

RADIOGRAPHIC EVALUATION OF CARDIAC SIZE IN FLYING FOX SPECIES (*PTEROPUS RODRICENSIS*, *P. HYPOMELANUS*, AND *P. VAMPIRUS*)

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Abstract: Dilated cardiomyopathy is a relatively common pathology in captive flying foxes (*Pteropus* spp.). The goal of this study was to establish quantitative reference range measurements that could be used to support a diagnosis of cardiac disease in these animals. Lateral and ventrodorsal thoracic radiographs from apparently healthy flying foxes ($n = 66$) of three species (Rodriguez island flying fox, *P. rodricensis*, $n = 18$; small island flying fox, *P. hypomelanus*, $n = 16$; and Malaysian flying fox, *P. vampyrus*, $n = 32$) were evaluated objectively to describe the cardiac appearance. Absolute and relative cardiac dimensions also were measured. The same methods were used to evaluate radiographs from flying foxes ($n = 9$) with known dilated or acute cardiomyopathy. The following ratios were most appropriate for categorizing normal cardiac silhouette size. In the ventrodorsal projection, heart width to thoracic width and heart width to clavicle length were the preferred measurements. In the lateral projection, heart width compared with thoracic height was the preferred measurement. From radiographs of the bats with known dilated and acute cardiomyopathy, the apicobasilar heart length compared with thoracic height and heart width compared with thoracic height on lateral films were the most sensitive ratios for diagnosing cardiomegaly.

Key words: Cardiac measurement, cardiomyopathy, megachiroptans, *Pteropus* spp., radiology.

INTRODUCTION

Dilated cardiomyopathy has been reported in several species of captive flying fox (*Pteropus* spp.) associated with hypovitaminosis E.³ Idiopathic dilated cardiomyopathy also has been described in an Indian flying fox (*P. giganteus*).¹⁰ Radiographic evaluation of cardiac size and subjective assessment of thoracic features is used in domestic animals as a primary diagnostic tool in the detection of heart disease and evaluation of its progression.^{1,18} Basic understanding of cardiovascular anatomy in bats is derived from limited studies performed primarily for scientific curiosity or by investigators attempting to apply their findings to human medicine.^{11,21} At this time, no studies have been published on the application of this knowledge to the

clinical diagnosis and treatment of cardiac disease in bats.

Bats are unique in the animal kingdom in that they are the only true flying mammals, and as such, share functional and structural features of both birds and mammals. This study used methods of cardiac measurement utilized in both birds and mammals^{1,2,7,8,16,17,20} to determine the absolute and relative cardiac measurements for the three species of flying fox studied. Moreover, this study assessed the usefulness of measurements taken for the evaluation of both normal and diseased flying fox thoracic radiographs, both within and across the tested species, and discussed the implications of subjective radiographic evaluations by using these same radiographs.

METHODS AND MATERIALS

Sixty-six lateral and ventrodorsal thoracic radiographs from three species of flying fox (Rodriguez island flying fox, *P. rodricensis*, $n = 18$, 275–386 g; small island flying fox, *P. hypomelanus*, $n = 16$, 430–880 g; and Malaysian flying fox, *P. vampyrus*, $n = 32$, 645–1,370 g) were evaluated as apparently healthy subjects in the initial study. These species were selected because of their size range and availability and because clinical cases of dilated cardiomyopathy have been reported in all three species. The bats in this study were housed either at the Lube Bat Conservancy (LBC), which is a private breeding and research facility in north-central Florida, or Disney's Animal Kingdom (DAK) in central

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Florida. The bats ($n = 36$) from LBC were radiographed at the Veterinary Medical Teaching Hospital (VMTH), University of Florida (Gainesville, Florida, USA) for suspected musculoskeletal injury, abdominal disease, and cardiac evaluation. The radiographs from DAK ($n = 30$) were taken primarily as part of the routine annual physical examinations.

Health status was based on physical examination and comparison of hematologic and plasma biochemical values to reference ranges and expected normal values.⁴ Because they were part of a study on dilated cardiomyopathy in flying foxes, seven bats also had a full cardiologic evaluation, including an electrocardiogram and echocardiogram, by a veterinary cardiologist. At the completion of this study, bats were still alive and healthy, or if deceased ($n = 7$), had no evidence of cardiac pathology on necropsy. Those radiographs of the bats that are still alive and apparently healthy were taken from 1.5–11 yr prior to completion of this study.

Radiographs were excluded from the study if the subjects were in an advanced state of pregnancy or showed radiographic evidence of pulmonary disease, hypovolemia, or physical immaturity. The youngest bat in this study was 1 yr old; although open tibial physes were still present in this individual, the relative thoracic size and anatomy were the same as those of adult bats. Heart size relative to body size probably reaches adult proportions shortly after the bat has started to fly, approximately 4–6 mo of age in flying foxes.⁶

Cardiac measurements from the apparently healthy bats were compared with those from animals with dilated ($n = 7$) or acute ($n = 2$) cardiomyopathy. Initial radiographs from bats with cardiac disease (*P. vampyrus*, $n = 3$; *P. hypomelanus*, $n = 5$; and *P. rodricensis*, $n = 1$) were taken during routine screening or because the animal had clinical signs of cardiac failure. Cardiomyopathy was confirmed at necropsy within 24 hr of the initial radiographs in seven of these bats, and within 1 and 4 mo in the other two, respectively. *Acute cardiomyopathy* was defined as cardiac disease detected on necropsy in an animal that died suddenly with no prior clinical signs of cardiac disease.

All animals were anesthetized and were maintained with isoflurane (Isoflo 99%, Abbott Animal Laboratories, North Chicago, Illinois 60064, USA; 5% induction, 2.5% maintenance) in oxygen for physical examination, jugular venipuncture, and radiology. The bats radiographed at the VMTH were maintained via endotracheal intubation, whereas those at DAK were maintained by mask anesthesia. At the VMTH, two machines were used to obtain

radiographs: the Sedecal A6590-01 (Sedecal Inc., Rio de Janeiro 28110, Brazil) and the Picker 189145C (Picker International, Cleveland, Ohio 44143, USA). At DAK, one radiograph machine (Bennett HFQ-12050P, Bennett X-ray Technologies, Copenague, New York 11726, USA) was used to obtain the images. The focal-film distance used for all radiographs was 40 cm. The film used at DAK was Kodak Diagnostic Film, with Kodak Lanex Cassettes, regular screens, and Kodak X-OMAT Cassette (Eastman Kodak Company, Rochester, New York 14650, USA). A wide variety of film and screens were used at the VMTH. Lateral and ventrodorsal radiographs were taken upon manual inflation by a technician (VMTH) or voluntary inspiration (DAK). Excessive rotation of the subject, under- or overexposure of films, the use of technique not suitable for thoracic evaluation, and the presence of artifacts were criteria for excluding radiographs from the study.

All measurements were made with adjustable electrocardiogram calipers (Staedtler 559 55 WP, Staedtler Inc., Chatsworth, California 91311, USA). Anatomic measurements taken from the lateral radiographs are illustrated in Figure 1. The measurements were the apicobasilar length of the heart (AB); the maximal heart width perpendicular to AB (CD); the distance between the cranial edge of the fifth rib and the caudal edge of the seventh rib perpendicular to the spine at the level of the heart base (R5-7); the vertical depth of the thorax from the ventral border of the spine to the dorsal border of the sternum at the level of the tracheal bifurcation (H); the width of the caudal vena cava when possible (CVC); and the width of the fifth rib at the level of the tracheal bifurcation (R5). The ratios AB/CD, AB/R5-7, CD/H, and CVC/R5 were calculated.

To determine the vertebral heart-scale score, AB was measured on a lateral radiograph using calipers that were then superimposed on the thoracic vertebrae starting at T4. The distance between the caliper points was estimated to the nearest 0.25 vertebrae. The CD was measured against the thoracic vertebrae in the same manner. These two measurements were added to generate the vertebral heart-scale score (VHS).^{7,15}

The anatomic measurements taken from the ventrodorsal radiographs are illustrated in Figure 2. These measurements were maximum length of the cardiac silhouette (L); maximum width of the cardiac silhouette perpendicular to L (W); the width of the thorax at the point where rib six articulates with the vertebral column (T); and the length of the

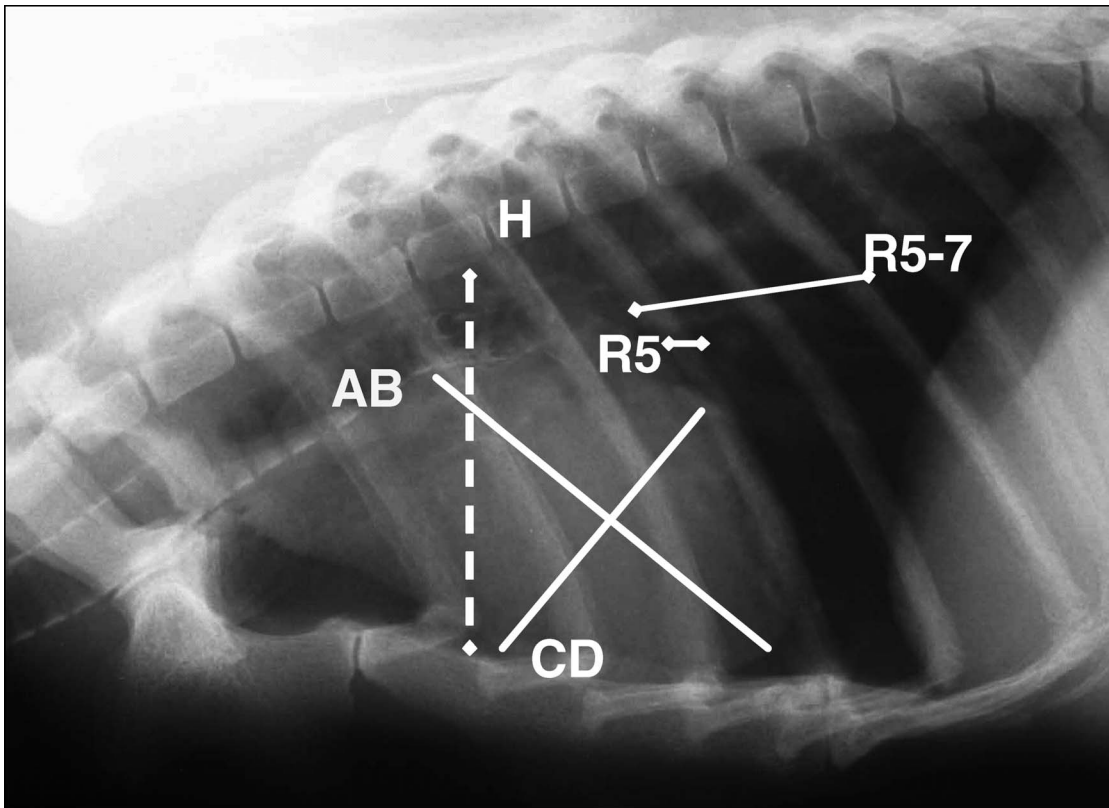


Figure 1. Lateral radiograph of an apparently healthy *Pteropus* sp. bat with diagram explaining measurements taken for the evaluation of cardiac size: **AB** = The apicobasilar length of the heart; **CD** = The width of the heart perpendicular to **AB** (measurement taken at widest aspect); **R5-7** = The distance between the cranial edge of the fifth rib and the caudal edge of the seventh rib perpendicular to the spine; **H** = The vertical depth of the thorax from the ventral border of the spine to the dorsal border of the sternum at the level of the tracheal bifurcation; **R5** = Measurement of the width of the fifth rib perpendicular to the spine at the level of the tracheal bifurcation. CVC not well visualized in this diagram.

clavicle (C). The following ratios were calculated: L/W, W/T, W/C, and L/C.

For all measurements the mean, range, standard deviation, and 95% confidence interval of mean were calculated. Quantile-quantile (Q-Q) plots were used to show that the data sets came from populations with a common distribution. The Q-Q plots of AB/CD and L/W were constructed for all species separately, then for all three species pooled. The Kolmogorov-Smirnov and Shapiro-Wilk tests of normality also were applied to these two ratios. For all other ratios, variances were calculated for each species separately and for all three species pooled. The VHS was analyzed by calculating mean and standard deviation for each species separately and for all normal bats pooled. A P value < 0.05 was considered statistically significant. Means, ranges, standard deviation, 95% confidence intervals, and

VHS calculations were performed similarly for the radiographs of bats with known heart disease.

A veterinary radiologist (MST) subjectively evaluated all radiographs from apparently healthy bats to compare the radiographic characteristics of these species with the published characteristics of other mammals and examined the radiographs from the bats with dilated and acute cardiomyopathy to describe the presentation of cardiac disease. The evaluations were not blinded from the radiologist (MST), because the first author (AG) participated in all readings and was aware of clinical status of the cases.

RESULTS

Direct evaluation

Radiographs from apparently healthy bats: In all three species, the heart was inclined cranially at a

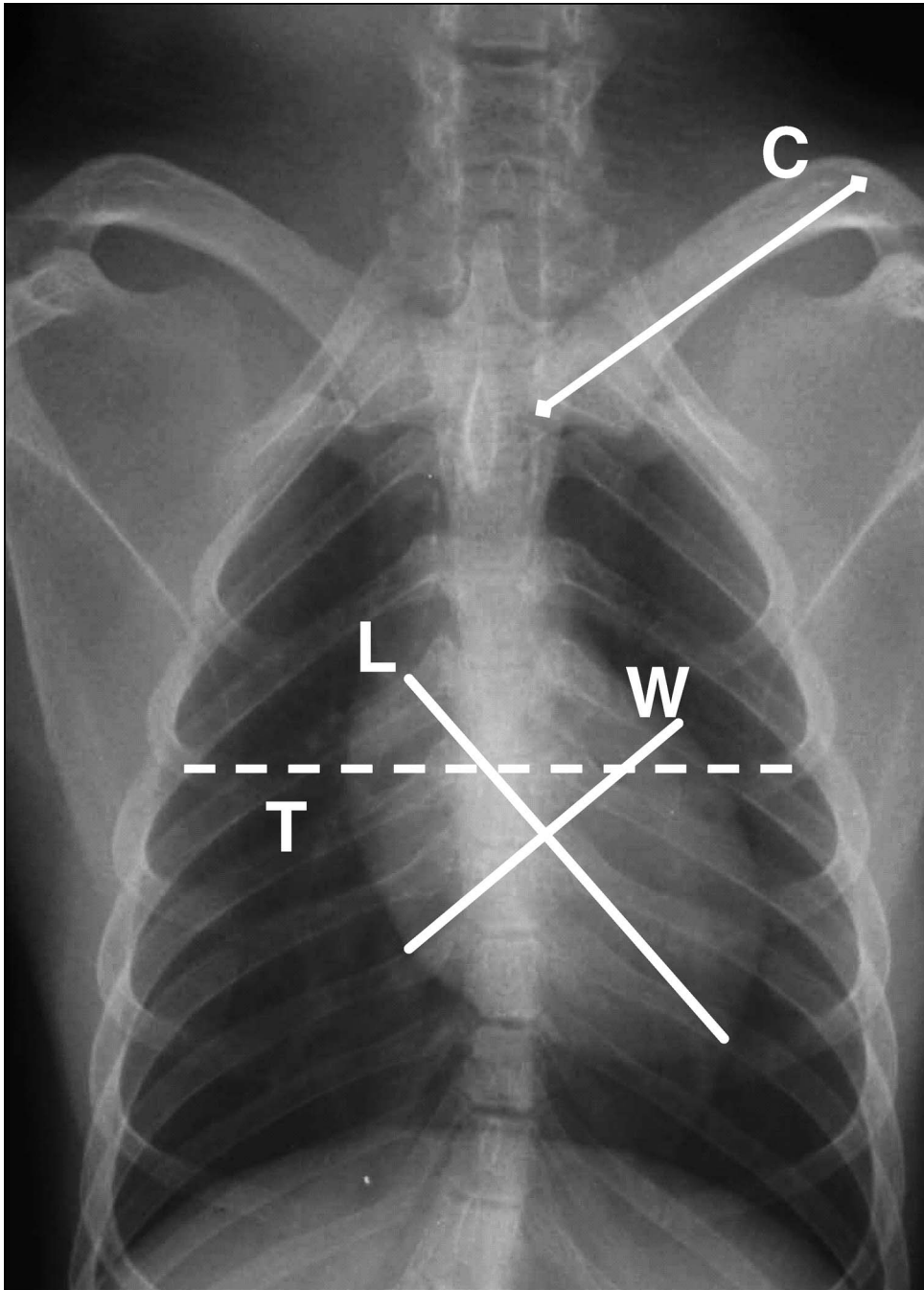


Figure 2. Ventrodorsal radiograph of an apparently healthy *Pteropus* sp. bat with diagram explaining measurements taken for the evaluation of cardiac size: **L** = Maximum length of the cardiac silhouette; **W** = Maximum width of the cardiac silhouette; **T** = The width of the thorax at the level of the 6th rib's articulation with the spine; **C** = The length of the clavicle.

45° angle in the lateral view, which often caused an area of increased opacity cranial to the cardiac silhouette. On the ventrodorsal projections, the cardiac apex was generally within the left caudal quadrant of the thorax. Occasionally, the heart appeared to occupy more of the left thorax than the right. As the species increased in size, the relative size of the cardiac silhouette increased; that is, *P. rodricensis* appeared to have a normal cardiac silhouette, comparable to domestic small mammals, whereas *P. hypomelanus* and *P. vampyrus* appeared to have enlarged hearts. The pulmonary vasculature and the caudal vena cava were not well visualized, but when observed, the caudal vena cava sloped dorsocranially. The trachea appeared variably elevated in all bats. However, the degree of elevation increased with increased flexion of the head.

In the radiographs of *P. hypomelanus*, the cardiac silhouette was wide cranially on the lateral projection, although this was not reflected in the heart width measurement, which was taken more caudally. This increased soft tissue cranial to the heart caused a mild tracheal elevation caudal to the thoracic inlet that was more pronounced than in the Rodriguez fruit bats (*P. rodricensis*).

The hearts of many of the healthy *P. vampyrus* appeared wide and round on the lateral projection with an increase in tracheal elevation. The trachea at the carina was always parallel to the vertebral column. The soft tissue opacity in the cranial thorax was separated more clearly from the heart than in the other two species, and it was clearly associated with the great vessels. The caudal lobar vessels were seen more easily than in the other species, and on several radiographs appeared to end abruptly without tapering. Radiographs of a clinically normal *P. vampyrus* are shown in Figure 3.

Radiographs from bats with cardiomyopathy: The radiographs of the two bats that died of acute cardiomyopathy appeared normal. The bats with dilated cardiomyopathy most commonly had generalized cardiomegaly that was most apparent on the ventrodorsal projection. Most hearts appeared oval to globoid on the ventrodorsal projection. In radiographs of these bats taken early in the progression of disease, cardiac elongation was the most common change. Five of the bats had a locally extensive increase in soft tissue opacity at the caudal heart and elevation of the left main stem bronchus, suggesting an enlarged left atrium. A moderate to severe dorsal elevation and compression of the trachea cranial to the carina, as well as elevation of the carina, were apparent in all affected bats except those with acute cardiomyopathy. Six of the bats had increased perihilar or generalized pulmonary

opacity. The lobar vessels were difficult to evaluate in most radiographs, although in repeated radiographs of three bats with advanced disease, caudal lobar vessels appeared enlarged, so the caudal lobar vein had a greater diameter than that of the corresponding artery. No substantial changes in caudal vena cava size were noted. Four bats had poor peritoneal serosal detail with pendulous abdomens. Radiographs of two bats treated for heart failure showed a decrease in pulmonary opacity and ascites and an apparent decrease in heart size in subsequent radiographs.

Objective measurements

Radiographs from apparently healthy bats: The Q-Q plots for the ratios AB/CD and L/W were completed for each species separately and for all three species pooled. The grouping of data points around the line of best fit suggested that the population was distributed normally. The significance values derived by the additional tests of normality (Shapiro-Wilk, range = 0.227–0.497; Kolmogorov-Smirnov, range = 0.179–0.200) support the null hypothesis that the data follow a normal curve. Ranges, means, and variances were calculated for the other ratios in all three species separately, as well as for all species pooled (Table 1). The ratios that are the most efficient for predicting normal cardiac measurements in bats are those with the lowest variances. For every species, as well as for the pooled data, three ratios had consistently low variances: CD/H (lateral projections), W/T, and W/C (ventrodorsal projections). These ratios had very low variances, ranging from 0.002–0.007. The highest variance (0.407–0.458) was consistently derived from the ratio CVC/R5.

For the vertebral heart-scale scores, a normal range for the species tested was derived using the mean \pm standard deviation. These were *P. rodricensis*, 9.8 ± 0.6 vertebrae; *P. hypomelanus*, 9.3 ± 0.8 vertebrae; and *P. vampyrus*, 9.2 ± 0.5 vertebrae. For the pooled data from all three species, the values were 9.4 ± 0.7 vertebrae with a standard error of 0.08.

Radiographs from bats with cardiomyopathy: The ratios derived from the measurements taken from these radiographs were compared with those derived from the normal radiographs of the same species. The ratio AB/H was higher than the normal range in eight out of nine of the abnormal bats; CD/H is increased in seven out of nine.

DISCUSSION

Heart weight as a percentage of body weight is a measurement that has been used in an attempt to

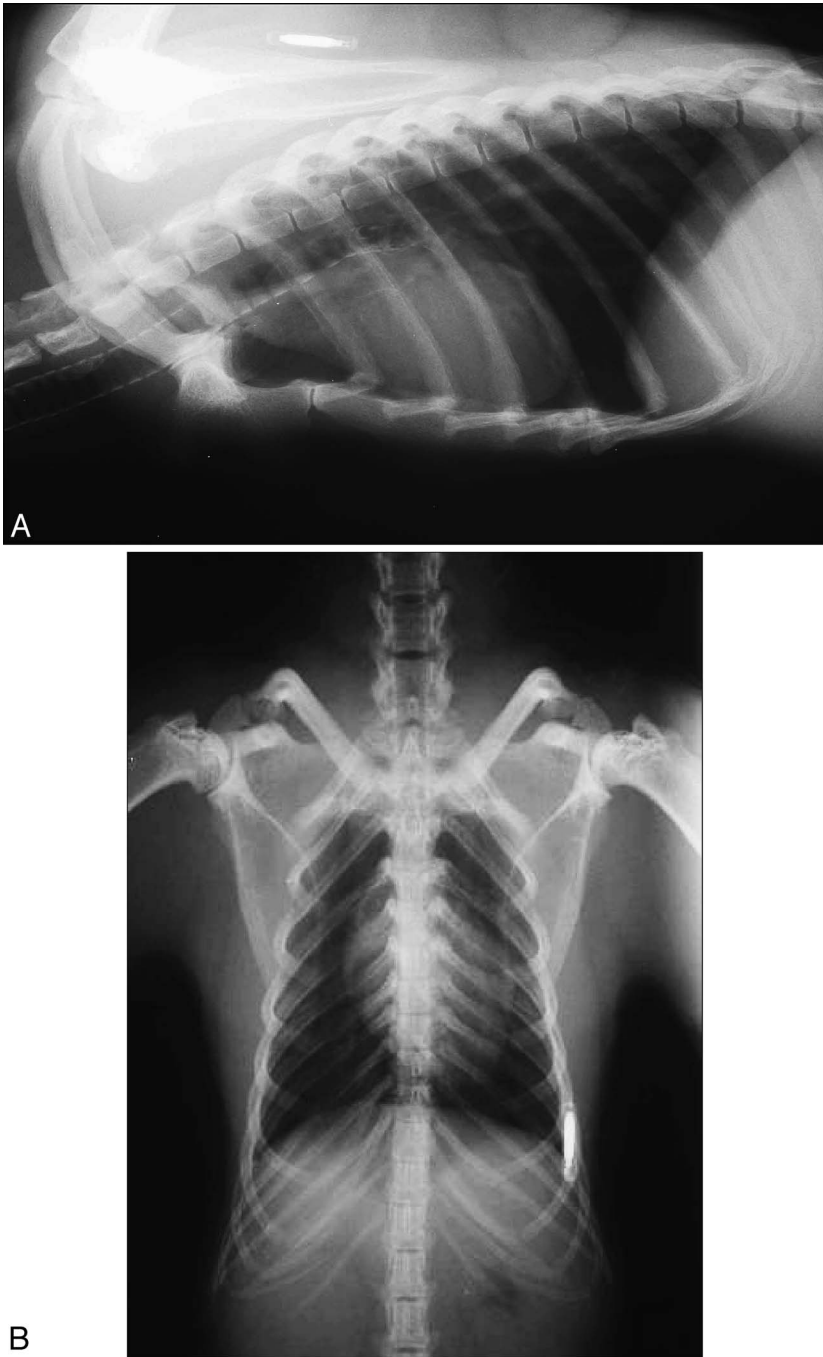


Figure 3. Lateral and ventrodorsal thoracic radiographs of an apparently healthy adult male *Pteropus vampyrus*. **A.** Lateral projection—normal: Heart is tilted cranially and length of heart is nearly equal to height of thorax. There is a dorsal deviation of trachea cranial to the carina. The cardiac silhouette is rounded. Soft tissue opacity at the cranial pole of heart is due to aortic redundancy or silhouetting of other great vessels. Lobar pulmonary vessels are not well visualized; caudal vena cava has a dorsocranial slope. Radio-opaque object in dorsal subcutaneous tissue is a microchip. **B.** Ventrodorsal projection—normal: Heart is tilted on its vertical axis about 30°. The cardiac silhouette fills more of the left half of thorax than the right. The heart is moderately elongate and the pulmonary vasculature is not well visualized. A radio-opaque microchip is seen superimposed over the left caudo-lateral thorax.

Table 1. Ranges, means, and variances for ratios used to evaluate radiographs of apparently healthy bats (*Pteropus rodricensis*, *P. hypomelanus*, and *P. vampyrus*). Abbreviations are provided in Figure 1.

Species		Range	Mean	Variance
Pr. ^a	AB/R5-7	2.22–2.94	2.62	0.058
	AB/H	0.94–1.26	1.16	0.012
	CD/H	0.65–0.89	0.76	0.004
	CVC/R5	Not measured		
	W/T	0.46–0.59	0.52	0.002
	W/C	0.83–1.00	0.92	0.003
	L/C	1.22–1.68	1.43	0.012
Ph. ^b	AB/R5-7	2.0–2.667	2.26	0.034
	AB/H	0.96–1.28	1.09	0.007
	CD/H	0.64–0.84	0.73	0.003
	CVC/R5	1.00–2.00	1.25	0.431
	W/T	0.45–0.68	0.56	0.003
	W/C	0.89–1.13	1.00	0.006
	L/C	1.25–1.75	1.51	0.016
P.v. ^c	AB/R5-7	2.17–2.79	2.43	0.051
	AB/H	0.87–1.28	1.08	0.013
	CD/H	0.59–0.88	0.76	0.005
	CVC/R5	1.33–2.50	1.94	0.407
	W/T	0.48–0.69	0.58	0.003
	W/C	0.80–1.17	0.92	0.006
	L/C	1.20–1.77	1.42	0.023
All	AB/R5-7	2.00–2.94	2.44	0.064
	AB/H	0.87–1.28	1.10	0.013
	CD/H	0.59–0.89	0.75	0.004
	CVC/R5	1.00–2.50	1.73	0.458
	W/T	0.45–0.69	0.56	0.004
	W/C	0.80–1.17	0.94	0.007
	L/C	1.20–1.77	1.45	0.019

^a Pr. = *Pteropus rodricensis*.

^b Ph. = *Pteropus hypomelanus*.

^c P.v. = *Pteropus vampyrus*.

compare cardiac output between species as well as between mammals and birds. Generally, mammalian hearts average 0.59% of body mass, whereas the heart mass of birds is 0.85% of body mass.¹³ When using this measurement, bats are more comparable to birds than other mammals. Heart weight as percentage of body weight for bat species weighing from 65–297 g ranges from 0.83–0.96%, similar to that of many birds, for which a range of 0.81–1.88 has been reported in one study,⁹ and close to three times that of a laboratory mouse (*Mus musculus*).⁵ However, bat heart size is also comparable to that of terrestrial animals with high cardiovascular demands, such as white-tailed deer (*Odocoileus virginianus*), with a heart weight of 0.90% of body mass,⁵ and greyhound dogs (*Canis lupus familiaris*), with a heart weight range of 1.2–1.4% of body mass.¹⁴ Many of the results of this present study do not reflect the bat's high heart

weight to body weight ratio. For example, the ratio W/T, the widest expanse of the heart relative to the thoracic width on a ventrodorsal radiograph, ranges from 45–68% with a mean of 0.56% in the radiographs studied. This measurement is well within the “two-thirds rule” for dogs and cats (*Felis sylvestrus catus*), which states that a normal heart width should be less than two-thirds the width of the chest.^{1,20} The W/T measurement for bats is also close to the 51–61% reported for psittacines.¹⁷ The VHS derived from the pooled data from all three bat species was 9.4 ± 0.7 vertebrae; this measurement is slightly lower than the reference range for adult dogs, 9.7 ± 0.5 vertebrae,¹⁵ but higher than that reported for adult cats, 7.5 ± 0.3 vertebrae.⁷ These results do not reflect the bat's significantly larger heart, perhaps because the bat also may have a larger thorax and longer thoracic vertebrae than other mammals have. Measurements of an animal's heart weight to body weight ratio also take into account the thickness and density of the heart muscle itself.

Although the VHS was developed originally as a screening test for cardiomegaly, it may function best as a means to detect changes and follow the progression of disease in an individual.¹⁸ The vertebral heart scale was increased in only five out of nine of the bats with cardiomyopathy, and the authors do not believe it to be very sensitive in diagnosing cardiomegaly without comparison to early radiographs of the same bat.

In the radiographs used in this study, the asymmetry of the heart's orientation within the thorax on ventrodorsal views and the increased sternal contact of the heart on lateral radiographs were striking when compared with the appearance of typical dog and cat thoracic films. These differences may be explained by the fact that the heart is actually longer than the depth of the thorax in some radiographs, as reflected in values for AB/H ranging from 0.865–1.280, with a mean of 1.104 for all three species of bat. This measurement correlates to the mean value of 0.89 reported for adult cats.²⁰ It is possible that the large size reported for the bat's heart is reflected in an increased apicobasilar length rather than width. The heart of the flying fox also subjectively appears somewhat elongate on ventrodorsal views.

The demands placed on a flying fox's cardiovascular system during flight suggest that the heart's stroke volume would be proportionally large. Surgical observation has shown that a bat's heart is elongate during systole and nearly spherical when full.⁶ However, in this study, multiple radiographs of the same bat show little difference in the mea-

surement of the heart. This finding suggests that the phase of the cardiac cycle has little impact on radiographic appearance of the heart in the flying fox, which has been shown to be true for other mammals as well.^{12,19}

The results of this study diverge from previously published reports of large cardiac size and increased cardiac output in normal bats, in part because of the species used in this study.⁶ The bat species that generated the heart weight to body weight ratio listed previously were mostly microchiropterans, which are insectivores and must chase their prey. Flying foxes, which are in the suborder Megachiroptera, are frugivorous and do not have to hunt and catch their food. Thus, their need for a large cardiac output may be reduced when compared with their insectivorous relatives.

The length of the heart commonly exceeds the depth of the chest in the flying fox, causing the heart to be positioned cranially at an angle about 30° from perpendicular to the spine and increasing sternal contact in a manner similar to older cats.⁸ In some healthy bats, increased soft tissue opacity cranial to the heart caused mild tracheal elevation caudal to the thoracic inlet, most pronounced in *P. rodricensis*. This increased opacity in the normal radiographs of this study could be a doubling over of the aortic arch, called a *redundant aorta*, also seen in older cats. However, all bats have paired cranial vena cavae as an adaptation for flight,⁶ so this opacity may be caused by silhouetting of several great vessels. In necropsied specimens of *P. giganteus*, the pulmonary arteries and veins were thick and stubby, with little branching before breaking into capillaries. It was assumed that this pattern was present in most other bat species.⁶ In this study, some pulmonary vessels were noted to end abruptly without tapering in the largest species, *P. vampyrus*, but this “blunting” was not seen in the other two species of bat.

The use of the clavicle as a standard for the comparison of cardiac size is not reported in small animal literature, due to its variable presence and small size in nonflighted mammals. However, it appears to work well for the comparison of cardiac width in these large bats on ventrodorsal radiographs. The clavicle is large in bats, so easy to measure.

In this study, the three ratios that consistently had the lowest variance in the normal population, W/T and W/C on ventrodorsal projection and CD/H measured on lateral projection, are considered by the authors to be the best ratios for estimating normal cardiac dimensions. These three measurements had means of 0.56, 0.94, and 0.75, respectively,

values that are easy to apply to the clinical evaluation of radiographs. It is interesting to note that two out of three of the most efficient ratios are measured on the ventrodorsal projection. Also, subjectively, generalized cardiomegaly was observed more easily in abnormal radiographs on a ventrodorsal projection. These findings suggest that ventrodorsal radiographs may be more sensitive for detecting cardiomegaly. This determination may be due partly to the ease of positioning an animal on its back compared to lateral recumbency. However, the ratio that most often was increased over the normal range in the abnormal radiographs was AB/H, followed by CD/H, both read on lateral projections. It is possible that these measurements would be increased more commonly in bats with cardiac pathology, although the small sample size of abnormal bats ($n = 9$) prevents the development of any definitive conclusions from the abnormal population. The study of many more abnormal radiographs is necessary to accurately characterize cardiac disease radiographically.

This study attempted to develop guidelines for interpretation of thoracic radiographs in bats, though a number of limitations are recognized. The sample size was only moderate. The number of abnormal animals in the study is low. The gender of the bats was not divided evenly, with only 14 females (4.71%). It would be interesting to compare the data from this population with that from a collection with an even gender distribution, although a study on heart weight to body weight ratios in greyhounds showed no significant gender differences.¹⁴ The study uses only three species of flying fox, so the ability to extrapolate the findings to other *Pteropus* species and other chiropterans needs to be further investigated. The immense variety of size and form of the chiroptera and the differences in their environment and behavior suggests further species should be investigated.

CONCLUSIONS

Radiographic evaluation of cardiac size in bats appears feasible. Although subjective assessment of thoracic radiographs by an experienced radiologist remains the most sensitive means of analyzing cardiac pathology, cardiac measurement may prove more accurate when used by a clinician with limited experience. When using subjective examination of radiographs as an assessment for cardiomegaly in the flying fox, the ventrodorsal view seems slightly more appropriate.

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