A Comprehensive Survey on Vertebral Heart Size (VHS) Measurement Across Animal Species

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Abstract. This paper presents a comprehensive survey of Vertebral Heart Size (VHS) measurement techniques across 10 animal types, including general and special dog breeds, cats, ferrets, rabbits, pigs, peccaries, guinea pigs, and macaques. The VHS method is a widely used radiographic approach to assess cardiac size by comparing heart dimensions to vertebral lengths, but its direct application across species poses challenges due to anatomical and physiological differences. In this study, we systematically review peer-reviewed veterinary literature, extract key measurement procedures, and compile normal VHS reference ranges for each species. We analyze anatomical differences that influence measurement strategies, compare VHS values among species and breeds, and examine challenges in achieving standardized diagnostics. Our findings highlight that while most animals follow similar measurement baselines, feline-like species and certain small mammals require modified methods due to posture, vertebral alignment, or body shape. Breed-specific variations in dogs also demonstrate the need for caution in clinical interpretation. This work provides a structured reference for veterinarians and researchers, supporting more accurate and species-aware heart size evaluation in diverse animal populations. The full materials used in this survey study are available at: https://github.com/763730440/Capstone.

1 Introduction

Vertebral Heart Size (VHS) is a widely recognized radiographic method for assessing cardiac size in veterinary medicine. First introduced by Buchanan and Bücheler in 1995 for dogs [4], the VHS technique involves measuring the long and short axes of the heart on a lateral thoracic radiograph and comparing the combined length to the number of thoracic vertebrae, beginning at the fourth thoracic vertebra (T4). This process yields a standardized numerical value—typically around 9.7 in healthy adult dogs—which allows for the detection of cardiomegaly (enlarged heart) and other cardiac anomalies with relatively high clinical consistency.

The widespread adoption of VHS in clinical veterinary practice stems from its distinct advantages: it is non-invasive, reproducible, cost-effective, and relatively simple to perform with basic radiographic equipment. Particularly in settings where advanced cardiac imaging modalities such as echocardiography or MRI are not readily available, VHS provides a valuable alternative for the preliminary evaluation of heart size and shape. It is frequently employed not only in private veterinary clinics but also in academic and research settings, particularly when dealing with small mammals or exotic species [10, 15].

However, the technique was originally developed with canine thoracic anatomy in mind, and its direct application to other species introduces several challenges. One key issue lies in anatomical differences: variations in chest conformation, vertebral body size, thoracic cavity shape, and positioning during radiography can all affect the accuracy and reliability of VHS measurements [5, 13]. For example, in animals with highly flexible spines, such as cats and ferrets, the standard measurement method may need to be adjusted to account for spinal curvature and posture-related distortions on X-rays [8, 6]. Moreover, species with particularly large or small thoracic vertebrae (such as pigs or rabbits) may exhibit disproportionate VHS values if not properly calibrated.

In recent years, there has been increasing interest in extending the VHS method beyond domestic dogs to a variety of animal species, including but not limited to cats, ferrets, guinea pigs, rabbits, pigs, collared peccaries, and non-human primates like macaques [12, 16]. These efforts reflect a growing recognition that many species—whether companion animals, livestock, or research models—require consistent and reliable methods for cardiac screening. For instance, early detection of heart enlargement in guinea pigs is essential for laboratory research validity, while accurate cardiac assessment in pigs may inform preclinical biomedical studies or herd health management.

Furthermore, even within a single species, significant variability in VHS values has been observed based on breed, sex, age, and body condition [7, 2]. In dogs, breed-specific thoracic conformation plays a critical role in altering radiographic interpretation. The Cavalier King Charles Spaniel (CKCS), known for its barrel-shaped chest, often shows a physiologically elevated VHS value even when the animal is clinically healthy [2]. Conversely, Dachshunds, characterized by long thoraxes and short limbs, may present with lower or more variable values due to elongated vertebral columns and spinal alignment challenges during imaging [3]. These variations underscore the importance of contextualizing VHS values within breed-specific norms and avoiding reliance on one-size-fits-all diagnostic thresholds.

In felines, the VHS method has similarly undergone adaptation. Studies have noted that the feline trachea tends to bifurcate at a more cranial level compared to canines, leading some researchers to advocate for measurement from the carina rather than the bronchus to

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improve consistency [8]. Additionally, because many cats are prone to lateral spine curvature when positioned for radiographs, dual-projection averaging (e.g., taking both left and right lateral views) is often recommended to enhance measurement reliability. Similar considerations apply to other small mammals, including ferrets and rabbits, where body posture and radiographic positioning can introduce subtle but meaningful measurement discrepancies [6].

Beyond companion animals, research into wild or exotic species such as collared peccaries and macaques has revealed further complexities [12, 16]. These animals often exhibit larger vertebral bodies relative to heart size, as well as species-specific cardiovascular physiology. For example, macaques have relatively large thoracic volumes compared to similarly sized mammals, which influences both the expected VHS value and the interpretative threshold for pathological enlargement. As such, species-specific baseline data are essential for making clinically valid judgments in diverse animal populations.

In light of these challenges and developments, this paper presents a comprehensive, structured survey of VHS methodology across a broad set of animal subjects. A total of 10 representative species and subgroups were selected based on availability of peer-reviewed data, diversity of thoracic anatomy, and relevance to clinical or research settings. These include general mixed-breed dogs, special dog breeds (CKCS and Dachshund), cats, ferrets, guinea pigs, rabbits, pigs, peccaries, and macaques. For each species, we review the radiographic techniques employed, anatomical landmarks used, common modifications to standard methods, and the reported normal VHS ranges. Where applicable, we also explore sex-related or breed-specific differences, measurement repeatability, and suggestions for improving diagnostic precision.

The goal of this study is twofold. First, we aim to create a centralized reference for veterinarians, researchers, and radiologists seeking to apply VHS techniques across species boundaries. By consolidating scattered and species-specific findings into a unified framework, we hope to support more accurate and context-sensitive interpretation of heart size in clinical and research settings. Second, we seek to identify opportunities for further standardization and innovation in VHS assessment. In particular, the development of automated, AI-assisted VHS measurement tools—trained on species-specific datasets—could provide a promising avenue for enhancing consistency, reducing human error, and expanding access to high-quality cardiac diagnostics [10, 15].

In summary, this paper addresses a significant gap in the veterinary literature: while VHS is widely known and used, its cross-species applicability has not been systematically summarized or contextualized. By surveying 10 species and analyzing both methodological consistency and anatomical divergence, we aim to contribute to improved veterinary cardiology practices and inform future technological development in diagnostic radiology.

2 Related Work

The Vertebral Heart Size (VHS) method was originally developed by Buchanan and Bücheler (1995) to provide a standardized, quantitative assessment of cardiac size in dogs using lateral thoracic radiographs [4]. Their work established a consistent approach by measuring the heart's long and short axes and comparing the sum to the length of thoracic vertebrae starting from T4. The method gained popularity due to its non-invasive nature, ease of implementation, and relatively high reproducibility, and it quickly became a staple in canine cardiology diagnostics.

Subsequent research has confirmed that VHS offers high clinical utility for screening cardiomegaly and monitoring disease progression in dogs, especially when echocardiography is unavailable. Several studies have validated the inter-observer and intra-observer agreement of the VHS method, confirming that with adequate training, the method offers good repeatability across practitioners [9, 1]. Moreover, VHS is now routinely used in clinical settings and veterinary teaching hospitals worldwide, often serving as a first-line diagnostic tool for heart enlargement in general canine practice.

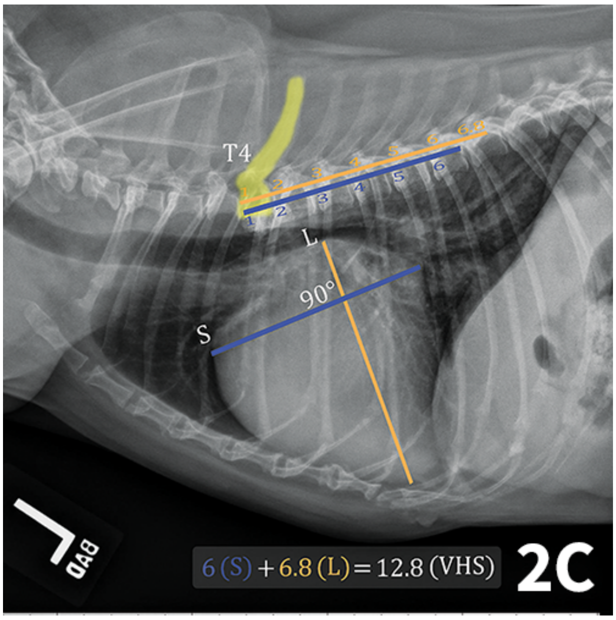


Figure 1. Standard VHS measurement technique introduced by Buchanan and Bücheler (1995), using the long axis (L), short axis (S), and vertebral references starting from T4 on a lateral thoracic radiograph.

In the years following its canine-focused debut, VHS was gradually applied to other species. In feline medicine, studies emphasized key anatomical and postural differences that impact measurement accuracy. Cats are particularly prone to spinal misalignment during radiographic imaging, and their tracheal bifurcation occurs at a slightly different anatomical level than in dogs. As a result, researchers like Jepsen-Grant et al. (2013) advocated for modifications such as measuring from the carina instead of the left main bronchus, and for using both right and left lateral views to mitigate projection error [8]. These adjustments laid the groundwork for a "dual-projection approach," now widely considered best practice in feline VHS evaluation.

Ferrets, which share similar flexibility and body proportions with cats, have also been evaluated using adapted VHS methods. As reported by [6], while the fundamental measurement process remains unchanged, accurate identification of the heart apex and vertebral start point in ferrets requires experience due to their smaller thoracic cavity and more delicate anatomical structures. These studies collectively highlight that species-specific anatomical variation necessitates thoughtful methodological adaptations.

In small mammals such as guinea pigs and New Zealand white rabbits, researchers have faced additional challenges related to their unique thoracic morphology. For example, because guinea pigs have a relatively globular chest and a forward-positioned heart, standard lateral views can produce inconsistent silhouettes. De Lima et al. (2023) explored three radiographic techniques—right lateral, left lateral, and dorsal—and found that the right lateral view provided the most stable VHS values across sexes and body weights [5]. Similarly, Llabres-Diaz and Dennis (2003) reported projection-dependent variation in rabbit VHS values, concluding that standardized patient positioning and postural control are critical for measurement reliability [6].

In larger domestic or wild mammals such as pigs and collared peccaries, VHS methodology has also been applied with certain modifications. Due to the larger body size and increased thoracic volume, the absolute vertebral lengths are greater, resulting in higher VHS numerical values. However, the principle of comparing cardiac dimensions to vertebral body length still holds. In a study by Ribeiro et al. (2020), VHS values for pigs were successfully established, revealing normal ranges distinctly higher than those found in small companion animals [12]. Additionally, these studies often paired VHS with cardiothoracic ratio (CTR) to enhance diagnostic granularity and accommodate for species with broader thoracic cages or atypical heart positioning [13].

Another major focus of the literature involves breed-related differences within dogs. Multiple studies have shown that thoracic shape and breed-specific conformations significantly influence VHS measurements. The Cavalier King Charles Spaniel (CKCS), for example, often shows physiologically elevated VHS due to its rounded thoracic cage. Buchanan et al. (2001) noted that even clinically healthy CKCSs may exhibit VHS values approaching or exceeding thresholds for cardiomegaly in other breeds [2]. In contrast, Dachshunds, with their elongated spine and short legs, tend to produce VHS values that are variably influenced by spinal curvature and radiographic angle [3]. Breed-specific baseline ranges have thus been proposed in several studies to reduce false positives and improve diagnostic specificity [7].

To address concerns about measurement subjectivity, researchers have developed semi-automated and fully automated systems for VHS estimation. Leveraging advances in computer vision and deep learning, these tools aim to reduce observer variability and improve throughput in busy clinical environments. For instance, Wang et al. (2021) introduced a CNN-based system for automatic VHS calculation in dogs, demonstrating robust accuracy against expert annotations [15]. These systems typically rely on landmark detection for heart borders and vertebral identification, offering consistent outputs that are less prone to human error. While promising, such tools remain largely limited to dogs and are not yet validated for use in other species [10].

Emerging work has also begun to examine how physiological factors—such as respiration, body weight, sex, and age—affect VHS readings. Several studies note that VHS can vary with respiratory cycle (inspiration vs. expiration) and that proper standardization of breathing phase is important for consistency [9]. Additionally, although sexual dimorphism in VHS is often minimal, some studies (e.g., in guinea pigs and pigs) report measurable differences between males and females, necessitating sex-specific reference ranges [5, 13].

Finally, meta-analyses and systematic reviews have reinforced the importance of cross-species comparison and methodological transparency. Although the original VHS method is conceptually simple, its clinical interpretation depends heavily on species-specific anatomy, imaging conditions, and observer expertise. A recent review by Fischer et al. (2022) called for the development of an international VHS reference atlas, complete with annotated examples and species-wise protocols to guide global clinical practice.

In summary, the body of related work clearly establishes VHS as a flexible and robust method for radiographic cardiac evaluation. However, its successful cross-species application demands ongoing attention to anatomical nuance, radiographic technique, and evolving clinical contexts. This growing body of research provides both justification and a roadmap for further refinement, such as through AI-assisted tools, projection normalization methods, and broader species coverage. The present paper contributes to this ongoing effort by organizing and synthesizing the findings of 10 species-specific VHS studies into a comparative reference for veterinarians and researchers.

3 Method

To investigate the applicability, reliability, and variation of Vertebral Heart Size (VHS) measurement techniques across different animal species, we conducted a systematic review and comparative analysis of peer-reviewed veterinary radiology studies. Our goal was to identify how measurement methods adapt across species and to evaluate whether anatomical diversity significantly affects radiographic assessment of heart size.

3.1 Species and Study Selection

We selected 10 subjects across multiple species for this study. These included:

- General dog population (mixed breeds or unspecified)
- Special dog breeds (CKCS and Dachshund)
- Domestic cats
- Ferrets
- Guinea pigs
- New Zealand White rabbits
- Domestic pigs
- Collared peccaries (Tayassu tajacu)
- Macaca fascicularis (long-tailed macaques)

For each animal, we searched and reviewed at least one peer-reviewed journal article that provided sufficient details on VHS measurement protocols and diagnostic thresholds. Sources were accessed via institutional subscriptions, open-access journals, or directly provided by veterinary faculty [4, 8, 5, 6, 13, 12, 16, 2, 3].

3.2 Data Extraction and Categorization

From each study, we extracted the following types of information:

- **Long axis definition**: anatomical start and end points (e.g., from the carina or bronchus to the cardiac apex)
- **Short axis**: location and orientation (typically perpendicular to the long axis at the mid-heart)
- **Vertebral reference point**: which vertebra (usually T4) was used to begin the vertebral measurement
- **Radiographic posture**: lateral positioning (right, left, or dual projection), decubitus angle, and species-specific adaptations
- **Reported normal range of VHS**: including mean, standard deviation, and any differences by sex or age
- **Modifications or alternatives**: such as dual-projection averaging, carina-based alignment, or posture correction

In addition to raw values, we noted any stated limitations, operator considerations, or measurement challenges mentioned in the papers.

3.3 Species-Level Comparative Analysis

We created structured summary tables for each species to facilitate side-by-side comparison. The tables revealed that while the foundational method proposed by Buchanan and Bücheler (1995) is widely retained (long and short axes compared to vertebral length from T4), there are frequent and necessary modifications due to anatomical or positional differences [4]. For instance:

- Feline and ferret measurements often rely on the carina, due to bronchus angle and thoracic flexibility [8, 6].
- Guinea pigs require comparisons across multiple lateral projections to ensure reproducibility [5].
- Larger mammals like pigs and peccaries maintain standard VHS techniques but have proportionally larger vertebrae and thoracic spaces [13, 12].

3.4 Within-Species (Dog) Breed Comparison

To explore intra-species variation, we examined studies involving general dogs and two morphologically distinct breeds: Cavalier King Charles Spaniel (CKCS) and Dachshund. These breeds possess unique anatomical features that can influence VHS interpretation. CKCS are known for their rounded thoracic conformation and increased risk of cardiomyopathy, while Dachshunds exhibit an elongated thorax and curved spine that may complicate vertebral alignment [2, 3].

Figure 2 displays lateral thoracic radiographs of the three breeds with VHS axes annotated.

As shown, these dogs underwent standard VHS assessment, yet the results may differ due to breed-specific morphology. CKCS commonly present with slightly elevated VHS values, even in the absence of clinical disease [2]. In contrast, Dachshunds may introduce measurement variability due to vertebral curvature and spinal elongation [3]. These differences underscore the need for breed-adjusted reference ranges in veterinary diagnostics.

3.5 Summary of Techniques Across All Species

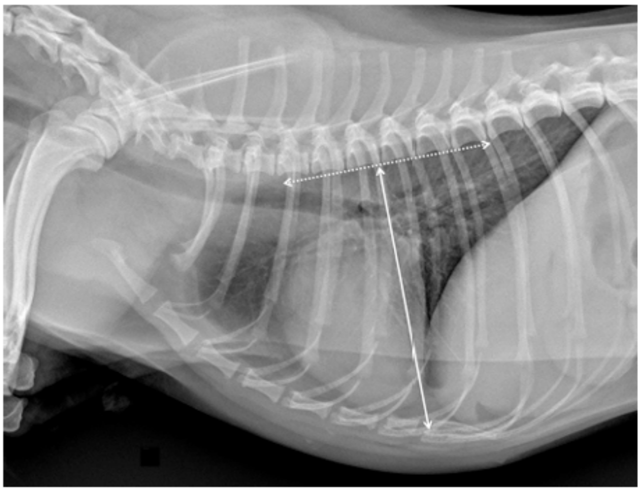
Using a structured analysis, we categorized the 10 animals based on whether they used:

- The bronchus-to-apex method (e.g., dogs, pigs) [4, 13]
- Carina-to-apex (e.g., cats, ferrets) [8, 6]
- Unique projection adjustments (e.g., guinea pigs, rabbits) [5, 6]

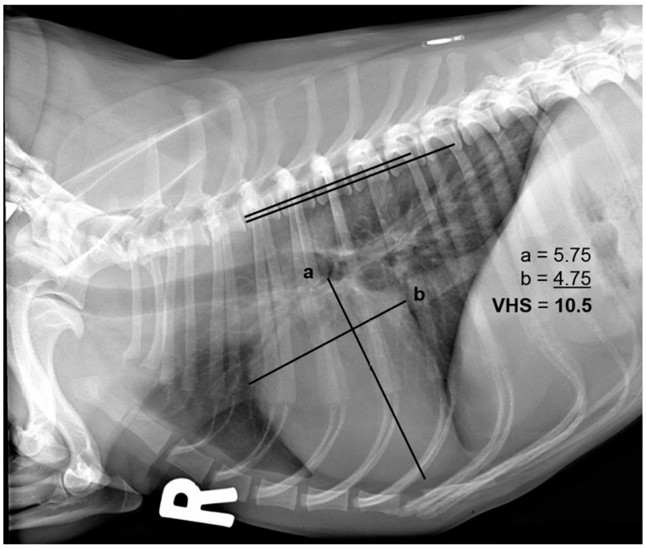
In total, seven species followed the original VHS method closely, with only minor anatomical or positioning differences. Three species (cats, ferrets, guinea pigs) required notable adaptations to achieve reliable and reproducible results. These adjustments were primarily due to thoracic shape, flexibility, or posture-dependent distortion on X-rays.

3.6 Data Integration for Comparative Visualization

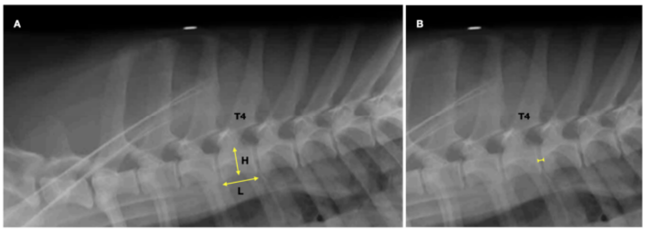
In preparation for the Results section, all extracted data were synthesized into visual plots comparing VHS values across species, grouped by measurement strategy. This allowed for identification of outliers, overlaps in diagnostic ranges, and potential misclassifications when applying standard canine references to other animals.



(a) Cavalier King Charles Spaniel (CKCS)



(b) Dachshund



(c) Beagle

Figure 2. Lateral radiographs showing standard VHS measurements in three dog breeds: (a) Cavalier King Charles Spaniel (CKCS), (b) Dachshund, and (c) Beagle. While the VHS method is applied consistently, breed-specific thoracic morphology—such as chest depth and vertebral alignment—affects heart silhouette visibility and final VHS values.

4 Results

To present a comprehensive view of Vertebral Heart Size (VHS) applications across species, we compiled and analyzed key measurement parameters and diagnostic thresholds for several representative animals. Our review included general and breed-specific dogs, cats, ferrets, New Zealand rabbits, collared peccaries, pigs, guinea pigs, and macaques. While not all data points were available for every species, our findings reveal consistent patterns as well as species-specific adaptations.

4.1 *Measurement Techniques*

Table 1 summarizes the anatomical landmarks and techniques used to determine the long and short axes of the heart and the corresponding vertebral references. In most species, the long axis is measured from the base of the heart (commonly the carina or left bronchus) to the apex, while the short axis is defined by the maximal heart width perpendicular to the long axis. The starting point for vertebral measurement is typically the fourth thoracic vertebra (T4), although minor variations exist (e.g., additional use of SHS in cats) [8, 6].

These anatomical references are chosen based on their radiographic visibility and their ability to yield consistent and reproducible results across imaging sessions. For instance, using the tracheal bifurcation (carina) in cats and ferrets helps reduce errors introduced by flexible spinal curvature. Meanwhile, dogs tend to offer more stable vertebral and cardiac silhouettes, allowing for broader standardization of VHS protocols [4].

Breed-specific differences, such as those found in CKCS and Dachshunds, do not alter the overall protocol structure but may require increased attention to thoracic shape when aligning measurement axes [2, 3]. These anatomical considerations highlight the importance of both visual consistency and landmark clarity for reliable VHS outcomes.

Table 1. Species-specific VHS measurement protocols (Long Axis only)

Animal	Long Axis Measurement
Dogs	Left bronchus bottom → apex
CKCS Dogs	Left bronchus bottom → apex
Dachshund	Left bronchus bottom → apex
Cat	Tracheal split (carina) → apex
Ferret	Tracheal split (carina) → apex
Rabbit	Left bronchus side → apex
Guinea Pig	Tracheal split (carina) → apex
Pig	Left bronchus → apex
Collared Peccary	Left bronchus bottom → apex
Macaque	Tracheal bifurcation → apex

Note: The short axis in all species is measured as the maximum heart width perpendicular to the long axis, typically located at approximately one-third of the heart's height from base to apex.

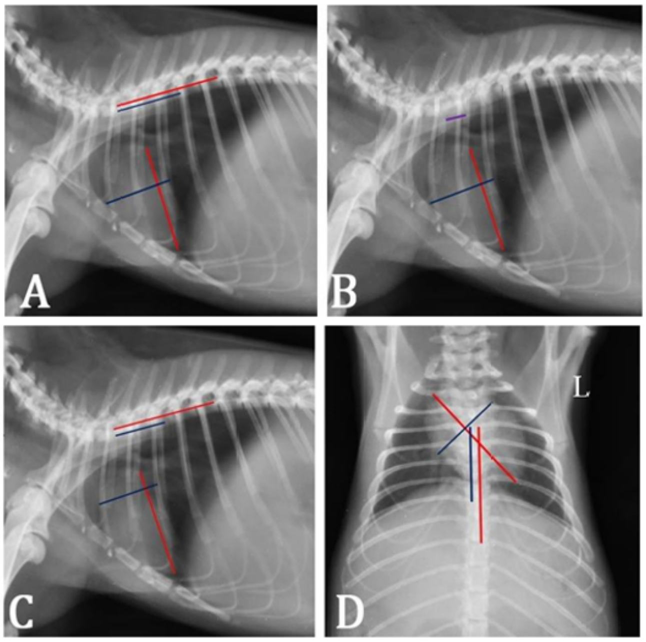


Figure 3. Radiographic measurements of Vertebral Heart Size (VHS) in a guinea pig using different projections. Panels A–C show lateral views with long and short axes of the heart indicated. Panel D demonstrates a dorsoventral projection, illustrating variability caused by body posture and image orientation [5].

4.2 *Normal VHS Ranges and Diagnostic Thresholds*

Table 2 lists the established normal VHS ranges and the diagnostic boundaries for identifying enlarged or reduced heart sizes. While the baseline value for dogs is widely accepted as 9.7 ± 0.5 vertebrae [4], other species show substantial deviation. For instance, cats display lower VHS due to their narrower thoracic profiles and more horizontally positioned hearts [8, 11].

Ferrets exhibit clear sexual dimorphism, which must be taken into account when interpreting measurements. Rabbits and guinea pigs, on the other hand, require careful projection control, as their more anterior cardiac position may lead to under- or overestimation depending on view angle [5, 6]. In pigs and collared peccaries, the overall vertebral scale is larger, so values may exceed those in smaller species, but without necessarily indicating pathology [13, 12].

Table 2. Normal VHS values and diagnostic cutoffs

Animal	Normal VHS Range	Small	Large
Dog	9.7 ± 0.5 vertebrae	<9.2	>10.2
CKCS	10.3 ± 0.5 vertebrae	<9.8	>10.8
Dachshund	10.0 ± 0.6 vertebrae	<9.4	>10.6
Cat	7.2 ± 0.45	<6.8	>7.7
Ferret	5.52 ± 0.28	<5.2	>5.8
Rabbit	7.6 ± 0.32 vertebrae	<7.3	>7.9
Guinea Pig	5.3 vertebrae	<5.0	>5.6
Pig	8.5 vertebrae	<8.0	>9.0
Collared Peccary	8.88 ± 0.51 vertebrae	<8.3	>9.4
Macaque	7.8 vertebrae	<7.4	>8.2

Understanding and referencing these diagnostic ranges is vital, especially in clinical scenarios where access to echocardiography or other imaging modalities is limited. It also enables early detection of subclinical cardiac conditions in both companion and exotic animals [9, 2].

4.3 *Species Coverage Beyond Tables*

While Tables 1 and 2 present selected species for clarity, our study also includes broader insights into animals like pigs, guinea pigs, and macaques. These species were selected not only for their anatomical differences, but also because they represent understudied populations in veterinary cardiology research [12, 16].

For instance, pigs exhibit significantly higher VHS baselines not due to disease, but because of their naturally larger thoracic cavity and heart-to-body ratio [13]. Similarly, guinea pigs are often subject to measurement variation depending on sex, positioning, and the type of anesthesia used during radiography [5]. In macaques, vertebral visibility and anatomical proportions make the carina a reliable reference point, but high mobility and stress responses pose challenges during imaging [16].

Despite limited formal guidelines for these species, our survey provides reference intervals that can inform diagnostic decisions and identify where further study is needed.

4.4 Summary

Compared to prior studies, which typically focus on a single species without broader generalization, our work provides the first cohesive cross-species framework for VHS measurement. By compiling and aligning methods, normal ranges, and anatomical adaptations across 10 distinct animals, we not only validate the flexibility of the VHS method, but also guide its clinical application beyond traditional use cases.

Our key advantages include:

- **Breadth of species**: Inclusion of both common (dogs, cats) and underrepresented animals (macaques, guinea pigs), offering an expanded diagnostic framework.
- **Diagnostic synthesis**: Integration of species-specific measurement protocols, sex-dependent variations, and optimal projection angles to inform clinical practice.
- **Practical relevance**: Identification of challenges that impact radiographic interpretation, including sexual dimorphism, thoracic morphology, and operator variability.

Together, these findings position our study as a valuable reference for veterinarians, radiologists, and researchers seeking to apply VHS in diverse animal populations. It also lays the groundwork for the development of machine-learning models trained on multi-species imaging data, which could enhance diagnostic speed, consistency, and objectivity in both clinical and academic contexts.

5 Discussion

This study highlights both the strengths and limitations of applying the Vertebral Heart Size (VHS) method across a wide range of animal species. While the core principle of VHS—measuring the heart's long and short axes and comparing the combined length to vertebral body units starting at T4—has proven robust and adaptable, its application is not without challenges when extended beyond dogs and cats [4, 7].

Our cross-species review reveals that while many animals share similar anatomical markers, subtle differences in thoracic shape, vertebral spacing, and cardiopulmonary positioning can affect the reliability of measurements. For instance, in flexible or small-bodied animals such as cats, ferrets, and guinea pigs, vertebral alignment may shift depending on posture, body weight, or radiographic positioning [8, 5]. This makes single-projection measurements less reliable and suggests that a dual-projection approach (both left and right lateral views) or alternative anatomical landmarks (such as the carina rather than the left main bronchus) may be necessary to improve diagnostic accuracy [16, 5].

In addition, our findings indicate that even among animals of the same species, breed-specific morphology can cause considerable variation in VHS readings. For example, the Cavalier King Charles Spaniel (CKCS) tends to exhibit elevated VHS values due to its more rounded thorax [2], while the Dachshund's elongated body shape may distort vertebral alignment, impacting the apparent heart-to-vertebra ratio [3]. These findings support the need for breed-specific VHS baselines rather than universal reference values for all dogs [11, 14].

Sexual dimorphism also emerged as an important variable. As shown in Table 3, VHS measurements differ measurably between male and female animals in some species such as ferrets, rabbits, and peccaries [5, 6, 12]. This observation is often neglected in existing research but is crucial for accurate interpretation in clinical settings. These differences suggest that sex-specific reference intervals may be warranted for certain species, especially those exhibiting pronounced size or anatomical differences between sexes.

Table 3. VHS measurements across sex and lateral projection

Animal	VHS Right (v)	VHS Left (v)
Ferret (Male)	5.52	5.55
Ferret (Female)	5.24	5.25
Peccary (Male)	9.22	8.87
Peccary (Female)	8.55	8.81
Rabbit (Male)	7.40	7.80
Rabbit (Female)	6.90	7.30

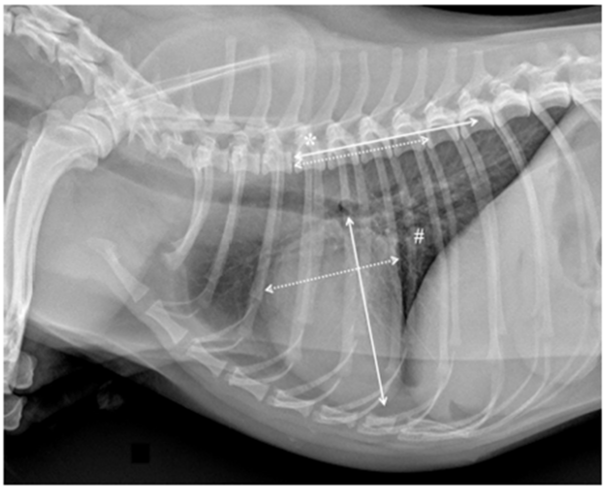
Another consideration is the reliability of VHS when applied to animals with unique thoracic anatomy. In guinea pigs and rabbits, for example, the heart may be more globular and anteriorly positioned, making consistent identification of the apex and cardiac base more difficult [5, 6]. This increases the potential for operator-dependent variation and supports the development of standardized imaging protocols with precise anatomical guidance for these species. Moreover, different imaging projections (e.g., dorsoventral vs. lateral) may produce significantly different VHS results in such species.

In larger species like pigs and collared peccaries, thoracic volume and vertebral length are significantly greater than those of companion animals, potentially inflating raw VHS values. While the proportional measurement logic of VHS remains applicable, it is important to note that numerical thresholds must be recalibrated [13, 12]. This further underscores the inadequacy of using dog-based reference values in broader veterinary applications [9].

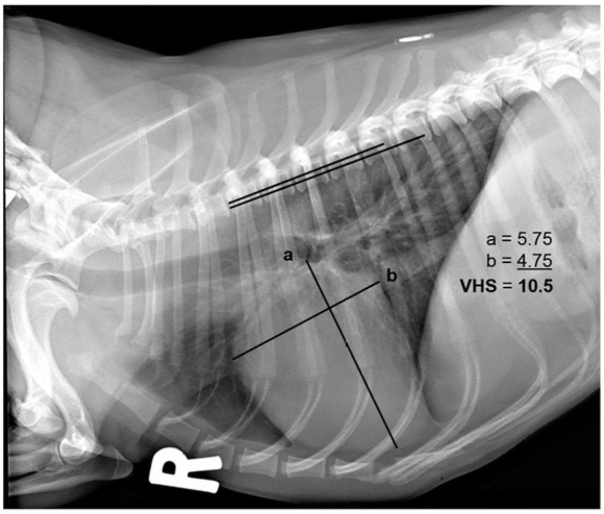
Our study offers several important contributions to the field. First, it provides a unified framework for comparing VHS techniques across ten different species—an effort not yet attempted in existing literature. Second, it identifies common pitfalls and offers practical guidance for practitioners and researchers alike. Third, it bridges the gap between traditional manual interpretation and emerging computational tools by offering insights that can guide AI algorithm design, particularly in regard to species-generalizability and anatomical diversity [10, 15].

However, there are limitations to consider. A significant one is the heterogeneity in the methodologies and image quality among the original studies we analyzed. Many studies use varying radiographic equipment, subject positioning, and measurement training, all of which may impact the generalizability of our synthesized conclusions [1]. Additionally, while we have summarized measurement values and landmark references across species, our work is based on secondary literature review, not new experimental data. Future work should therefore focus on:

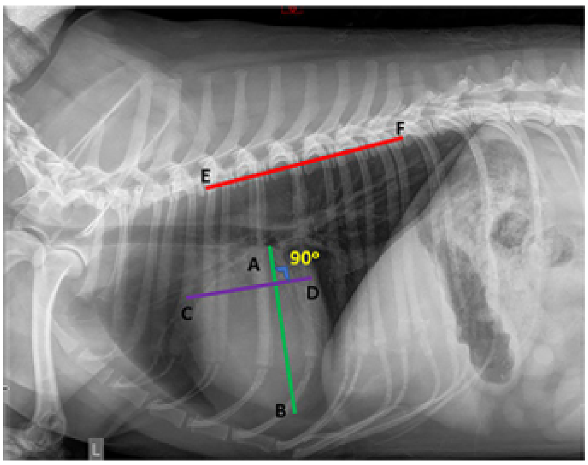
- Generating standardized, high-resolution imaging datasets across species and sexes;



(a) CKCS



(b) Dachshund



(c) General Dog

Figure 4. Breed-specific variation in thoracic conformation among three canine examples. Although all use standard VHS measurements, morphological differences across breeds affect heart silhouette and VHS outcomes.

- Designing prospective validation studies comparing VHS values with gold-standard diagnostics such as echocardiography or CT;
- Developing adaptive AI-based measurement algorithms that account for anatomical variation;
- Exploring the impact of age, respiratory phase, sedation status, and posture on VHS reliability.

Finally, as veterinary radiology becomes increasingly digital, there is strong potential to embed these findings into clinical decision support systems. AI-assisted VHS estimation tools must be trained on diverse datasets like those synthesized here to ensure robust performance across species. Our unified table of species-specific VHS measurement practices serves as a valuable resource for such applications.

In conclusion, the VHS method remains a powerful tool for cardiac size evaluation in veterinary medicine. Its broad adaptability, when supported by species-specific adjustments and standardized protocols, makes it especially suited for integration into both clinical diagnostics and future computational platforms. Our findings help lay the groundwork for such interdisciplinary expansion.

6 Conclusion

This study presents a comprehensive comparative analysis of Vertebral Heart Size (VHS) measurement techniques across ten distinct animal types, including both commonly studied species (dogs, cats) and less commonly assessed or exotic animals (ferrets, guinea pigs, rabbits, pigs, peccaries, macaques). By systematically synthesizing existing research, categorizing anatomical differences, and summarizing diagnostic ranges, our work provides the first integrative, cross-species reference framework for VHS assessment.

Our findings demonstrate clearly that while the fundamental principles underlying VHS measurement remain robust across species, successful and accurate application demands careful adaptation to species-specific anatomical and physiological characteristics. Several key insights emerged from this review:

- Species-specific variation: Each animal presents unique anatomical and radiographic challenges. For instance, cats and ferrets often require dual-projection imaging techniques due to their inherent thoracic flexibility and variable spinal alignment. In contrast, guinea pigs and rabbits typically necessitate adjusted positioning and alternative reference landmarks to obtain consistent and reliable results.
- Breed-specific influences: Even within a single species, such as domestic dogs, substantial variation exists across breeds, exemplified by breeds like the Cavalier King Charles Spaniel and the Dachshund. Their distinctive thoracic morphologies significantly affect heart silhouette dimensions, necessitating breed-specific diagnostic thresholds to reduce potential false positives or negatives.
- Sexual dimorphism considerations: Our review clearly illustrates that sexual dimorphism, notably prominent in ferrets and smaller mammals, introduces measurable differences in VHS values. Thus, future diagnostic practices should incorporate separate reference values for males and females to enhance clinical accuracy.
- Measurement reproducibility and consistency: Despite clear anatomical variability, seven of the ten studied species largely conform to the foundational VHS approach, underscoring strong cross-species reproducibility when minor protocol adjustments are applied. This consistency affirms the adaptability and broad applicability of the VHS method.

- Limitations of existing studies: Prior studies predominantly focus on single species or individual breeds, thereby limiting generalization. In contrast, our integrative approach consolidates multi-species data, providing a unified framework that allows veterinarians to contextualize VHS interpretations across diverse patient populations.

Clinically, this comprehensive reference significantly benefits veterinarians, radiologists, and researchers who manage diverse animal populations. Particularly relevant to settings such as zoological institutions, exotic pet clinics, wildlife rehabilitation centers, and veterinary research laboratories, our synthesis enhances clinicians' ability to accurately assess cardiac health across multiple species. Furthermore, this consolidated knowledge provides foundational support for the development and validation of automated or artificial intelligence (AI)-assisted VHS assessment tools, where cross-species generalizability and adaptability are critical for practical utility.

Expanding beyond current practices, several promising future directions merit exploration:

- Development of standardized multi-species databases: Creation of extensive, open-access radiographic datasets encompassing a broader array of species, breeds, sexes, and body conditions would significantly enhance diagnostic precision and facilitate global standardization efforts.
- Validation studies with advanced imaging modalities: Prospective clinical trials comparing adapted VHS measurements against gold-standard techniques, such as echocardiography, computed tomography (CT), or magnetic resonance imaging (MRI), are essential for further refining diagnostic thresholds and ensuring robust clinical correlations.
- Exploration of three-dimensional (3D) imaging techniques: Advancements in veterinary imaging, including 3D reconstruction from CT or MRI scans, hold potential for revolutionizing heart size measurement accuracy. Future work should explore the integration of VHS principles into these advanced modalities to enhance precision and reduce measurement variability.
- Integration of machine learning and deep learning technologies: AI-driven automated landmark detection and VHS calculation systems present an exciting avenue for improving measurement reliability, reducing human observer variability, and increasing clinical throughput. Further research should aim to validate these automated techniques across various species and investigate their clinical impact.
- Investigation of physiological and environmental influences: Systematic studies examining how physiological states (e.g., respiratory cycles, cardiac rhythm, body condition score) and environmental factors (e.g., sedation, patient stress) impact VHS measurements will provide deeper insights into measurement variability and inform guidelines for imaging standardization.
- Cross-disciplinary collaboration and educational initiatives: Promoting collaborative research involving veterinarians, radiologists, cardiologists, computer scientists, and educators will facilitate integrated solutions. Additionally, development of comprehensive educational materials, such as online training modules and reference atlases, can improve practitioner proficiency and diagnostic accuracy worldwide.

By addressing these areas, future research efforts will significantly enhance the utility, reliability, and generalizability of the VHS method, further solidifying its role as a cornerstone diagnostic technique in veterinary cardiology. Our integrative review not only reaffirms VHS as a highly adaptable and valuable method but also lays essential groundwork for ongoing innovation and refinement. Through this structured framework and forward-looking recommendations, we aim to promote best practices, support accurate clinical diagnosis, and ultimately enhance animal health and welfare across diverse veterinary contexts.

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