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Biologging is suspect to cause corneal opacity in two populations of wild living Northern Bald Ibises (*Geronticus eremita*)

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Abstract

Background: In this paper, we present evidence that biologging is strongly correlated with eye irritation, with sometimes severely impairing effects. A migratory population of the Northern Bald Ibis (*Geronticus eremita*, NBI) is reintroduced in Europe, in course of a LIFE + project. Since 2014, all individuals have been equipped with GPS-devices. Remote monitoring allows the implementation of focussed measures against major mortality causes.

Methods: Initially all birds carried battery-powered devices, fixed on the lower back of the birds. Since 2016 an increasing amount of birds has been equipped with solar-powered devices, fixed on the upper back, the more sun-exposed position. In 2016, we observed opacity in the cornea of one eye (unilateral corneal opacity; UCO) during a regular health monitoring for the first time.

Results: By 2018, a total of 25 birds were affected by UCO, with varying intensity up to blindness. Clinical examination of the birds revealed no clear cause for the symptoms. However, only birds carrying a device on the upper back were affected (2017 up to 70% of this group). In contrast, none of the birds carrying devices on the lower back ever showed UCO symptoms. This unexpected relationship between tagging and UCO was discovered in 2017. After we took countermeasures by removing the device or repositioning it on the lower back, we observed an immediate reduction of the incidence rate without any new cases reported since January 2019. NBI roost with their head on the back, one eye closely placed to the device if it was positioned on the upper back. Thus, we conclude that the most parsimonious explanation for the symptomatology is either a repetitive slight temperature rise in the corneal tissue due to electromagnetic radiation by the GSM module of the device or a repetitive slight mechanical irritation of the corneal surface. Concrete evidence is missing so far. Meanwhile, cases of UCO were found in another NBI population.

Conclusion: Our observations indicate that further research in the fast-growing field of biologging is urgently needed. The findings question the positioning of devices on the upper back in birds roosting with the head on the back.

Keywords: Blindness, Electromagnetic radiation, Endangered bird species, Eye opacity, GPS-devices, Mechanical irritation, Reintroduction, Solar-powered

Background

Biologging, defined as the use of miniaturized animal-attached tags for logging and/or relaying of data (Rutz and Hays 2009), is a fast-growing field of basic and applied research in biology. Rapid technological development over the last decades allowed developing small

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and light devices applicable to an even wider range of species throughout taxa down to the smallest birds and even large insects (Wikelski et al. 2007; Kays et al. 2015). Also the scope of applications steadily increases, conventional radio tracking and remote GPS-monitoring is completed by the measurement and transmission or logging of biological and environmental parameters and even video footage (Bluff and Rutz 2008). Consequently, the importance of biologging for basic and applied research is constantly expanding (Rutz and Hays 2009; Kays et al. 2015). Visions about future applications are far reaching, including the use of birds populations of various moving animal species as living sentinels for climate change and other environmental threats (Pschera 2014; Wikelski and Tertitski 2016), the fisheries management (Lowerre-Barbieri et al. 2019) or instant anti-poaching tags to prevent species from environmental crime (O'Donoghue and Rutz 2016; Fritz et al. 2019).

Placement of the devices ranges from intra-peritonealor subcutaneous implants (Mellish et al. 2007; Wascher et al. 2009) to external placement at different locations of the animal's body (Kays et al. 2015). In birds, as a proprietary animal group for biologging, a common position for external attachment is the lower back, where the device is fixed by various types of leg-loop harnesses. This position was found to be drag-reduced compared to other body positions (Bowlin et al. 2010; Pennycuick et al. 2012). However, at this position the device is usually covered by wing-feathers when the bird is perching. This is a significant disadvantage for solar-powered devices which are dependent on sun exposure. Therefore, solar-powered devices are mainly placed at a more sun-exposed upper back position, fixed by various types of wing-loop harnesses.

The rapidly increasing application of biologging technology also causes a growing debate on trade-offs, deleterious effects and related ethical issues (Bowlin et al. 2010; Vandenabeele et al. 2012; Thaxter et al. 2016; Bodey et al. 2018). In birds, controversial discussions on impairing effects of biologging are mainly focussed on the ratio of tag mass to body mass, and in many biologging studies tag mass below a 5% threshold is the major justification for tag-use (Bodey et al. 2018). However, in a study with 80 seabird species Vandenabeele et al. (2012) found that devices with only 3% of the bird's body mass resulted in an increase in energy expenditure for flight ranging from 4.67% to 5.71%. In a meta-analysis Bodey et al. (2018) even found negative effects upon survival, reproduction and parental care when tags weight more than 1% of species' body mass. Moreover, a recent study indicates that the miniaturization of biologging devices has not resulted in a decrease in the relative device mass borne by animals, but instead has prompted researchers to monitor smaller and smaller species (Portugal and White 2018).

Furthermore, there is increasing evidence that the weight of the device relative to the carriers' body mass is not the only and probably even not the major parameter which causes impairing effects. There is increasing evidence that in flying and aquatic animals aerodynamic respectively hydrodynamic forces can vary considerably dependent on the shape and profile of the housing as well as placement on the body (Obrecht et al. 1988; Bowlin et al. 2010; Pennycuick et al. 2012; Thaxter et al. 2016). For example, computational fluid dynamics modelling indicates that a conventional tag can induce up to 22% larger drag compared to a streamlined tag (Kay et al. 2019).

In this case study, we describe a hitherto unknown physiological effect, the so-called unilateral corneal opacity (UCO), which occurred in a reintroduced population of the Northern Bald Ibis (*Geronticus eremita*; Fritz et al. 2019) with strong evidence for a causal relationship to biologging.

Methods

Study system

The European LIFE + reintroduction project, LIFE Northern Bald Ibis (*Geronticus eremita*, NBI) aims to establish a migratory population in Central Europe with a migration tradition to the southern Tuscany (Fritz et al. 2017, 2019; http://www.waldrapp.eu). A steadily increasing number of wild living birds migrate between the common wintering site and three breeding sites north of the Alps. Chicks fledge every year in the wild and follow experienced conspecifics to the wintering site.

Biologging is a pivotal measure for an efficient and focussed management of a migratory species with large scale movements. This is particular due to an endangered species like the NBI where little is known about the former migratory behaviour (Bowden et al. 2008; Serra et al. 2014; Fritz and Unsöld 2015). Since 2014, all individuals in the release population are equipped with GPS tags. This allows remote monitoring of the whole population, as a basic requirement for efficient measures against the main causes of mortality (Fritz 2015; Fritz et al. 2019).

End of 2018, the NBI release population consisted of 102 individuals (Fritz et al. 2019). In 2018, a total of 21 NBIs returned independently to one of the two breeding areas north of the Alps, Kuchl (Austria) and Burghausen (Bavaria). They raised a total of 26 fledglings, and all together migrated to the wintering site in autumn. The reintroduction is still ongoing, with the establishment of further migratory breeding colonies (Fritz et al. 2017, 2019).

Data collection

Since the start of the European LIFE + project (LIFE + 12-BIO_AT_000143) in 2014, all individuals in the release population were equipped with GPS devices. Different tag types were used (Table 1). From 2014 to 2015, all birds carried battery powered devices (type 1), fixed via leg-loop harness on the lower back. In 2016 and 2017, some birds' type 1 tags were replaced by type 2 solar-tags and all newly released or wild-hatched birds were equipped with type 2 solar-tags. End of 2017, 72% of the whole population ($N = 84$) still carried type 1 battery powered devices at the lower back position, while 28% carried type 2 solar-tags fixed at the upper-back. In 2018, most of the type 1 and type 2 devices were replaced by type 3 solar-tags, so that end of 2018 84% of the whole population ($N = 102$) carried type 3 solar-tags. The relative mass of all tags was below 5% of the birds' body mass (females 1.257 g, SD = 60 g, $N = 20$; males 1.390 g, SD = 58 g, $N = 20$), and all solar-tags were below 3% of the birds' body mass.

During a routine veterinary screening in spring 2016, an adult male (ID 027; Table 2) was found to have a serious opacity at the cornea of the left eye. This was the first time that UCO was observed in our population. We assumed it to be a singular case with traumatic cause. The affected bird died one month later during the spring migration due to unknown reasons. During a routine screening at the beginning of 2017, two birds with severe panuveitis were detected (ID 144, ID 057). In both cases the destruction of one eye was obvious. In one female (ID 144, Table 2) the ongoing inflammation leads to the removal of her eyeball.

Alarmed by these cases, most birds in the release population were successively caught and screened. Even with the plain eye and without any ophthalmological instruments the opacities were obvious for the observer. In 2017, a total of 16 cases of UCO were detected in total and in 2018, again eight cases. Thus, together with the single case in 2016, a total of 25 birds were found to suffer from UCO. Thanks to the increased awareness of the symptoms, UCO could be detected in an early stage in most birds.

Depending on the degree of corneal opacity (Fig. 1) we distinguished five stages of UCO, from stage 1 with small-scale opacity, where iris and pupil are fully recognizable, to stage 5 with complete corneal opacity, where the iris and pupil are no longer visible. Allocation of the intensity score was done by eight coders based on pictures of the affected eyes (Table 2). In 11 cases, no pictures were taken and allocation was done out in the field by one field manager (D. Trobe) only.

Statistical analysis

Statistical analyses were made using the software R version 3.6.1 (R Core Team 2014). The frequency of incidences of UCO was compared using Chi-squared tests and side preferences during roosting were compared with a Wilcoxon signed rank test. A Yates continuity correction was used for Chi-squared tests to prevent overestimation of statistical significance when frequencies were low. In cases where one observed frequency was zero, the asymptotic approximation of χ^2 is unreliable and p-values were estimated using a Monte Carlo method with 106 replicates.

Ethical standards

Release of the NBI in course of the European LIFE project is done in accordance with the IUCN Reintroduction Guidelines and is approved by the regarding national authorities. Equipment with GPS-devices is approved and even mandatory for the NBIs reintroduction in Bavaria (Government of Bavaria, Approval 55.1-8646.NAT_03-10-1) and Baden-Württemberg (Regierungspräsidium Tübingen, Approval 55-4/8852.41). Tagging is done by experienced field managers (D. Trobe, C. Esterer) based on current standards. All birds in the population are visually monitored during their stay in the wintering or breeding site. Health monitoring and veterinary care is carried out in accordance with the IUCN Reintroduction Guidelines and under responsibility of Alexandra Scope, Veterinarian at the Veterinary University of Vienna. Birds with conspicuous behaviour or obvious problems can be recaught for further examination and potential treatment (Fritz et al. 2019).

Table 1 Used tag types

	Power supply	GNSS	Data transmission	Initial mounting	Weight (gram)	% body weight male	% body weight female
Type 1	Battery	GPS	GSM / GPRS	Leg-loop	42	3,0	3,3
Type 2	Solar	GPS	GSM / GPRS	Wing-loop	20	1,4	1,6
Type 3	Solar	GPS	GSM / GPRS	Wing-loop	22	1,6	1,8

Table 2 Individuals affected by Unilateral Eye Opacity in the Northern Bald Ibis release population during the period 2016–2018

ID	Sex	Generation[a]	Breeding area	Tag type	Date of tag attachment	Date of tag detected	Age at detection (months)	% wing-loop devices at detection[b]	Affected eye	Intensity allocation [c]	Measure after detection	Effect of measure[d]
27	Male	F1	Burghausen	Type 2	Jan-16	Mar-16	47	23	Left	3,8	None	Unknown
57	Female	F1	Burghausen	Type 2	Feb-16	Jan-17	32	32	Right	4,4	None	Deterioration
144	Female	F0	Burghausen	Type 2	Oct-16	Jan-17	9	32	Left	4,4	Removal	Deterioration
101	Male	F1	Burghausen	Type 2	Apr-16	Feb-17	21	32	Right	2,7	None	Unknown
116	Male	F1	Kuchl	Type 2	Feb-16	Feb-17	21	32	Left	3,1	Removal	Recovery
103	Female	F1	Burghausen	Type 2	Feb-16	Mar-17	22	34	Left	1,3	None	Unknown
67	Female	F1	Kuchl	Type 2	Feb-16	Mar-17	32	34	Left	3,3	None	Deterioration
142	Female	F0	Kuchl	Type 2	Oct-16	Mar-17	11	34	Right	3,0	None	
111	Male	F1	Kuchl	Type 2	Feb-16	Mar-17	22	34	Right	1,3	None	Deterioration
112	Female	F1	Kuchl	Type 2	Feb-16	Mar-17	23	33	Right	1,3	Removal	
123	Male	F0	Kuchl	Type 2	Nov-16	Mar-17	11	34	Left	1,3	None	Unknown
184	Female	F0	Ueberlingen	Type 2	Oct-17	Nov-17	8	36	Right	1,4	Re-positioning	Recovery
183	Female	F0	Ueberlingen	Type 2	Oct-17	Nov-17	8	36	Right	2,0	Re-positioning	Recovery
133	Female	F0	Burghausen	Type 2	Oct-16	Nov-17	20	36	Left	0,9	Re-positioning	Recovery
32	Female	F1	Burghausen	Type 2	Mar-17	Dec-17	55	28	Left	1,3	Removal	Recovery
29	Male	F1	Kuchl	Type 2	Sep-17	Dec-17	56	28	Right	0,9	Removal	Recovery
203	Male	F1	Burghausen	Type 2	Aug-17	Dec-17	7	17	Right	1,3	Removal	Recovery
182	Female	F0	Ueberlingen	Type 3	Mar-18	Aug-18	17	55	Right	2,3	Re-positioning	Recovery
180	Male	F0	Ueberlingen	Type 3	Mar-18	Oct-18	19	63	Left	4,1	Re-positioning	Recovery
178	Female	F0	Ueberlingen	Type 3	Mar-18	Nov-18	20	63	Right	3,5	Re-positioning	Recovery
208	Male	F1	Burghausen	Type 3	Mar-18	Nov-18	18	63	Left	1,3	Re-positioning	Recovery
204	Male	F1	Burghausen	Type 3	Mar-18	Dec-18	19	63	Left	3,0	Re-positioning	Recovery
230	Male	F0	Ueberlingen	Type 3	Oct-18	Dec-18	8	66	Right	1,3	Re-positioning	Recovery
197	Female	F1	Burghausen	Type 3	Mar-18	Dec-18	20	63	Right	2,3	Re-positioning	Recovery
265	Male	F1	Kuchl	Type 3	Aug-18	Dec-18	7	64	Left	3,3	None	Unknown

[a] F0 Founder generation, released after human-led migration; F1=first generation hatched in the wild

[b] Proportion of the population with devices at the wing-loop position, the rest carried devices at the leg-loop position

[c] Mean allocation by eight participants due to pictures of the affected eye; grey background indicates cases where DT allocated the intensity in the field without picture

[d] Unknown effect means that the bird died or got lost before the effect could be evaluated

Fig. 1 Intensity of the one-eye opacity symptomatology at discovery in five categories, depending on the degree of opacity of the cornea, from small-scale opacity, where the iris and pupil are entirely sharp recognizable (state 1, left) to a complete clouding of the cornea, where the iris and pupil are no longer clearly visible (state 5, right) (Picture Copyright: Waldrappteam, LIFE Northern Bald Ibis)

Results

In spring 2017, we recognized a clear relationship between UCO and biologging. Only birds with solar-powered tags (type 2), fixed via wing-loop on the upper back, have been affected. This was remarkable, because beginning of 2017, only 25 out of 79 individuals (32%) carried type 2 devices, while all the rest (68%) were equipped with battery-powered devices (type 1), fixed with leg-loops on the lower back. This pattern holds for all 25 UCO cases, without any exception, resulting in a highly significant deviation from the expected frequency distribution (Chi-squared test with Yates' continuity correction, $\chi^2 = 39.46$, df $= 1$, $p = 3.34 \times 10^{-10}$).

Until the end of 2017, we used only solar tags of type 2 (Table 1). In 2018, we started using another type of solar tags (type 3; Table 1), also placed on the upper back. In the following, we had eight cases of UCO with birds carrying a type 3 device. None of these birds carried a type 2 device before, therefore a delayed effect of a type 2 device can be excluded. Thus, we have no indication for a causal relationship between a special type of solar-tag and the symptomatology.

From 2017, different measures were taken after detection of the symptoms, either removal of the solar-tag ($N = 5$) or re-positioning of the solar-tag from the upper back to the lower back, fixed via leg-loop harness ($N = 10$). In those cases where the effect of the measure could be determined removing or repositioning the device leads significantly more often to recovery than taking no action ($\chi^2 = 13.36$, $p = 0.004$, Pearson's Chi-squared test). In fact, in all except of one case (ID 144; see next paragraph) taking either measure led to recovery within a few months.

If no measures were taken, survival was found to be significantly lower ($\chi^2 = 14.52$, $p = 0.00014$, Pearson's Chi-squared test). We have no cases where an affected bird has recovered if the tag remained; rather the opacity further advanced and became irreversible. This was particularly indicated by the early cases (ID 057, ID 144), where the device was not immediately removed from the upper back position, because a relationship was not suspected at that time. In these cases, the condition has worsened progressively until the birds lost all sight in the regarding eye. In one case (ID 144), the affected eye even had to be removed due to severe inflammation.

Eye opacity was found in birds from three different breeding colonies (Table 2) and in both males ($N = 12$) and females ($N = 13$). Affected birds were partly members of the founder generation (F0: $N = 10$), stemming from different European zoos, and partly wild-born (F1: $N = 15$). Kinship data and genetic data (Wirtz et al. 2018) did not hint at any particular relationship between the affected individuals. Left and right eyes were equally affected by UCO (left: $N = 12$, right: $N = 13$).

NBI roost with their head on the back. In this position, one eye comes close to a device fixed on the upper-back position (Fig. 2). To test, if individual side preference in head positioning during roosting may explain the unilaterality, we surveyed a group of 32 human-raised juvenile NBI. All of the birds changed between left side (overall

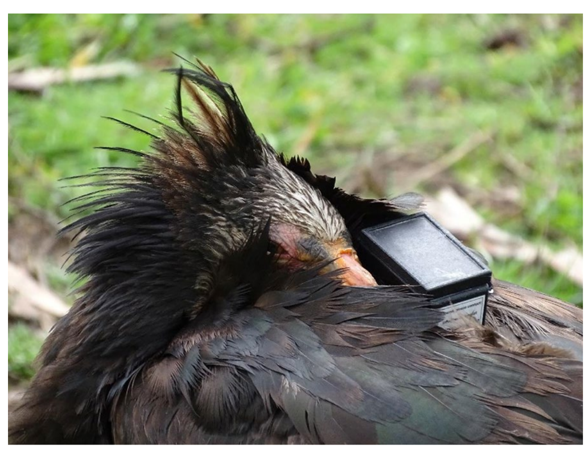

Fig. 2 Juvenile Northern Bald Ibis in a characteristic sleep and rest position with the head on the back, the bill between the wings and one eye very close to the GPS device (Picture Copyright: Waldrappteam, LIFE Northern Bald Ibis)

51.2% of all instances) and right side (48.8%). A non-parametric sign test suggests no difference between the two sides (Wilcoxon signed rank test, $W = 202.5$, $p = 0.4975$, two-tailed). Thus, individual side preference in head positioning during roosting cannot explain the unilaterality.

Discussion

Since 2014, all NBI of the release population carry GPS devices to allow remote monitoring of the whole population. In addition, we regularly observe most of the birds and an essential part of the individuals are caught once a year for veterinary screening. Observation and screening was the reason that we became aware of the UCO symptomatology, which was completely unknown so far.

Several ophthalmological examinations in living animals (ID 057, ID 144), in enucleated eyes (ID 144, ID 067) or in eyes of dead birds (ID 116 and others) were performed by veterinary ophthalmologists and human physicians. The examinations revealed no clear cause for the symptoms. The general appearance was partial or complete cloudiness of the cornea. This can be caused by infections of conjunctiva and corneal tissue. However, virologic and bacteriological examinations did not provide any significant results nor did the histological examinations (ID 067) reveal any evidence of infection. Also, no indications for a trauma or a mechanical damage of the cornea surface were found. Fluorescein tests were negative in all tested cases.

The course of the disease seems to affect first only the superficial stroma of the cornea. In several cases, the cornea showed vessel ingrowth. In advanced stages, the lens of the affected eye was cataractous and partial liquefaction and vacuolization of lens material had occurred. These eyes showed inflammatory changes like conjunctivitis and uveitis. Squeal of inflammation and lens material resorption led to iridodonesis, dyscoria and posterior synechiae formation. Two affected birds (ID 144, ID 057) were treated with antibiotics and cortisone, without noticeable effect. Therefore, no further birds were treated.

It became apparent that UCO is related to the placement of a GPS-device via wing-loop harness at the upper back. This was substantiated by each new case. The habit of the birds to roost with the head on the back suggests a plausible causal relationship between the placement of the GPS device and UCO. This roosting position brings one eye close to the device placed at the upper-back position. Thus, a cumulative proximity effect on the nearby eye during roosting phases seems to be the most parsimonious proximate cause for UCO. We initially assumed that the symptoms are caused by a particular type of tag (type 2; Table 1). For this reason, we switched to a new type of solar transmitter (type 3) at the beginning of 2018. But it soon became evident, that type 3 causes the same symptoms.

A striking feature of UCO is that in all cases only one eye is affected, left and right equally. We found no individual side preference, when the birds turn the head to the back into the sleeping position, as an obvious explanation for unilaterality. This also corresponds with patterns found in three birds (ID 184, 133, 029) which were twice affected by UCO, initially with type 2 devices and later on with type 3 devices at the same wing-loop position. In one case (ID 184), the same eye was repeatedly affected, while in two individuals (ID 133, 029) the other eye was affected the second time. Thus individual side preference may be triggered by the onset of illness. In particular, if the visual acuity of one eye is affected by UCO, the bird may tend to position the head mainly in a way that the unaffected eye is used for regular vigilance during roosting (Fig. 2).

Since UCO was initially unknown for other NBI populations or other species, we assumed the ultimate cause for the disease could be a population-specific effect. However, genetics or environmental effects like contamination seem unlikely given the aetiology and incidence pattern. Two infections are known to incidentally cause uveitis under specific conditions, Toxoplasmosis (Vickers et al. 1992; Williams et al. 2001) and the West Nile Virus (Pauli et al. 2007; Wünschmann et al. 2017). However, these infections rather affect the retina than the cornea. Moreover, the consistent unilaterality as well as the fast recovery of the carrier after removal or repositioning of the device can hardly be explained by such infectious diseases.

A further potential cause for the symptoms is proximity effects by specific chemical components of the used devices. For example, solar panels can be provided with a coating containing organometallic compounds, which are known to have toxic effects (Wai-Yeung and Cheuk-Lam 2010). Also, silicon tetrachloride, included in new types of solar-panels, can lead in combination with water to the formation of hydrochloric acid which causes tissue-damages (Braga et al. 2008). However, to our knowledge such compounds were not used in either of the devices. We can also exclude light reflection by the solar panel as a potential cause for UCO, because the panel of the type 3 solar-tag is non-reflective (Fig. 2).

By exclusion of these seemingly implausible ultimate causes for UCO, we ended up with two remaining hypotheses. One is a persistent slight mechanical irritation of the corneal front stroma in the nearby eye during roosting. However, examination of several eyes revealed no indication for mechanical damage of the cornea surface. Moreover, such a mechanical effect requires frequent physical contact between the corneal surface and the device. But even though the eye is close to the device during roosting, a frequent direct contact between the cornea and the device seems unlikely.

The second hypothesis is a proximity effect of transmitted electromagnetic radiation by the GSM component in the range of radio waves, with peak power up to 2 watts (D. Mindaugas, personal communication; http://www.ornitela.com). Several studies indicate that this radiation may cause negative effects on the organism, like DNA breakage, abnormal brain functions, reduced sperm mobility or increased reactive oxygen species concentrations (Al-Khlaiwi and Meo 2004; Daniels et al. 2009; Mailankot et al. 2009; Kesari et al. 2013). However, authors like Ziegelberger (2009) question these general effects.

In contrast, thermal proximity effects of electromagnetic radiation are well measurable. Mobile phones, held on the ear, cause a temperature rise of up to 2.9 °C in the surrounding tissue, particularly in the ear channel (Tahvanainen et al. 2007; Rusnani and Norsuzila 2008; Forouharmajd et al. 2018). Animal studies indicate that temperature rises even below 1 °C can provoke a variety of behavioural and physiological disorders in sensible tissues (Hyland 2000). Corneal tissue is known to be amongst the most thermally vulnerable areas of the body, mainly due to limited thermo-regulation because of low blood supply (Shafahi and Vafai 2010).

A solar-tag transmits several times a day, dependent on the setting and the availability of solar energy. If animals stay outside the optimal network coverage, which happens regularly, connection setup and transmission require radiation close to peak power. Under these circumstances, the transmission of the device exceeds the maximum energy emitted by legally sold mobile devices (maximum SAR level 1.6 watts per kg; Lee et al. 2017).

We conclude that a thermal effect due to electromagnetic radiation is the most probable cause for UCO. However, a verification of this assumption remains pending. It also has to be noted that battery warming could likewise cause significant temperature rise in the nearby tissue (Tahvanainen et al. 2007). Also, an empirical proof is needed about the effect of battery-powered devices at the upper-back position; so far, we only have data from solar-powered devises causing UCO.

Conservation implications

From 2016 till start of the countermeasures end of 2017, a total of 34 individuals were equipped with GPS-devices at the upper-back position. 17 of these birds (50%) were affected by UCO. The effective fitness-impairing effect of UCO in our reintroduced population is difficult to estimate, because of the countermeasures taken from 2017. In most cases, removal or re-positioning of the device had led to a fast regeneration of the eye. But without appropriate measures the fitness of up to 50% of the individuals carrying a device on the upper back position could have been seriously impaired.

This is a substantial proportion, particularly in a founder population of an endangered species. However, the general relevance seemed limited, since the symptoms were only observed in our population. This changed end of 2019, when nine NBIs of an independent release population in Andalusia (Proyecto eremita; López and Quevedo 2016) were caught and screened upon our suggestion. All those birds carried solar-tags on the upper back and five of them showed various degrees of UCO (Fig. 3). This discovery proves that UCO can affect NBI in general.

Morphological and behavioural peculiarities may cause a particular susceptibility of this species to the disease. But there is no evidence to suggest that these symptoms are limited to the NBI. Amlaner and Ball (1983) state that by far most of the commonly reported sleeping attitude for birds is with the bill lying on the bird's back or tucked under the scapulars wing feathers. The lack of evidence in other bird species may simply be caused by the difficulty to recognize the symptomatic in the wild. This assumption is strengthened by the fact that birds of the Spanish release population were equipped with GPS-tags on the upper-back position since years. But despite of regular monitoring, discovery of UCO happened just recently, after raised awareness due to our observations.

UCO may also be related to fitness-impairing effect observed of biologging, where the causal relationship is yet unknown. For example, during an ongoing reintroduction project of the Nippon Ibis (*Nipponia nippon*) at

Fig. 3 Northern Bald Ibis of the Spanish reintroduction project, Projecto Eremita, with the same UCO as in the migratory population of the Waldrappteam. (Picture Copyright: Miguel Quevedo, Zoobotánico, Jerez)

Sado Island (Nagata and Yamagish 2013) the post-release monitoring indicated that birds released with solar-powered GPS tags on the back had a significantly lower survival rate compared to released birds without GPS device. Consequently, no further birds are equipped with GPS devices for release (H. Nagata, personal communication).

Conclusion

The observations and data presented in this paper and the corresponding ones in the Andalusian NBI project suggest that tags fixed via wing-loop harness on the upper back position are the proximate cause for UCO, across sex, age and origin. However, the available data do not allow drawing final conclusions about the causal mechanism. In this context, further investigations are needed, with a particular focus on thermal proximity effects caused by electromagnetic radiation.

Our findings give no reason to question biologging in general, but the UCO example highlights that a comprehensive monitoring of tagged individuals is needed and that it is important to consider apparently unrelated side effects. The call for more systematic documentation and publication of failures and potentially impairing effects of biologging to support more rigorous science and to further improve bird welfare seems well founded. We also agree with the increasingly expressed demand that ethical standards of biologging studies should not be limited to the compliance with an arbitrary 5% or 3% rule related to the body mass (Portugal and White 2018). Other possible effects of biologging should be taken into consideration (Schacter and Jones 2017; Bodey et al. 2018; Geen et al. 2019). In any case biologging affects the individual to a certain extent and potentially in unexpected ways; this burden and risk for the individuals needs to be kept as low as possible.

In our project, we continue with remote monitoring. But all devices are attached on the lower-back via leg-loop harnesses. This position is clearly sub-optimal for solar-tags, because the solar panels are easily covered by wing feathers when the bird is not flying. But despite of a continuous monitoring, no bird with a device on the lower back ever showed UCO symptoms.

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Authors' contributions

JF, CE, DT and AS conceived the study and collected the data. JF, BE, BG, MU, BV, HW and AS analysed the data and performed statistical analyses. JF, BV, HW and AS wrote the paper, with BG and BE providing major contributions. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used are available for the mentioned investigations from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable: the study does not involve humans. All authors adhered to the 'Guidelines for the use of animals in research' as published in Animal Behaviour (1991;41:183–6). This study complies with all current Austrian laws and regulations concerning work with wildlife. Biologging is done in the context of the European LIFE + reintroduction project (LIFE + 12-BIO_AT_000143, LIFE Northern Bald Ibis), in accordance with the IUCN Reintroduction Guidelines as well as regarding European and National law. GPS tracking of all released individuals is a requirement for the national approvals in Baden-Wuerttemberg (55-4/8852.41—Waldrapp—Üb.) and Bavaria (55.1-8646.NAT_03-10-1).

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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