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Mortality and morbidity in captive Livingstone's fruit bats *Pteropus livingstonii*

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Keywords: Livingstone's fruit bat, morbidity, mortality, Pteropodidae, *Pteropus livingstonii*

Article history:
Received: 26 Jul 2020
Accepted: 21 Jul 2022
Published online: 31 Jul 2022

Abstract
Medical and pathology records were reviewed for 161 Critically Endangered Livingstone's fruit bats *Pteropus livingstonii* (LFBs) held at Jersey Zoo and Bristol Zoological Gardens between 1992 and 2017, representing over 95% of the historical population managed at these institutions. The association of mortality and morbidity in relation to age (immature: 0 days–2.5 years, adults: 2.5–15 years, geriatric >15 years) and sex was analysed. Overall, 427 individual medical problems were identified in 56% of the population. The most common causes of morbidity were wounds (34.9%, n=150), localised inflammation (12.9%, n=55) and fractures (10.8%, n=46). Wounds were predominantly located in patagia (25.0%, n=38) and digits of the forelimbs (22.0%, n=33), with males at greater risk than females. Immature specimens were more likely than adult and geriatric animals to suffer wounds. Localised inflammatory lesions showed an increased risk associated with age. Females were found to be more likely to suffer from fractures. Eighty-eight deaths were recorded; the most common identified causes of mortality were early foetal death (18.2%, n=16), heart diseases (14.8%, n=13) and conspecific aggression (10.2%, n=9). Males and geriatric animals had a greater risk of suffering cardiac disease. This study determines the most common medical problems encountered in LFBs in captivity and establishes grounds for additional research into specific pathologies in this species.

Background

Livingstone's fruit bat *Pteropus livingstonii* (LFB) is a pteropid species endemic to the Republic of the Comoros (Smith and Leslie 2006). It is listed as Critically Endangered by the International Union for Conservation of Nature (Sewall et al. 2016). The wild population estimate is 1,260 individuals (Daniel et al. 2017).

A captive population was established between 1992 and 1995, with 17 individuals (10 males, 7 females) from the wild (Trewhella et al. 1995; Young et al. 1993). Between 1992 and July 2017, 161 individuals have been held in six different zoological institutions. All animals had been housed in Jersey Zoo (JZ) and/or Bristol Zoological Garden (BZG) at some point in their lives. Most of the current captive population is held in these two institutions, accounting for 94% of the population in July 2017 (n=63). The recods demonstrate that 129 births have occurred in captivity, predominantly between March and June (n=83).

Diets and enclosures have changed over time. Since 2003, JZ specimens have been housed with a small colony of Rodrigues fruit bats *Pteropus rodricensis* in a heated enclosure with clear polycarbonate walls and ceiling, and a natural earth floor. The dimensions are 38 m long × 8 m wide × 3.5–5 m high, allowing flight. Environmental temperature is maintained between 20 and 30°C. The basic diet is fruit, vegetables, eggs, and occasional, seasonally available leaves, supplemented with an extruded primate leaf-eater diet (Mazuri Leaf-Eater Primate, Dietex International Ltd., Witham, UK).

In BZG, bats are housed in a heated room with solid walls, ceiling and floor. The dimensions are 4 m long × 4 m wide × 6.1 m high. The floor of the whole indoor enclosure is covered with bark substrate. Ambient temperature is maintained at 22–24°C by radiators. There is an outdoor aviary to which the bats have access in good weather. Its dimensions are 9 m long × 11 m wide × 13.5 m high. Their diet consists of a 50:50 mixture of an extruded primate leaf-eater diet (Mazuri-Leaf Eater Primate, Dietex International Ltd.) and an extruded New World primate pellet (Mazuri New World Primate Diet, Dietex International Ltd.) plus a mixture of fruit and vegetables.

The aim of this study was to determine the medical problems encountered in captive-held LFBs.

Action

Medical records from LFBs while housed at JZ and BZG between January 1992 and July 2017 were reviewed (n=161, 82 males (50.93%), 53 females (32.92%), 26 undetermined (16.15%). The records were reviewed using ZIMS for Medical (Species360, Minneapolis, USA) by sharing husbandry and medical records electronically between both institutions. Animals included in this study were divided into three age groups: immature (0 days–2.5 years), adult (2.5–15 years) and geriatric (over 15 years). All seventeen wild-caught animals were categorised as adults (2.5 years) at capture.

Morbidity categories were established based on veterinary diagnosis through observation, physical examination and diagnostic tests. If a definitive diagnosis could not be determined, the most relevant clinical sign was allocated to a category. If more

Table 1. Causes of morbidity identified and defined with descriptions providing specific details to illustrate the criteria for diagnosis in certain categories.

Cause of morbidity	Definition
Abdominal hernia	Protrusion of the abdominal adipose tissue or abdominal organs through the abdominal wall
Abscess	Localised collection of pus within the integumentary tissue
Anaemia	Decreased red blood cell count accompanied by lethargy and anorexia
Arthritis	Joint disorder with pain, stiffness and/or inflammation diagnosed by radiography
Bacterial pleuritis	Tachypnoea and increased respiratory noises detected during thoracic cavity auscultation, caused by coccoid bacteria identified by post-mortem bacteriology
Claw trauma	Damage, pain and/or inflammation of the claw unit caused by trauma
Dental pathology	Dental lesions due to disease, trauma, excessive dental wear or teeth loss
Dermatitis	Inflammation of the skin with rupture of the epidermis layer diagnosed by visual inspection and cytology or histology
Dystocia	Abnormal labour due to unknown inherent condition of the dam or the foetus
Fracture	Break in a bone
Heart disease	Cardiac disorder based on clinical signs, radiography and echocardiography
Hypothyroidism	Endocrine disease of thyroid gland characterised by low blood value of thyroxine (T4) and accompanied by stunted development
Localised inflammation	Detection of cardinal signs of inflammation (redness, swelling, heat, pain, loss of function) by visual inspection in a well-defined anatomical area
Luxation	Dislocation of a bone from a joint diagnosed by manual palpation or radiographic study
Nasal discharge	Clear serous fluid from the nares of unknown aetiology diagnosed by observation
Neoplasia	Abnormal cell proliferation, diagnosed by histopathology ante- or post-mortem, not being the cause of death
Ocular pathology	Specific unilateral or bilateral eye disorder including anisocoria, conjunctivitis and uveitis
Paraplegia	Paralysis of both lower extremities due to undetermined cause
Peritonitis	Lethargy and low temperature accompanied by severe necrotising steatitis, pancreatitis and hepatitis diagnosed post-mortem
Pneumonia	Tachypnoea and increased respiratory noises accompanied by pulmonary mineralisation observed in radiograph caused by unknown aetiology
Rectal prolapse	Protrusion of the rectal mucous membrane through the anus
Renal failure	Increased blood values of creatinine and blood urea nitrogen accompanied by lethargy and anorexia
Steatitis	Subcutaneous adipose tissue inflammation, showing increased consistency on palpation and diagnosed through histopathology following surgical excision
Tick *Ixodes apronophorus*	Detection of tick attached to the skin of the specimen, accompanied by localised inflammation
Vaginal discharge	Either abnormal or bloody discharge from vagina unrelated to pregnancy
Wound	Discontinuity of the skin caused by conspecific aggression or other traumatic event

https://doi.org/10.19227/jzar.v10i3.562

than one abnormality was observed on the same day, these were identified as separate medical problems. Clinical incidental findings (medical findings discovered while carrying out diagnostic tests for other purposes) were also identified and recorded. A definition of each morbidity category is described in Table 1.

Causes of mortality were determined based on post-mortem examination findings and ante-mortem medical history. For euthanised animals, cause of death was determined as the primary reason for euthanasia. If the cause of mortality was not clear, it was considered undetermined. Mortality aetiology was classified as infectious, non-infectious or undetermined. A definition of each mortality category is presented in Table 2.

Morbidity and mortality prevalence in each category were calculated as a percentage of the whole population and stratified for each age group and sex. Specific anatomical location for certain pathologies (arthritis, dental pathologies, dermatitis, fractures, localised inflammation and wounds) was identified due to the elevated number of instances and the location of the pathology being relevant to understanding the potential cause and determining the prognosis.

Animal weights for adults housed in BZG and JZ between 1992 and 2015 were evaluated to determine if the captive population was overweight, as this could be a contributing factor to some of the medical problems observed. Weights recorded during an active medical problem or after developing a chronic problem were discarded. Those from pregnant females from six months before to one year after giving birth were not considered. Mean weight and standard deviation (calculated from the maximum and minimum weights recorded in each specimen through each individual's adult and geriatric life) were calculated for captive males and females. Weights of wild specimens when caught were analysed separately.

Correlations between the different groups (stratified by sex or age) were analysed using Pearson's chi-squared test. A model based on binary logistic regression was developed for each morbidity and mortality category to provide insight into the relationship between a qualitative dependent variable and one or more explanatory independent variables or covariates. An odds ratio (OR) corresponding to independent variables was estimated, and variables were considered to be associated with the outcome if the OR was greater than 1. For model development, the patients were not considered as the unit of study, but rather the unit of analysis was each independent consultation. Data were analysed using IBM SPSS 19.0 for Windows (IBM Corp., Armonk, NY, USA) and the P-value threshold for statistical significance was set at $P<0.005$.

Table 2. Causes of mortality identified and defined with descriptions providing specific details to illustrate the criteria for diagnosis in certain categories.

Cause of mortality	Definition
Aborted foetus	Foetus in early development stage with non-inflated lungs and/or incomplete development
Conspecific aggression	Death due to fatal injuries caused by conspecific specimen
Degenerative joint disease	Animals with chronic arthritic changes observed in radiographies. Euthanasia was performed due to a compromised quality of life due to the degenerative joint disease.
Fungal encephalitis	Death due to infection of central nervous system caused by *Rhizomucor* sp. isolated in fungal culture
Heart disease	Death or euthanasia due to cardiac pathology based on ante-mortem clinical signs, radiography and echocardiography combined with gross findings and histopathology during post-mortem
Hypothyroidism	Euthanasia due to thyroid gland insufficiency associated with poor development, dermatitis, decreased blood value of thyroxine (T4) and histological findings
Neoplasia	Death due to neoplastic pathology diagnosed based on histopathology
Peritonitis	Death due to severe inflammation of the peritoneum supported by gross findings and histology during post-mortem examination
Pneumonia	Death due to pulmonary inflammation base on gross findings and histology
Renal failure	Death due to renal pathology associated with ante-mortem increased blood values of blood urea nitrogen and creatinine, with renal pathology observed in gross and histological examination
Septicaemia failure	Death due to generalised infection where several organs were affected, and infectious agents were observed in histopathology and/or culture
Starvation/maternal neglect	Death due to poor maternal care or nutrition; all animals presented with an empty gastrointestinal tract
Trauma	Death due to fatal traumatic injuries without evidence of conspecific aggression
Undetermined	Either necropsy not performed or definitive diagnosis could not be established

Consequences

Body weights

A total of 1283 weight records fitting the criteria described were found from 74 specimens, representing 72% of the total population over 2.5 years old maintained in captivity (Table 3).

Morbidity

Forty-five different clinicians documented a total of 427 morbidity events. During the study period, 72 animals (44.7%) presented no medical problems. Morbidity prevalence is presented by age group and sex in Table 4.

Table 3. Weight analysis: mean and standard deviation calculated from Livingstone's fruit bats when captured in the wild and while being held in captivity, and maximum and minimum weight from each individual.

Weights (g)	Male	Female
When captured from the wild	587±96 (n=11)	673±90 (n=7)
Average in captivity	914±164 (n=44)	862±162 (n=30)
Maximum in captivity	1163±294 (n=44)	1139±291 (n=30)
Minimum in captivity	712±123 (n=44)	668±128 (n=30)

Table 4. Causes of morbidity by age class and sex, presented as total number of cases and percentage within each category.

Morbidity category	Age class			Sex		Total
	Immature	Adult	Geriatric	Male	Female	
Abdominal hernia		1 (0.40%)	1 (0.70%)		2 (1.35%)	2 (0.50%)
Abscess	2 (5.26%)	2 (0.80%)	2 (1.35%)	2 (0.70%)	4 (2.70%)	6 (1.40%)
Anaemia		1 (0.40%)		1 (0.40%)		1 (0.20%)
Arthritis		8 (3.30%)	19 (12.80%)	20 (7.20%)	7 (4.70%)	27 (6.30%)
Bacterial pleuritis			1 (0.70%)		1 (0.70%)	1 (0.20%)
Claw trauma	2 (5.26%)	13 (5.40%)	6 (4.05%)	12 (4.30%)	9 (6.10%)	21 (4.90%)
Dental pathology	2 (5.26%)	8 (3.30%)	19 (12.80%)	15 (5.40%)	14 (9.50%)	29 (6.80%)
Dermatitis	1 (2.63%)	17 (7.00%)	12 (8.10%)	26 (9.30%)	4 (2.70%)	30 (7.00%)
Dystocia		2 (0.80%)			2 (1.35%)	2 (0.50%)
Fracture	6 (15.79%)	30 (12.45%)	10 (6.80%)	26 (9.30%)	20 (13.50%)	46 (10.80%)
Heart disease	1 (2.63%)	6 (2.50%)	8 (5.40%)	14 (5.00%)	1 (0.70%)	15 (3.50%)
Hypothyroidism	1 (2.63%)				1 (0.70%)	1 (0.20%)
Localised inflammation	1 (2.63%)	30 (12.45%)	24 (16.20%)	32 (11.50%)	23 (15.50%)	55 (12.90%)
Luxation		8 (3.30%)	6 (4.05%)	10 (3.60%)	4 (2.70%)	14 (3.30%)
Nasal discharge		3 (1.20%)		3 (1.10%)		3 (0.70%)
Neoplasia		2 (0.80%)	1 (0.70%)	2 (0.70%)	1 (0.70%)	3 (0.70%)
Ocular pathology		5 (2.10%)	1 (0.70%)	3 (1.10%)	3 (2.00%)	6 (1.40%)
Paraplegia		2 (0.80%)		2 (0.70%)		2 (0.50%)
Peritonitis	1 (2.63%)				1 (0.70%)	1 (0.20%)
Pneumonia		1 (0.40%)			1 (0.70%)	1 (0.20%)
Rectal prolapse			1 (0.70%)	1 (0.40%)		1 (0.20%)
Renal failure			2 (1.35%)	2 (0.70%)		2 (0.50%)
Steatitis		1 (0.40%)	3 (2.00%)	3 (1.10%)	1 (0.70%)	4 (0.90%)
Tick	1 (2.63%)	1 (0.40%)	1 (0.70%)	1 (0.40%)	2 (1.35%)	3 (0.70%)
Vaginal discharge		2 (0.80%)			2 (1.35%)	2 (0.50%)
Wound	20 (52.63%)	99 (40.70%)	31 (20.95%)	105 (37.30%)	45 (30.40%)	150 (34.90%)
Total	38 (8.90%)	241 (56.44%)	148 (34.66%)	279 (65.30%)	148 (34.70%)	427

Journal of Zoo and Aquarium Research 10(2) 2022
https://doi.org/10.19227/jzar.v10i3.562

Figure 1. Chronic localised swelling causing ankylosis between claw and distal phalanx in digit 1, left hind limb. Note that this animal had digit 5 previously amputated due to a similar injury.

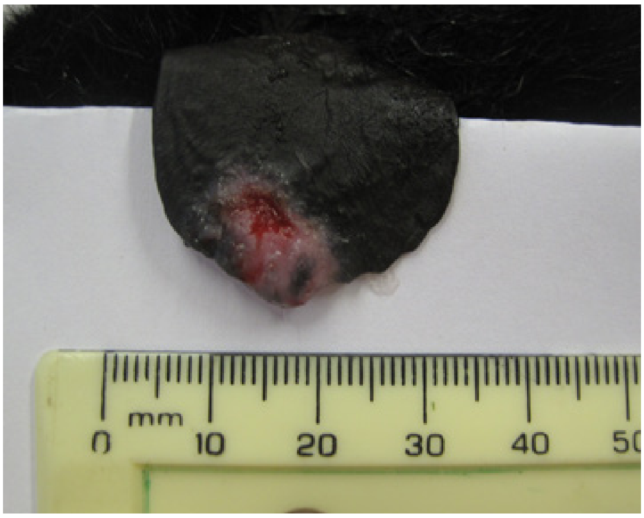

Figure 2. Dermatitis with loss of pigmentation and ulceration in the caudal margin of the pinna, left ear.

Forty-three medical abnormalities were considered incidental findings, including dental abnormalities (n=18), resolved fractures (n=6), wounds to the patagium (n=6), localised inflammation (n=5), arthritis (n=4), claw trauma (n=1), vaginal discharge (n=1), haemangioma (n=1) and conjunctivitis (n=1).

Wounds (n=150) were the most common pathology. A total of 104 wounds were reported in males (69.8%) and 98 in adult individuals (65.77%). Some individuals sustained more than one wound over the course of their lives. Most wounds were identified on the patagium (n=38) and digits of the forelimbs (n=33), followed by head injuries (n=29), especially to the rostral aspect of the mandible (n=9). Statistically, wounds are more likely to occur in immature and male bats (Table 5).

Localised inflammations were very frequently observed, mostly seen on digits (n=26) (Figure 1), primarily forelimb digit 1 and mostly the distal phalanx/claw; followed by the rostroventral mandible (n=7) then the periorbital area (n=5). Swellings noted between the nail and distal phalanx and interphalangeal joints revealed ankylosis during joint manipulation in some individuals. Geriatric animals were more likely to suffer from such ankylosis (Table 5).

Frequent pathologies affecting the integument were dermatitis and onychopathies. The pinna was the most frequently recorded location for dermatitis (n=21) (Figure 2); it was bilateral in 10 cases and unilateral in 11. Dermatitis of the patagium was recorded in six cases. Most onychopathies (n=21) presented in the forelimb

Table 5. Association between variables through odds ratio (OR) and logistic regression (Nagelkerke), stratified by sex, age and type of birth (wild/captive born).

	Male	Female	Immature	Adult	Geriatric	Captive-born	Wild-born	Constant	Nagelkerke
Wounds	OR=1	OR=0.546 P=0.013	OR=3.077 P=0.006	OR=1.929 P=0.011	OR=1			OR=0.390 P<0.001	R^2=0.099 P<0.001
Localised inflammation			OR=0.122 P=0.043	OR=0.656 P=0.164	OR=1			OR=0.235 P<0.001	R^2=0.036 P=0.021
Dermatitis	OR=1	OR=0.266 P=0.016						OR=0.117 P<0.001	R^2=0.047 P=0.006
Fractures						OR=0.38 P<0.004	OR=1		
Arthritis			OR=0 P=0.998	OR=0.238 P=0.001	OR=1			OR=0.175 P<0.001	R^2=0.114 P<0.001
Dental pathologies	OR=1	OR=2.173 P=0.054	OR=0.295 P=0.115	OR=0.182 P<0.001	OR=1			OR=0.141 P<0.001	R^2=0.118 P<0.001
Heart disease (morbidity)	OR = 1	OR=0.127 P=0.048						OR=0.06 P<0.001	R^2=0.064 P=0.008
Heart disease (mortality)	OR=1.462 P=1	OR=0.142 P=1	OR=0.164 P=0.12	OR=0.63 P=0.551	OR=1			OR=0.606 P=1	R^2=0.44 P<0.001

digits (n=12), predominantly digit 1 (n=8). In two cases multiple claws were affected. The location was not recorded in two cases. Females were diagnosed with dermatitis less frequently than males (Table 5).

Skeletal disorders, such as fractures, arthritis and luxation were significant contributors to morbidity. Of the total fractures (n=46), 30 were reported in forelimbs, especially digit fractures. Hindlimb fractures were less common (n=12). Fractures affecting multiple bones were observed on three occasions. Fractures were less likely to occur in captive-born animals (wild-born OR=1, captive-born OR=0.38, P<0.004). Analysis of the combined effects of age and sex on fractures showed adult females were diagnosed with fractures more frequently than immature females and geriatric males (immature female OR=1.098, P=0.930, adult female OR=2.366, P=0.012, geriatric male OR=1; constant OR=0.2, P<0.001; Nagelkerke R^2=0.074, P=0.002). Luxations (n=14) were observed equally in fore and hindlimbs (n=5 each) with the coxofemoral joint most affected (n=4). Arthritic changes (n=27) were most often observed in hindlimbs (n=16), predominantly the digits (n=8) and stifles (n=6) (Figure 3). Geriatric animals were more likely to present with arthritis (Table 5).

Dental abnormalities were reported in 29 cases, but 18 of these were incidental findings. Canine teeth were affected in most cases (72.4%, n=21). Dental pathologies included periodontal abscess, tooth fracture, tooth loss, tooth wear and congenital malocclusion. Tooth fracture was reported in fifteen cases, thirteen of which were canines (Figure 4). Dental diseases were mostly observed in geriatric animals (n=18) and adults (n=8), with geriatric individuals and females more likely to present with these issues (Table 5).

Diagnosis of cardiac disease was based on clinical signs, radiographic findings, and echocardiographic measurements under general anaesthesia. Six animals did not present any clinical cardiac signs prior to ultrasound examination, including one immature male with severe dilation of the right side of the heart due to mitral valve insufficiency and one geriatric male with aortic valve insufficiency. Males were more likely to be diagnosed with cardiac diseases (Table 5).

Neoplasia cases included a laryngeal squamous cell carcinoma in a geriatric female, and a metastatic osteosarcoma and a cutaneous cervical haemangioma, both diagnosed in adult males.

Prevalence of pathologies between institutions (JZ/BZG) and sex, institution and type of birth (wild or captive), and sex and type of birth were not significantly different (P=0.232, P=0.949 and P=0.811, respectively). Therefore, sex, institution and wild or captive-born variables are not associated with each other in this study.

Mortality

Ninety-four deaths were reported during this period, representing 58.38% of the total population. Forty-seven animals (50%) died without previous clinical signs. Euthanasia was carried out on twenty-nine specimens (33%).

Eighty-eight necropsy reports of animals housed at JZ and BZG, representing 93% of captive population deaths, were reviewed. Full gross post-mortem examination was performed by ten different prosectors in 76 animals (86.4%). Histopathology was carried out in fifty-one cases by seven different pathologists. Microbiology culture (bacterial and fungal) was performed in 18 cases.

Causes of death, by age group and sex, are presented in Table 6. Early foetal death was reported in sixteen cases. Full post-mortem examination was not performed in six cases due to the early stage of foetal development. Congenital malformation and dystocia were considered the aetiology in two cases respectively. In the remaining cases, a cause could not be determined.

Table 6. Causes of mortality by age class and sex, presented as total number of cases and percentage within each category. NA=Not applicable.

Cause of death	Age class			Sex			Total
	Immature	Adult	Geriatric	Male	Female	Undetermined	
Conspecific aggression	8 (25.00%)		1 (4.55%)	3 (7.00%)	2 (7.40%)	4 (22.20%)	9 (10.20%)
Degenerative joint disease	1 (3.13%)	1 (5.60%)	5 (22.70%)	4 (9.30%)	3 (11.10%)		7 (7.95%)
Early foetal death	NA	NA	NA	6 (13.95%)	2 (7.40%)	8 (44.40%)	16 (18.20%)
Fungal encephalitis			1 (4.55%)		1 (3.70%)		1 (1.10%)
Heart disease	1 (3.13%)	4 (22.20%)	8 (36.40%)	12 (27.90%)	1 (3.70%)		13 (14.80%)
Hypothyroidism	1 (3.13%)				1 (3.70%)		1 (1.10%)
Neoplasia		1 (5.60%)	1 (4.55%)	1 (2.30%)	1 (3.70%)		2 (2.30%)
Peritonitis	1 (3.13%)				1 (3.70%)		1 (1.10%)
Pneumonia	1 (3.13%)					1 (5.60%)	1 (1.10%)
Renal failure			2 (9.10%)	2 (4.65%)			2 (2.30%)
Septicaemia	1 (3.13%)	3 (16.70%)	2 (9.10%)	3 (7.00%)	3 (11.10%)		6 (6.80%)
Starvation/maternal neglect	4 (12.50%)			2 (4.65%)	2 (7.40%)		4 (4.55%)
Trauma	3 (9.38%)	4 (22.20%)	1 (4.55%)	2 (4.65%)	4 (14.80%)	2 (11.10%)	8 (9.10%)
Undetermined	11 (34.38%)	5 (27.80%)	1 (4.55%)	8 (18.60%)	6 (22.20%)	3 (16.70%)	17 (19.30%)
Total	32 (44.44%)	18 (25.00%)	22 (30.56%)	43 (48.90%)	27 (30.70%)	18 (20.4%)	88

https://doi.org/10.19227/jzar.v10i3.562

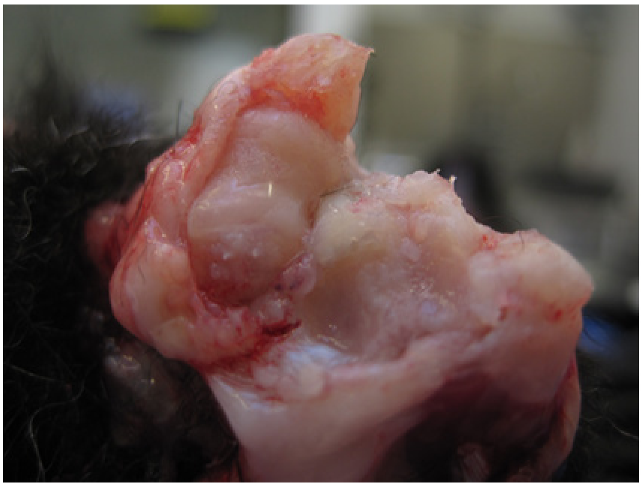

Figure 3. Severe arthrosis in stifle observed during post-mortem examination showing loss of articular cartilage accompanied by bone and fibrous tissue proliferation.

Figure 4. Right maxillary canine fracture.

Heart diseases were the second most significant overall cause of death (n=13) and the main cause of death in adult and geriatric animals. Of these, 12 were characterised as dilated cardiomyopathy (Figures 5 and 6). There was a single case of congenital mitral valve insufficiency diagnosed in an immature male. Diagnosis was confirmed through gross examination and histopathology. Six animals were euthanised due to poor prognosis and limited response to treatment. All heart disease cases were diagnosed between 2011 and 2017. Males were more likely to die from heart diseases, while a proportional increased risk was noted as animals grew older (Table 5).

Infectious disease was relatively uncommon (n=8, 9.1%). Etiological agents were identified by histopathology and culture. *Rhizomucor* sp. was isolated and considered the cause of a single fungal encephalitis case. *Ochrobactrum anthropi* and *Bacillus cereus* were implicated in one case of septicaemia. Bacteria consistent with *Yersinia* sp. were seen on histopathology in another septicaemia case. *Staphylococcus* sp. was identified in a third case of septicaemia. Other cases of septicaemia were attributed to unidentified coccoid bacteria on two occasions, and to coccobacilli bacteria in another. An unidentified bacterium was observed on histopathology and considered responsible for the single case of pneumonia.

Specific medical problems have been described in captive LFBs

Figure 5. Transversal section of a Livingstone's fruit bat heart following fixation with formalin, showing no gross or histological lesions that would suggest cardiac disease.

Figure 6. Transversal section of a heart affected by dilated cardiomyopathy, showing left and right ventricles, following fixation with formalin.

(Barbon et al. 2017; Killick et al. 2017) but no thorough reviews of captive mortality and morbidity in this species have been published.

Wounds accounted for over one third of morbidity events. It is presumed that many of these wounds were due to intraspecific aggression as males and immature animals were more prone to suffer injuries. The social structure observed in LFB and other *Pteropus* species includes dominant males selecting a roosting territory that they protect from other males (Courts 1997a; Markus 2002). Animal density, sex ratios, heat sources and food distribution may be factors contributing to wound-causing behaviours.

It is suspected that the aetiology for many of the fractures and trauma is in-flight crashes or falls. LFBs start flying at three months of age (Trewhella et al. 1995). All forelimb fractures reported in immature animals were after four months of age. Females showed an increased prevalence of fractures. This may correlate with the increased patterns of activity described in captive females and subordinate males when compared with more sedentary, dominant males (Courts 1997a). A recent study into flight patterns exhibited by pteropid species at JZ (Bell et al. 2019) showed increased flight pattern complexity in Rodrigues fruit bats when compared with LFBs, which motivated a doubling of the enclosure size described in this study with the objective of increasing complexity of flight patterns and manoeuvrability; it is also expected to decrease flight-associated trauma.

The recorded occurrence of early foetal deaths and conspecific aggression towards immature individuals will have a negative effect on the capacity to increase an ex-situ population, accentuated by the k-selected reproductive strategy of pteropid bats (few offspring are produced, and the energy used to make each individual is high) (Pierson and Rainey 1992). Early foetal death in grey bats *Myotis grisescens* has been linked to stress associated with disturbances of the roost area and handling (Gunier 1971). Current knowledge of behaviour, endocrinology and gestation in captive LFBs is too limited to establish whether stress could increase the prevalence of abortions. Field observations describe changes in female foraging behaviour, including ranging less far from roosts in the month prior to giving birth (Trewhella et al. 1995). Although birth clustering between March and June suggests birth seasonality, as observed in wild tropical fruit bats (Baker and Baker 1936), the same was not obvious in captive LFBs. This may be a consequence of captivity, where seasonal food availability does not impact reproduction (Bronson 1985). Detecting pregnant captive females and providing them with secluded areas and limiting disturbance by other bats prior to giving birth may help to reduce abortions. To do this, techniques to diagnose and monitor pregnancy, e.g. ultrasonography or hormonal analysis, could be utilised.

Inbreeding within the captive population, as has been observed in humans (Hussain 1998) and domestic animals (Reinartz and Distl 2016), may contribute to the abortions observed. Given the small number of founder animals, a genetic study should establish the degree of inbreeding within the population to determine if this could be the case.

Dietary deficiencies need to be evaluated as a potential underlying cause for abortions. A calcium-restricted diet in insectivorous big brown bats *Eptesicus fuscus* showed a positive relationship between maternal mass and litter mass in addition to an abortion in one of the females on the restrictive diet (Booher 2008). Protein is another nutritional component that may require closer examination as a potential contributor to abortions and poor reproductive success, as it has been implicated in other species (Elango and Ball 2016; Serrano Pérez et al. 2020). Despite the relatively low protein requirements of non-reproductive fruit bats and their ability to adapt to low-protein diets (Dempsey 1999), requirements in pregnant females may be higher, as suggested by insectivorous behaviour observed in captive LFBs, especially females (Courts 1997b).

Food presentation, leading to selective feeding, has been linked with a decrease in reproductive success in a captive colony of Rodrigues fruit bats (Sanderson et al. 2004). A detailed diet analysis in pregnant females could provide insights into potential deficits during gestation as the nutritional requirements may be different during this period.

Dilated cardiomyopathies have been described in *Pteropus* species associated with hypovitaminosis E (Heard et al. 1996) and of unknown aetiology (Miller et al. 1986). In our small dataset there is a significant bias towards cardiac disease in adult males, as has been observed in dogs *Canis lupus familiaris* (Martin et al. 2009). Genetic research may establish if this presumptive linkage is possible. In addition, captive animals with limited flying incentive spend more time in inversion than wild bats. There is a lack of stimuli to move once animals, especially dominant males, find a suitable area in the enclosure. Elevation of cardiac markers and histological changes have been observed in straw-coloured fruit bats *Eidolon helvum* subjected to forced prolonged inversion (Ashaolu and Ajao 2014). Initial development of diagnostic imaging tools (Dickson et al. 2016; Drane et al. 2018) and medical management (Killick et al. 2017) have been described in LFBs. However, additional investigations into the potential causes of this condition and its further characterisation are required.

The main limitation of this retrospective study is that it involves multiple clinicians and pathologists, over time, with no prior agreed-upon standardisation of diagnosis of the different medical problems described. Although the review period is relatively long, the overall sample size is very small for a thorough epidemiological study. In many cases the cause of death or specific medical problem could not be established due to limited findings during post-mortem examination or diagnostic workup.

Despite these limitations, the study highlights the main medical problems noted in this species in captivity. It confirms the need for standardisation of routine wellness protocols and post-mortem examinations and establishes future research requirements for this Critically Endangered pteropid bat.

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