Avian ophthalmic peculiarities

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ABSTRACT: *Morphology and physiology of bird eyes are similar to mammals; although, there are peculiarities that should be considered for a correct interpretation of an ophthalmic examination. While the ophthalmology of domestic species is already well established, there are gaps to be filled regarding birds, particularly due to the large number of existing species. This literature review consists of a brief contribution regarding peculiarities of anatomy, physiology, and ophthalmic semio technique of the avian eye.*

Key words: *anatomy, eye physiology, intraocular pressure, ophthalmic examination, tear test, wild animals.*

Particularidades oftálmicas em aves

RESUMO: *A morfologia e a fisiologia dos olhos das aves são similares àquelas de mamíferos, mas existem particularidades que devem ser consideradas para a correta interpretação do exame oftálmico. Enquanto a oftalmologia de espécies domésticas já é bem estabelecida, ainda há diversas lacunas no que tange às aves, particularmente devido ao grande número de espécies existentes. Este trabalho objetiva realizar uma revisão bibliográfica abrangendo anatomia, fisiologia e semiologia oftálmica de aves.*

Palavras-chave: *animais selvagens, anatomia, exame oftálmico, fisiologia ocular, teste lacrimal, pressão intraocular.*

INTRODUCTION

Birds' vision is highly specialized, being adapted to their lifestyle, habitat, and physical activities. Their visual acuity is excellent and color vision is well developed (CUTHILL et al., 2000; WILLIAMS, 2012). It is believed that most birds, except for some nocturnal species, are able to detect light in the ultraviolet spectrum (CUTHILL et al., 2000), an ability that plays an important role in camouflage and orientation, as well as inter- and intraspecific communication based on reflection of ultraviolet light in the plumage (CUTHILL et al., 2000; BAYÓN et al., 2007; WILLIAMS, 2012).

While the ophthalmology of mammalian domestic species is already well established, it is noted that there are still several gaps to be filled regarding domestic and wild birds, particularly due to the large number of existing species. This literature review consists of a brief contribution to the anatomy, physiology, and ophthalmic semio technique of the avian eye.

Eyelids and ocular adnexa

Birds have upper and lower eyelids and a nictitating membrane (or third eyelid). The

lower eyelid is usually more mobile than the upper eyelid, and capable of covering most of the eyeball during blinking (MURPHY, 1993; WILLIS & WILKIE, 1999; MONTIANI-FERREIRA, 2001). Eyelids have a fibroelastic tarsal plate without the presence of meibomian glands (MURPHY, 1993; WILLIS & WILKIE, 1999; BAYÓN et al., 2007). In both eyelids, near the edges, there are modified eyelashes called filoplumes, for protection and tactile function (MURPHY, 1993; HARRIS et al., 2008; BALDOTTO, 2012).

Muscles of the eyeball are thin and undeveloped, being one of the reasons why ocular mobility is limited (WILLIS & WILKIE, 1999; BAYÓN et al., 2007). That is compensated by the movement of the head, which can rotate up to 270° (SICK, 1993). There are four straight muscles, two oblique muscles, the pyramidal muscle and a square muscle (BAYÓN et al., 2007).

Nictitating membrane is well developed and highly mobile (WILLIS & WILKIE, 1999; BAYÓN et al., 2007), and may be thin, almost transparent, or thicker and white, with interspecific variation (WILLIS & WILKIE, 1999; HARRIS et al.,

2008; BALDOTTO, 2012; RODARTE-ALMEIDA et al., 2013; MEEKINS et al., 2015). It is usually positioned dorsonasally in the conjunctival sac, between the upper eyelid and the eyeball, moving in a ventrotemporal direction (BAYÓN et al., 2007; HARRIS et al., 2008). However, in some species, such as the caracara (*Caracara plancus*), it is found in the palpebral rim of the nasal corner, moving in a nasotemporal direction (BALDOTTO, 2012). This movement is due to contraction of the pyramidal muscle, located in the retrobulbar space, which originates from the posterior region of the sclera, surrounding the optic nerve (WILLIS & WILKIE, 1999; KERN & COLITZ, 2013), and the square muscle, also located in the posterior region (KERN & COLITZ, 2013).

There is no gland in the third eyelid, and the lacrimal gland is situated in the inferotemporal section of the eyeball (WILLIS & WILKIE, 1999), being absent in penguins and owls (BAYÓN et al., 2007). Despite its name, the lacrimal gland plays a secondary role on bird's tear production (BAYÓN et al., 2007). The harderian gland is the main source of tears in birds, and it lies in the retrobulbar region, adjacent to the sclera, near the base of the third eyelid (WILLIS & WILKIE, 1999; BAYÓN et al., 2007; WILLIAMS, 2012). The duct comes out from this gland and opens into the conjunctival sac, between the eyeball and third eyelid (WILLIS & WILKIE, 1999) and two lacrimal points drain the secretions into the nasolacrimal duct (WILLIS & WILKIE, 1999; BALDOTTO, 2012). There are no Meibomian glands (KERN & COLITZ, 2013).

Tear production can be measured in birds. The Schirmer tear test (STT) strip has a width of 0.5cm, which makes it difficult to insert it into the conjunctival sac of birds which have a smaller palpebral fissure (LANGE et al., 2014). Consequently, the wetting of the strip's length cannot be determined in such case (SMITH et al., 2015). KORBEL & LEITENSTORFER (1998) suggested cutting the filter paper lengthwise to reduce its width by half, allowing insertion into the conjunctival sac. However, due to the possibility of error in cutting the tapes, the measurement may not be accurate (SMITH et al., 2015). In larger birds, there are studies standardizing STT reference values, described in table 1.

An alternative is to use the phenol red string test, which could be a less stressful method for birds, requiring only 15s (WILLIS & WILKIE, 1999; SMITH et al., 2015). There are normal values reported for several species, as described in table 1. If bird species values are unknown, healthy cage mates

can provide values comparable to physiological ones (WILLIAMS, 2012).

LANGE et al. (2012) have suggested the use of endodontic absorbent paper points to measure tear production because they have good absorptive properties, are sterile and have a standardized size, being a practical and easy to use alternative. In addition, its small size provides the possibility of insertion into the conjunctival sac of small species (LANGE et al., 2014). There are reference values (mean \pm standard deviation) for canary (*Sicalis flaveola*) (5.10 \pm 0.26mm/min), chestnut-bellied seed finch (*Sporophila angolensis*) (4.11 \pm 0.34mm/min) (LANGE et al. 2014), Lear's macaw (*Ara leari*) (13.37 \pm 1.22mm/min), blue-and-yellow macaw (*Ara ararauna*) (16.74 \pm 1.38mm/min) (MONÇÃO-SILVA et al., 2016), Caatinga parakeets (*Eupsittula cactorum*) (8.74 \pm 2.0mm/min) and yellow-chevroned parakeet (*Brotogeris chiriri*) (5.89 \pm 1.48mm/min) (OLIVEIRA et al. 2017).

Orbit and paranasal sinuses

In most birds, the supraorbital margin is formed by the frontal bone, while the infraorbital margin is constituted of the suborbital ligament, constituted of fasciae. In Psittaciformes, there is a bone, the suborbital arch. Cranial edge of the orbit is bordered by the lacrimal bone and the caudal edge by the laterosphenoidal bone (PAUL-MURPHY et al., 1990). Predators show a short orbital process of the lacrimal bone, which protrudes from the middle third of the supraorbital margin, directed dorsolaterally and which provides a fixation area for the orbital fascia, protecting the eyeball in the orbit (PYCRAFT, 1903). The striped owl has a well-developed post-orbital process that constitutes the lateral border of the orbital cavity (RODARTE-ALMEIDA et al., 2013).

The sesamoid bone of the sclera, whose function is to redirect the path of the tendon of the third eyelid pyramidal muscle, was described for the first time by MAHECHA & OLIVEIRA (1999) in Strigiformes, showing different dimensions and shapes in the different species studied. In the striped owls, this bone was found to be ventral to the ring of scleral ossicles (RODARTE-ALMEIDA et al., 2013).

The infraorbital sinus and part of the cervical air sac system are located in several groups of birds, lateral to the eyeball, on the nasal and rostroventral sides. The sinus may be connected to pneumatized sections of cranial bones, which spread to the upper parts of the beak, jaw and orbit (BAYÓN et al., 2007; WILLIAMS, 2012). The most important feature of the orbit is the proximity of the eyeball to

Table 1 - Reference values for Schirmer tear test (mean \pm standard deviation mm/min) and phenol red thread test (mean \pm standard).

| -----Schirmer tear test----- | | |
|---|-----------------------------|-------------------------------|
| Species | Reference values (mm/min) | Authors |
| American flamingo (<i>Phoenicopterus ruber</i>) | 12.3 \pm 4.5 ¹ | MEEKINS et al. (2015) |
| Bald eagle (<i>Haliaeetus leucocephalus</i>) | 14 \pm 2 | KUHN et al. (2013) |
| Blue-and-yellow macaw (<i>Ara ararauna</i>) | 7.1 \pm 0.76 ² | FALCÃO et al. (2017a) |
| Blue-fronted parrot (<i>Amazona aestiva</i>) | 6.2 \pm 0.1 ¹ | FALCÃO et al. (2017b) |
| Brown pelican (<i>Pelecanus occidentalis</i>) | 5.45 \pm 1.88 | O'CONNELL et al. (2017) |
| Common buzzard (<i>Buteo buteo</i>) | 12.47 \pm 2.66 | BARSOTTI et al. (2013) |
| Duck (<i>Anas platyrhynchos</i>) | 6.2 \pm 2.2 ³ | MOOD et al. (2017) |
| Eastern-screech-owl (<i>Megascops asio</i>) | \leq 2-6 ⁴ | HARRIS et al. (2008) |
| Eurasian black vulture (<i>Aegypius monachus</i>) (OD) ⁵ | 10.9 \pm 3.3 | KOMNENOU et al. (2013) |
| Eurasian black vulture (<i>Aegypius monachus</i>) (OS) ⁶ | 11.9 \pm 3.3 | KOMNENOU et al. (2013) |
| Eurasian tawny owl (<i>Strix aluco</i>) | 3.2 \pm 0.4 ¹ | WILLIAMS et al. (2006) |
| Eurasian tawny owl (<i>Strix aluco</i>) | 3.12 \pm 1.92 | BARSOTTI et al. (2013) |
| European kestrel (<i>Falco tinnunculus</i>) | 6.20 \pm 3.67 | BARSOTTI et al. (2013) |
| Goose (<i>Anser anser</i>) | 5.5 \pm 2.6 ³ | MOOD et al. (2017) |
| Great grey owl (<i>Strix nebulosa</i>) | 9.8 \pm 2.8 | WILLS et al. (2016) |
| Griffon vultures (<i>Gyps fulvus</i>) (OD) ⁵ | 6.4 \pm 1.8 | KOMNENOU et al. (2013) |
| Griffon vultures (<i>Gyps fulvus</i>) (OS) ⁶ | 6.5 \pm 1.8 | KOMNENOU et al. (2013) |
| Humboldt penguin (<i>Spheniscus humboldti</i>) | 6.45 \pm 2.9 | SWINGER et al. (2009) |
| Little owl (<i>Athene noctua</i>) | 3.5 \pm 1.96 | BARSOTTI et al. (2013) |
| Ostrich (<i>Struthio camelus</i>) | 16.3 \pm 2.5 | GHAFFARI et al. (2012) |
| Snowy owl (<i>Bulbo scandiacus</i>) | 9.8 \pm 2.4 | WILLS et al. (2016) |
| Southern caracara (<i>Caracara plancus</i>) | 7.84 \pm 3.05 | BALDOTTO (2012) |
| Striped owl (<i>Asio clamator</i>) | 5.03 \pm 3.29 | RODARTE-ALMEIDA et al. (2013) |
| -----Phenol red thread test----- | | |
| Species | Reference values (mm/15s) | Authors |
| American flamingo (<i>Phoenicopterus ruber</i>) | 24.2 \pm 4.4 | MEEKINS et al. (2015) |
| Blue-and-yellow macaw (<i>Ara ararauna</i>) | 11.14 \pm 0.38 | MONÇÃO-SILVA et al. (2016) |
| Caatinga parakeet (<i>Eupsittula cactorum</i>) | 3.51 \pm 2.2 | OLIVERA et al. (2017) |
| Common mynah (<i>Acridotheres tristis</i>) | 19.2 \pm 2.5 | RAJAEI et al. (2015) |
| Eastern-screech-owl (<i>Megascops asio</i>) | 15 \pm 4.3 | HARRIS et al. (2008) |
| <i>Falco</i> sp. | 30.6 \pm 4.2 | SMITH et al. (2015) |
| Yellow-chevroned parakeet (<i>Brotogeris chiriri</i>) | 1.67 \pm 1.95 | OLIVEIRA et al. (2017) |

¹Modified Schirmer, ²Under anesthesia, ³Mean \pm 2 standard deviations, ⁴Range, ⁵Right eye, ⁶Left ey.

the cervicocephalic diverticulum of the infraorbital sinus. Increase of this diverticulum in cases of sinusitis or other diseases of the upper respiratory tract can lead to a series of ophthalmic conditions due to their proximity to the orbit, such as periorbital swelling, orbital compression, conjunctivitis, exophthalmia or intraocular inflammation (WILLIS & WILKIE, 1999; KERN & COLITZ, 2013; WILLIAMS, 2012).

Ocular bulb

The eyeball of birds is large in comparison to the size of the skull, occupying up to 50% or more of the cranial volume, being its posterior segment larger than the anterior segment (BAYÓN et al., 2007; KERN & COLITZ, 2013). The orbits are separated by the interorbital septum, a broad and thin bony structure (PYCRAFT, 1903; BAUMEL et al., 1993).

Bone elements that support the sclera are present in several species of vertebrates, and birds possess scleral ossicles (FRANZ-ODENDAAL & HALL, 2006). These are located in the eye, caudal to the limbus and usually form a ring, without connecting to the other elements of the skull (FRANZ-ODENDAAL & HALL, 2006). Its posterior extremities form a continuous border with the cartilaginous lamina of the sclera (RODARTE-ALMEIDA et al., 2013). The shape of the scleral ossicles varies between birds, and can be flattened, slightly convex or concave, dictating the general shape of the ocular bulb (BAUMEL et al., 1993; FRANZ-ODENDAAL & HALL, 2006; LIMA et al., 2009). Two main functions of the ossicles have been described: protecting and supporting the eyeball, minimizing deformation during flight or diving, as well as assisting the ciliary muscles in visual accommodation (WALLS, 1942 apud FRANZ-ODENDAAL & HALL, 2006). The positioning of the ossicles does not vary between species, but the number and shape of the ossicles do (FRANZ-ODENDAAL & HALL, 2006). LIMA et al. (2009) carried out a study with 208 birds of 18 different orders, in which the anatomy of the ossicles of these birds was described; shape and arrangement and number of plates were different between species, with intra and interspecific numeric variation and also between the eyes of the same individual. RODARTE-ALMEIDA et al. (2013) also reported intraspecific and individual variation in striped owls.

There are three typical eyeball formats in birds: flat, globose, and tubular (WILLIS & WILKIE, 1999; BAYÓN et al., 2007). In the flat eyeball, there is a short anteroposterior axis on the ciliary region, that is flat or partially concave, convex cornea and posterior hemispheric segment (present in parrots and passerines) (WILLIS & WILKIE, 1999; BAYÓN et al., 2007). In the globose form, the ciliary region protrudes further into the posterior pole, with a concave shape (found in diurnal birds of prey, crows, etc.) (BAYÓN et al., 2007). In the tubular eyeball, the intermediate segment is concave and extends posteriorly, forming a tube before joining the posterior segment (present in nocturnal birds; BAYÓN et al., 2007).

It is possible to measure the intraocular pressure of birds with applanation tonometer (Tonopen®), which requires the instillation of topical anesthetic on the surface of the cornea 10 to 15s before the measurement, or a rebound tonometer (Tonovet®, Tonovet Plus®), that doesn't require topical anesthesia (WILLIS & WILKIE, 1999; BAYÓN et al., 2007; WILLIAMS, 2012). Tip of the rebound tonometer can be used on corneas around 3

mm thick, while the applanation tonometer tip requires a cornea with at least twice that thickness (WILLIAMS, 2012). So, it's advised to notice that smaller birds may require the use of rebound tonometer in order to obtain their intraocular pressure, since readings with applanation tonometers provide non-reliable readings (WILLIS & WILKIE, 1999). In a study conducted with the Tonopen® in 275 birds of 39 species, the values varied between 9.2 and 16.3mmHg (WILLIS & WILKIE, 1999). Other reference values for applanation and rebound tonometry are described in tables 2 and 3, respectively. Papers regarding the use of TonoVet Plus for birds, stabilising reference values, weren't reported.

Anterior pole

Cornea of most bird species is thinner than that of mammals (WILLIS & WILKIE, 1999), except for some diurnal birds of prey and waterfowl (WILLIAMS, 2012). It has five layers, with Bowman's membrane below the epithelium (WILLIS & WILKIE, 1999; MONÇÃO-SILVA et al., 2016).

The iris color may vary according to the species, and there may also be intraspecific alteration, depending on the amount and types of pigments, degree of vascularization, age, sex and diet (WILLIS & WILKIE, 1999; BORTOLOTTI et al., 2003; KERN & COLITZ, 2013; WILLIAMS, 2012; RODARTE-ALMEIDA et al., 2013), exposure to polychlorinated biphenyls (BORTOLOTTI et al., 2003) and reproductive season (O'CONNELL et al., 2017). There is a wide range of colors that can be observed, from brown to yellow to blue (BORTOLOTTI et al., 2003; BALDOTTO, 2012; WILLIAMS, 2012; RODARTE-ALMEIDA et al., 2013; MEEKINS et al., 2015).

The musculature of the bird iris is composed mainly of striated muscle fibers, which allow the voluntary contraction of the pupil, which makes it difficult to evaluate the pupillary light reflex (WILLIS & WILKIE, 1999; BAYÓN et al., 2007; WILLIAMS, 2012). The use of topical or intracameral neuroblockers for pharmacological dilation of the pupil, such as non-depolarizing muscle relaxants, is mandatory (BAYÓN et al., 2007; WILLIAMS, 2012). Induction of mydriasis with the use of topical rocuronium bromide is reported in the common buzzard (*Buteo buteo*), little owl (*Athene noctua*) (BARSOTTI et al., 2010a), tawny owl (*Strix aluco*) (BARSOTTI et al., 2010b) and European kestrel (*Falco tinnunculus*) (BARSOTTI et al., 2012) without adverse side effects.

Discrete anisocoria may be normal in stress situations and is commonly described in birds

Table 2 - Reference values for applanation tonometry (mean \pm standard deviation mmHg).

| Species | Reference values (mmHg) | Authors |
|---|-------------------------|--------------------------------------|
| American flamingo (<i>Phoenicopterus ruber</i>) | 16.1 \pm 4.2 | MEEKINS et al. (2015) |
| American kestrel (<i>Falco sparverius</i>) | 8.5 \pm 4.4 | LABELLE et al. (2012) |
| Bald eagle (<i>Haliaeetus leucocephalus</i>) | 20.6 \pm 2.0 | STILES et al. (1994) |
| Bald eagle (<i>Haliaeetus leucocephalus</i>) | 21.5 \pm 1.7 | KUHN et al. (2013) |
| Barred owl (<i>Strix varia</i>) | 11.7 \pm 3.8 | LABELLE et al. (2012) |
| Black-footed penguin (<i>Spheniscus demersus</i>) | 31.77 \pm 3.30 | GONZALEZ-ALONSO-ALEGRE et al. (2014) |
| Blue-and-yellow macaw (<i>Ara ararauna</i>) | 7.0 \pm 2.0 | MONÇÃO-SILVA et al. (2016) |
| Brown pelican (<i>Pelecanus occidentalis</i>) | 10.86 \pm 1.61 | O'CONNELL et al. (2017) |
| Common buzzard (<i>Buteo buteo</i>) | 17.2 \pm 3.53 | BARSOTTI et al. (2013) |
| Cooper's hawk (<i>Accipiter cooperii</i>) | 16 \pm 1.8 | LABELLE et al. (2012) |
| Eastern-screech-owl (<i>Megascops asio</i>) | 11 \pm 1.9 | HARRIS et al. (2008) |
| Eastern-screech-owl (<i>Megascops asio</i>) | 9.3 \pm 2.6 | LABELLE et al. (2012) |
| Eurasian eagle owl (<i>Bubo bubo</i>) | 9.35 \pm 1.81 | JEONG et al. (2007) |
| European kestrel (<i>Falco tinnunculus</i>) | 8.53 \pm 1.59 | BARSOTTI et al. (2013) |
| Golden eagle (<i>Aquila chrysaetos</i>) | 20.6 \pm 2.0 | STILES et al. (1994) |
| Great horned owl (<i>Bulbo virginianus</i>) | 10.8 \pm 3.6 | STILES et al. (1994) |
| Great horned owl (<i>Bubo virginianus</i>) | 9.9 \pm 2.4 | LABELLE et al. (2012) |
| Humboldt penguin (<i>Spheniscus humboldti</i>) | 20.36 \pm 4.1 | SWINGER et al. (2009) |
| Lear's macaw (<i>Ara leari</i>) | 7.0 \pm 1.75 | MONÇÃO-SILVA et al. (2016) |
| Little owl (<i>Athene noctua</i>) | 9.83 \pm 3.41 | BARSOTTI et al. (2013) |
| Ostrich (<i>Struthio camelus</i>) | 18.8 \pm 3.5 | GHAFFARI et al. (2012) |
| Red-tailed hawk (<i>Buteo jamaicensis</i>) | 20.6 \pm 3.4 | STILES et al. (1994) |
| Red-tailed hawk (<i>Buteo jamaicensis</i>) | 20.3 \pm 2.8 | LABELLE et al. (2012) |
| Southern caracara (<i>Caracara plancus</i>) | 19.18 \pm 3.06 | BALDOTTO (2012) |
| Striped owl (<i>Asio clamator</i>) | 13.81 \pm 5.63 | RODARTE-ALMEIDA et al. (2013) |
| Swainson's hawk (<i>Buteo swainsoni</i>) | 21.5 \pm 3.0 | STILES et al. (1994) |
| Tawny owl (<i>Strix aluco</i>) | 15.6 \pm 3.4 | WILLIAMS et al. (2006) |
| Tawny owl (<i>Strix aluco</i>) | 11.21 \pm 3.12 | BARSOTTI et al. (2013) |
| Turkey (<i>Meleagris gallopavo</i>) | 25 ¹ | BAYÓN et al. (2007) |
| Turkey vulture (<i>Cathartes aura</i>) | 15.0 \pm 2.1 | LABELLE et al. (2012) |

¹Single value of reference provided by the author.

(MONTIANI-FERREIRA, 2001; HARRIS et al., 2008). There is direct (WILLIS & WILKIE, 1999; HARRIS et al., 2008) and consensual pupillary light reflex; although, difficult to observe routinely (LI & HOWLAND, 1999).

Iridocorneal angle in birds is well developed, and it can be observed that the trabecular meshwork extends through the iris stroma (BAYÓN et al., 2007; RODARTE-ALMEIDA et al., 2013). The lateral extension of the anterior chamber is broad, continuing posteriorly, between

the ciliary body and the sclera, being referred to as the ciliocleral sinus (EVANS & MARTIN, 1993). This sinus is crossed by a large network of elastic fibers that make up pectinate ligaments with wide openings, called spaces of iridocorneal angle or spaces of Fontana (EVANS & MARTIN, 1993). RODARTE-ALMEIDA et al. (2013) described these ligaments as well-developed in owls and with extensive trabecular meshwork, especially in the temporal region of the eye, making it possible to observe the spaces of iridocorneal angle without

Table 3 - Reference values for rebound tonometry (mean \pm standard deviation mmHg).

| Species | Reference values (mmHg) | Authors |
|---|------------------------------|-----------------------|
| American flamingo (<i>Phoenicopterus ruber</i>) (OD) ¹ | 10.9 \pm 1.8 | MOLTER et al. (2014) |
| American flamingo (<i>Phoenicopterus ruber</i>) (OS) ² | 11.1 \pm 2.3 | MOLTER et al. (2014) |
| American flamingo (<i>Phoenicopterus ruber</i>) | 9.5 \pm 1.7 | MEEKINS et al. (2015) |
| American kestrel (<i>Falco sparverius</i>) | 6.8 \pm 1.7 | LABELLE et al. (2012) |
| Barn owl (<i>Tyto alba</i>) | 10.8 \pm 3.8 | REUTER et al. (2011) |
| Barred owl (<i>Strix varia</i>) | 8.3 \pm 3.2 | LABELLE et al. (2012) |
| Black-footed penguin (<i>Spheniscus demersus</i>) (OD) ¹ | 30.41 \pm 4.27 | MERCADO et al. (2010) |
| Black-footed penguin (<i>Spheniscus demersus</i>) (OS) ² | 28.13 \pm 6.84 | MERCADO et al. (2010) |
| Blue-and-yellow macaw (<i>Ara ararauna</i>) | 11.49 \pm 0.22 | FALCÃO et al. (2017a) |
| Blue-and-yellow macaw (<i>Ara ararauna</i>) | 7.71 \pm 0.08 ³ | FALCÃO et al. (2017a) |
| Blue-fronted parrot (<i>Amazona aestiva</i>) | 6.4 \pm 0.1 | FALCÃO et al. (2017b) |
| Common buzzard (<i>Buteo buteo</i>) | 26.9 \pm 7.0 | REUTER et al. (2011) |
| Common kestrel (<i>Falco tinnunculus</i>) | 9.8 \pm 2.5 | REUTER et al. (2011) |
| Cooper's hawk (<i>Accipiter cooperii</i>) | 10.7 \pm 1.4 | LABELLE et al. (2012) |
| Domestic pigeon (<i>Columba livia</i>) | 6.1 \pm 0.9 | MOOD et al. (2016) |
| Domestic pigeon (<i>Columba livia</i>) | 11.7 \pm 1.6 | PARK et al. (2017) |
| Duck (<i>Anas platyrhynchos</i>) | 10.2 \pm 2.2 ³ | MOOD et al. (2017) |
| Eastern-screech-owl (<i>Megascops asio</i>) | 9 \pm 1.8 | HARRIS et al. (2008) |
| Eastern-screech-owl (<i>Megascops asio</i>) | 6.3 \pm 1.3 | LABELLE et al. (2012) |
| Eurasian eagle owl (<i>Bubo bubo</i>) | 10.45 \pm 1.64 | JEONG et al. (2007) |
| Eurasian sparrow hawk (<i>Accipiter nisus</i>) | 15.5 \pm 2.5 | REUTER et al. (2011) |
| Goose (<i>Anser anser</i>) | 9.1 \pm 2.0 ⁴ | MOOD et al. (2017) |
| Great grey owl (<i>Strix nebulosa</i>) | 9.6 \pm 2.6 | WILLS et al. (2016) |
| Great horned owl (<i>Bubo virginianus</i>) | 9.9 \pm 2.2 | LABELLE et al. (2012) |
| Long-eared owl (<i>Asio otus</i>) | 7.8 \pm 3.2 | REUTER et al. (2011) |
| Northern goshawk (<i>Accipiter gentilis</i>) | 18.3 \pm 3.8 | REUTER et al. (2011) |
| Peregrine falcon (<i>Falco peregrinus</i>) | 12.7 \pm 5.8 | REUTER et al. (2011) |
| Red kite (<i>Milvus milvus</i>) | 13.0 \pm 5.5 | REUTER et al. (2011) |
| Red-tailed hawk (<i>Buteo jamaicensis</i>) | 19.8 \pm 4.9 | LABELLE et al. (2012) |
| Snowy owl (<i>Bulbo scandiactus</i>) | 9.1 \pm 1.9 | WILLS et al. (2016) |
| Tawny owl (<i>Strix aluco</i>) | 9.4 \pm 4.1 | REUTER et al. (2011) |
| Turkey vulture (<i>Cathartes aura</i>) | 11.7 \pm 1.0 | LABELLE et al. (2012) |
| White-tailed sea eagle (<i>Haliaeetus albicilla</i>) | 26.9 \pm 5.8 | REUTER et al. (2011) |

¹Right eye, ²Left eye, ³Under anesthesia, ⁴Mean \pm 2 standard deviations.

use of lens for gonioscopy in the unarmed eye of young birds.

Birds have excellent visual accommodation capacity, a process of changing the focal length of the lens by means of altering the corneal curvature associated with anterior movement and lens deformation (BAYÓN et al., 2007; KERN & COLITZ, 2013; WILLIAMS, 2012). Lens is transparent and has a variable shape, being almost spherical in nocturnal birds and anteriorly flat in diurnal species (WILLIS & WILKIE, 1999; BAYÓN et al., 2007). Under the peripheral region of the lens there is a modified fibrous

annular pad (WILLIS & WILKIE, 1999; WILLIAMS, 2012) that allows attachment between the lens and ciliary body, and consequently with the muscles responsible for accommodation, which are called Brucke's and Crampton's muscles (BAYÓN et al., 2007; KERN & COLITZ, 2013; WILLIAMS, 2012).

Crampton's muscle originates in the sclera, below the scleral ossicles, and contracts to flatten the cornea along its periphery and bulges the center, increasing refractive power (BAYÓN et al., 2007; KERN & COLITZ, 2013; WILLIAMS, 2012). Brucke's muscle pulls the ciliary body

forward, decreasing the tension applied to the annular pad by the tenacular ligament of the ciliary body (BAYÓN et al., 2007; KERN & COLITZ, 2013; WILLIAMS, 2012). Deformation of the lens is also caused by the pressure of the circumferential muscle of the iris, which bulges the central portion of the lens, increasing its refractive power (WILLIAMS, 2012). Density of this muscle differs between species and is well developed in diving birds, where it is necessary to compensate for the lack of refraction of the cornea underwater (WILLIAMS, 2012).

Posterior pole

The retina is atapetal and avascular, being nourished primarily by the choroid (WILLIS & WILKIE, 1999; KERN & COLITZ, 2013; RUGGERI et al., 2010). The vascularization and pigmentation of the choroid determine its coloration, usually gray or reddish, and it is possible to visualize the choroidal vessels in some species (BAYÓN et al., 2007; KERN & COLITZ, 2013; RODARTE-ALMEIDA et al., 2013).

The type of photoreceptors and their density varies according to the visual ecology of the species, but usually rods and cones are present (WILLIS & WILKIE, 1999; CUTHILL et al., 2000; BAYÓN et al., 2007). Some species present double cones and have oil droplets (WILLIS & WILKIE, 1999; CUTHILL et al., 2000) with a high content of carotenoids, which function is to filter the ultraviolet radiation that reaches the photoreceptors (CUTHILL et al., 2000). Generally, there is a region with a high density of cones, the *area centralis* (WILLIS & WILKIE, 1999).

In some birds, there is a fovea, a region of retinal depression where there is a dense arrangement of cones and a thinning of the layers of the retina, which allows more intense light stimulation in this region (WILLIS & WILKIE, 1999). According to the number of foveas, birds can be classified as afoveal, monofoveal and bifoveal (BAYÓN et al., 2007). Poultry have an afoveal retina and an *area centralis*, having lower visual acuity compared to other birds (MONTIANI-FERREIRA, 2001). The monofoveal retinas have a central fovea (most birds) or temporal fovea (nocturnal predators, swallows), with or without an *area centralis* around the fovea (MURPHY, 1993; OROSZ, 2007; RUGGERI et al., 2010). In the bifoveal retinas, there is a main central fovea and an auxiliary one, with or without *area centralis* between the foveas (passerines, diurnal predators and other birds that hunt during flight)

(MURPHY, 1993; MONTIANI-FERREIRA, 2001; BAYÓN et al., 2007; OROSZ, 2007; RUGGERI et al., 2010).

The pecten (*pecten oculi*) is a tissue projection that emerges from the choroid towards the vitreous body, located above the optic disc and reported in almost all birds. It is pigmented, with blackish coloration, and highly vascularized (WILLIS & WILKIE, 1999; BAYÓN et al., 2007; RUGGERI et al., 2010). It is assumed that the pecten has the primary function of retinal nutrition and maintenance of intraocular pressure (WILLIS & WILKIE, 1999; FERREIRA et al., 2016). FERREIRA et al. (2016) used vascular Doppler ultrasonography to determine blood flow parameters of the pecten in ducks, with results suggestive of high metabolic activity in the pecten, indicating possible nutritional functions, production of aqueous humor and regulation of intraocular pressure.

The pecten is morphologically classified according to its shape and number of folds: conical, found in kiwis (*Apteryx australis*); in the form of wing or flag, reported in ostriches (*Struthio camelus*) and rheas (*Rhea americana*); and folded or pleated, reported in all other species (KERN & COLITZ, 2013). The optic disc is long and oval, but it cannot be observed by ophthalmoscopy, since it is located below the pecten, which obstructs its visualization (WILLIS & WILKIE, 1999; BAYÓN et al., 2007; WILLIAMS, 2012).

CONCLUSION

The field of avian ophthalmology is broad and needs constant research and updates in order to start to fill the gaps. As noted, the numerous features inherent to the avian eye make it essential to investigate and report the reference values and peculiarities in the different genus and, sometimes, species. It is necessary to know the anatomical and physiological characteristics of the birds to adapt materials and procedures and to be able to correctly interpret the findings of physical and complementary examinations.

DECLARATION OF CONFLICTING INTERESTS

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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