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ORIGINAL INVESTIGATION

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The heart to single vertebra ratio: A new objective method for radiographic assessment of cardiac silhouette size in dogs

Dario Costanza[1] | Adelaide Greco[1] | Diego Piantedosi[2] | Dario Bruzzese[3] | Maria Pia Pasolini[2] | Pierpaolo Coluccia[1] | Erica Castiello[1] | Cláudia Sofia Baptista[4,5] | Leonardo Meomartino[1]

[1]Interdepartmental Centre of Veterinary Radiology, University of Napoli "Federico II", Napoli, Italy

[2]Department of Veterinary Medicine and Animal Productions, University of Napoli "Federico II", Napoli, Italy

[3]Department of Public Health, University of Napoli "Federico II", Napoli, Italy

[4]Department of Veterinary Clinics, UPVet, Institute of Biomedical Sciences Abel Salazar, University of Porto (ICBAS-UP), Porto, Portugal

[5]Animal Science Studies Centre, Associate Laboratory for Animal and Veterinary Science (AL4AnimalS), Porto, Portugal

Correspondence
Dario Costanza, Interdepartmental Centre of Veterinary Radiology, University of Napoli "Federico II", Via Federico Delpino 1, 80137, Napoli, Italy.
Email: dario.costanza@unina.it

Abstract

Vertebral heart size (VHS) is widely determined in clinical practice as an objective method to assess the cardiac silhouette dimensions. However, a key limitation is that it is difficult to determine VHS in dogs with vertebral alterations. This retrospective, method comparison, observer agreement study sought to overcome this limitation by using the heart-to-single vertebra ratio (HSVR), by evaluating the level of agreement between VHS and HSVR, as well as the intra- and inter-observer agreement for HSVR. Three independent observers retrospectively evaluated thoracic radiographs obtained over a set time period. Exclusion criteria were the presence of alterations of the thoracic spine and the inability to clearly outline the cardiac silhouette. The lengths of the vertebral bodies, from the fourth to eighth thoracic vertebra, and VHS were measured on each radiograph. The HSVR was calculated by dividing the sum of the cardiac long and short axes by the length of each vertebral body. Eighty dogs of different breeds were included in the final analysis. Lin's concordance correlation coefficients revealed strong correlations between VHS and HSVR (0.91–0.96), and the Bland–Altman plots showed low bias (0.01–0.2) between the methods. The mean absolute errors indicated low average magnitudes of error (0.11–0.28). The intraclass correlation coefficients showed good to excellent inter-observer (0.87–0.92; $P = 0.000$) and intra-observer (0.87–0.99; $P < .001$) agreement. In the authors' opinion, this new method, which is less time consuming and more objective, could offer a valuable alternative to VHS.

KEYWORDS
canine, cardiology, thoracic radiography, vertebral heart scale, vertebral heart score

1 | INTRODUCTION

Although echocardiography is considered the gold standard modality for studying the heart, radiography plays a fundamental role in assessing the size of the cardiac silhouette and ruling out the presence of concomitant pulmonary disorders such as vascular congestion, pulmonary edema, and pneumonia.[1] However, radiographic assessment of the cardiac silhouette dimensions is not always straightforward and is quite subjective; indeed, variations may occur owing to different inherent

Abbreviations: CCC, concordance correlation coefficient; CI, confidence interval; DICOM, digital imaging and communications in medicine; HSVR, heart to single vertebra ratio; HSVR^{T4}, heart to single vertebra ratio determined using the fourth thoracic vertebra; HSVR^{T5}, heart to single vertebra ratio determined using the fifth thoracic vertebra; HSVR^{T6}, heart to single vertebra ratio determined using the sixth thoracic vertebra; HSVR^{T7}, heart to single vertebra ratio determined using the seventh thoracic vertebra; HSVR^{T8}, heart to single vertebra ratio determined using the eighth thoracic vertebra; ICC, intraclass correlation coefficient; LA, cardiac long axis; MAE, mean absolute error; SA, cardiac short axis; SD, standard deviation; T4, fourth thoracic vertebra; T5, fifth thoracic vertebra; T6, sixth thoracic vertebra; T7, seventh thoracic vertebra; T8, eighth thoracic vertebra; VHS, vertebral heart size.

conformations of the thorax among different canine morphotypes.[2] Over the years, several methods have been proposed to objectively determine the dimensions of the cardiac silhouette.[3–5] However, these methods are not widely used in clinical practice because of their limitations, including variations in cardiac silhouette inclination, thoracic conformation, the breathing phase in which the radiograph is acquired, difficulty in correctly positioning the patient, the presence of concurrent lung pathologies that alter the cardiothoracic ratio, and the inaccuracy of determining the anatomical landmarks used for measurements.[4,6,7] In 1995, Buchanan and Bücheler described the vertebral heart score (VHS) as an objective method for assessing heart size.[8] Since then, a number of studies have evaluated its reliability by assessing the intra- and inter-observer agreement, the effects of sex, breathing, cardiac cycle, body condition score, and recumbency on the measurements, and determined indices for individual breeds that tend to deviate from the initially reported cut-off values.[9–25] VHS is very useful in clinical practice because it is relatively simple to determine at initial and follow-up examinations.[19,26,27] However, some limitations exist, including the difficulty of determining VHS in patients with *spondylosis deformans*, reduced intervertebral disc spaces, or vertebral malformations such as hemivertebrae, butterfly vertebrae or wedge vertebrae. Of note, vertebral abnormalities artifactually increase VHS.[11,24]

We hypothesized that a single vertebra preserves its proportion to the respect of the whole body as well as the thoracic vertebral tract proposed by Buchanan and Bucheler.[8] The use of a single vertebra, without shape and dimensions alterations, could allow the clinician to objectively evaluate cardiac silhouette dimensions, even in patients with thoracic spine alterations. Therefore, the primary aim of this study was to develop a novel method, termed the heart-to-single vertebra ratio (HSVR). Secondary objectives were to test the level of agreement between the newly described method and VHS, and to evaluate the intra- and inter-observer agreement among three observers with different levels of experience.

2 | MATERIALS AND METHODS

2.1 | Selection and description of subjects

This single-center, retrospective, method comparison, observer agreement study was approved by the Clinical Ethical Review Board of the University of Naples “Federico II” (PG/2022/0062754). The electronic records of canine patients referred to the Interdepartmental Centre of Veterinary Radiology of the University of Naples ‘Federico II’ in the set study period between September 2018 and January 2021 were retrieved from the picture archiving and communication system (dcm4chee-arc-light version 5.11.1, http://www.dcm4che.org) and the images were reviewed. Radiography was performed for various reasons, including cardiologic screening, pre-anesthetic evaluation, and exclusion of metastases. All radiographic examinations were obtained on awake, unsedated patients during inspiration and used a computed radiography system (Agfa CR-30, Agfa HealthCare, Mortsel, Belgium) equipped with a focused Potter–Bucky grid and a focus-to-film distance of 100 cm. The dogs were restrained manually or with sandbags, attempting to avoid spinal or heart mispositioning that could cause geometric distortions or make it difficult to correctly visualize the anatomical landmarks. All radiographic examinations included at least the right-lateral view, which was used to assess the heart dimensions. Exclusion criteria were as follows: (a) presence of alterations affecting the thoracic spine (e.g., hemivertebrae, butterfly vertebrae, spondylitis, *spondylosis deformans*, kyphosis, or reduced intervertebral disc space); (b) inability to correctly visualize the cardiac silhouette (e.g., pleural effusion, right middle lung lobe increased opacity, cardiac neoplasm, or mediastinal masses); (c) positioning or technical errors (e.g., overexposure, underexposure, or motion artefacts); and (d) skeletal immaturity.

2.2 | Data recording and analysis

The breed, sex, weight (in kilograms), and age (in years) were recorded for each dog. The decisions on whether to include or exclude radiographs were made by a second-year Ph.D. student in diagnostic imaging (D.C). All the selected radiographs, in DICOM format, were anonymized by the same author before submitting them to three observers to assess the inter-observer agreement. One month later, the same author randomly selected from the same set of radiographs a smaller sample using the “randbetween” tool (Microsoft Excel version 16.52 2021, Microsoft Corp., Redmond, WA, USA) to assess the intra-observer agreement among the three observers. All radiographic measurements were performed using the right-lateral view by three independent operators with different levels of experience using the ‘line’ function in an open-source DICOM viewer (Horos version 3.3.6, 64-bit, Nimble Co LLC d/b/a Purview, Annapolis, MD, USA, https://www.horosproject.org) on the same workstation (iMac 5K, 27-inch, Apple Inc., Cupertino CA, USA). Observers 1 (L.M.) and 2 (A.G.) are professors of veterinary radiology with a PhD and >25 and >10 years of experience, respectively. Observer 3 (D.P.) is a professor of cardiology with a PhD and >15 years of experience. All the observers were blind regarding the clinical data and reasons for thoracic radiography. All measurements were performed one time by each observer, independently and blinded to the results reported by the other observers by following the same oral and written instructions provided in a portable document format file (Supporting Information S1). First, the length of the vertebral body of the fourth (T4), fifth (T5), sixth (T6), seventh (T7), and eighth (T8) thoracic vertebrae, including the respective caudal intervertebral disc space, was measured. Then, the cardiac long axis (LA) and short axis (SA) were measured as described by Buchanan and Bücheler (Figure 1).[8] The LA was defined as the axis traced from the ventral border of the carina (the origin of the left mainstem bronchus) to the cardiac apex, and the SA was defined as the line perpendicular to the LA at the point of the maximum width of the cardiac silhouette. To calculate VHS, the two axes were repositioned over the thoracic vertebrae starting from the cranial endplate of T4. VHS was then expressed as the number of thoracic vertebrae (v) to the nearest 0.1v.

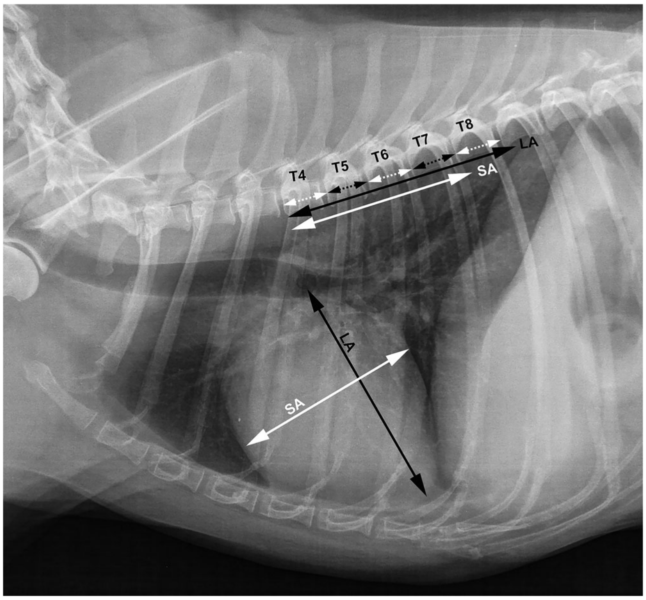

FIGURE 1 Representative right lateral thoracic radiographic image (kVp 80; mAs 4) of a mixed-breed dog depicting the measurements of the length of each single vertebral body between T4 and T8, including the corresponding caudal intervertebral disc spaces (black and white dotted arrows labelled T4–T8). The cardiac long axis (LA) and short axis (SA) were measured as described by Buchanan and Bücheler.[8] In this method, the LA (black doubled-headed arrow) was traced from the ventral border of the carina to the cardiac apex and the SA (white doubled-headed arrow) was traced perpendicular to LA at the point of the maximum width of the cardiac silhouette, and then transposed ventral to the column starting from the T4 cranial endplate

Additionally, the sum of the cardiac axes (LA+SA) was divided by the length of the vertebral body, including the respective caudal intervertebral disc space, for T4, T5, T6, T7, and T8 to determine $HSVR^{T4}$, $HSVR^{T5}$, $HSVR^{T6}$, $HSVR^{T7}$, and $HSVR^{T8}$, respectively. All data were reported independently by each operator in an electronic spreadsheet (Microsoft Excel version 16.52 2021, Microsoft Corp.). One month later, to assess the degree of intra-observer agreement, the measurements were repeated once, in a single session, independently by each of the three observers on a smaller sample of thirty re-anonymized and re-randomly selected radiographs.

2.3 | Statistical analyses

Statistical analyses were performed by a professor in biostatistics and epidemiology with a PhD in statistics (D.B.) using open-source statistics software (R version 4.0.1, R Foundation for Statistical Computing, Austria, https://www.R-project.org). Descriptive statistics were calculated for age, weight, and breed. Numerical variables were summarized using the median value and range (minimum to maximum). The concordance between the HSVR and VHS values for the 80 radiographs as determined by observer 1, who was considered the most experienced observer, was assessed using Lin's concordance correlation coefficient (CCC) with the corresponding 95% Confidence Interval (95% CI).[28] The

TABLE 1 Reasons for thoracic radiography for included dogs and numbers (%) of dogs in each reason category

Reasons for thoracic radiography for included dogs	*n* = 80 (%)
Exclusion of metastases	25 (31.25%)
Cardiomyopathies	22 (27,5%)
Cough	16 (20%)
Pre-anesthetic evaluation	9 (11.25%)
Suspected tracheal collapse	2 (2.5%)
Suspected oesophageal regurgitation	1 (1.25%)
Suspected aspiration pneumonia	1 (1.25%)
Pulmonary hypertension	1 (1.25%)
Systemic thromboembolism	1 (1.25%)
Systemic Leishmaniasis	1 (1.25%)
Dirofilariosis	1 (1.25%)

strength of the agreement was scored using the cut-off values proposed by McBride[29] and further analyzed using Bland–Altman plots. Error between the VHS and HSVR values was estimated using the mean absolute error (MAE). Intra- and inter-observer agreement was assessed using intraclass correlation coefficients (ICC) and the results were interpreted as suggested by Koo and Li.[30] In all analyses, $P < 0.05$ was considered statistically significant.

3 | RESULTS

A total of 300 thoracic radiographic examinations were performed during the time period. After applying the exclusion criteria, radiographs for 80 dogs (23 intact females, 26 spayed females, 23 intact males, and 8 castrated males) were included in the final sample for assessing the agreement between VHS and HSVR and among the observers. The exposure settings (kilovoltage peak, milliampere, and seconds) varied according to the size of the dog and the body condition score. Reasons for radiographic examination included suspicions of heart disease, and other reasons are summarised in Table 1. One month later, 30 radiographs, randomly selected from the same set, were used for assessing the intra-observer agreement. The median age was 11 years (range 1–16 years) and the median bodyweight was 10 kg (range 1.3–30.5 kg). The breeds represented were mixed-breed (n = 48), Dachshund (n = 4), Beagle (n = 4), Maltese (n = 4), English Cocker Spaniel (n = 3), Miniature Poodle (n = 3), Yorkshire Terrier (n = 2), Jack Russell Terrier (n = 2), and one of the each following: Chihuahua, Standard Poodle, Dalmatian, Doberman Pinscher, Labrador Retriever, German Shepherd, Pitbull, Irish Setter, Shih Tzu, and English Springer Spaniel. The CCC showed substantial agreement of $HSVR^{T7}$ (0.983; 95% CI 0.974–0.989), $HSVR^{T8}$ (0.964; 95% CI 0.946–0.977), $HSVR^{T6}$ (0.96; 95% CI 0.94–0.973), and $HSVR^{T5}$ (0.958; 95% CI 0.936–0.972) with VHS, and moderate agreement of $HSVR^{T4}$ with VHS (0.938; 95% CI 0.90–0.95) (Figure 2A–E). The Bland–Altman plots for HSVR versus VHS showed a bias of 0.019 for $HSVR^{T7}$ (±0.18; 95% CI −0.34

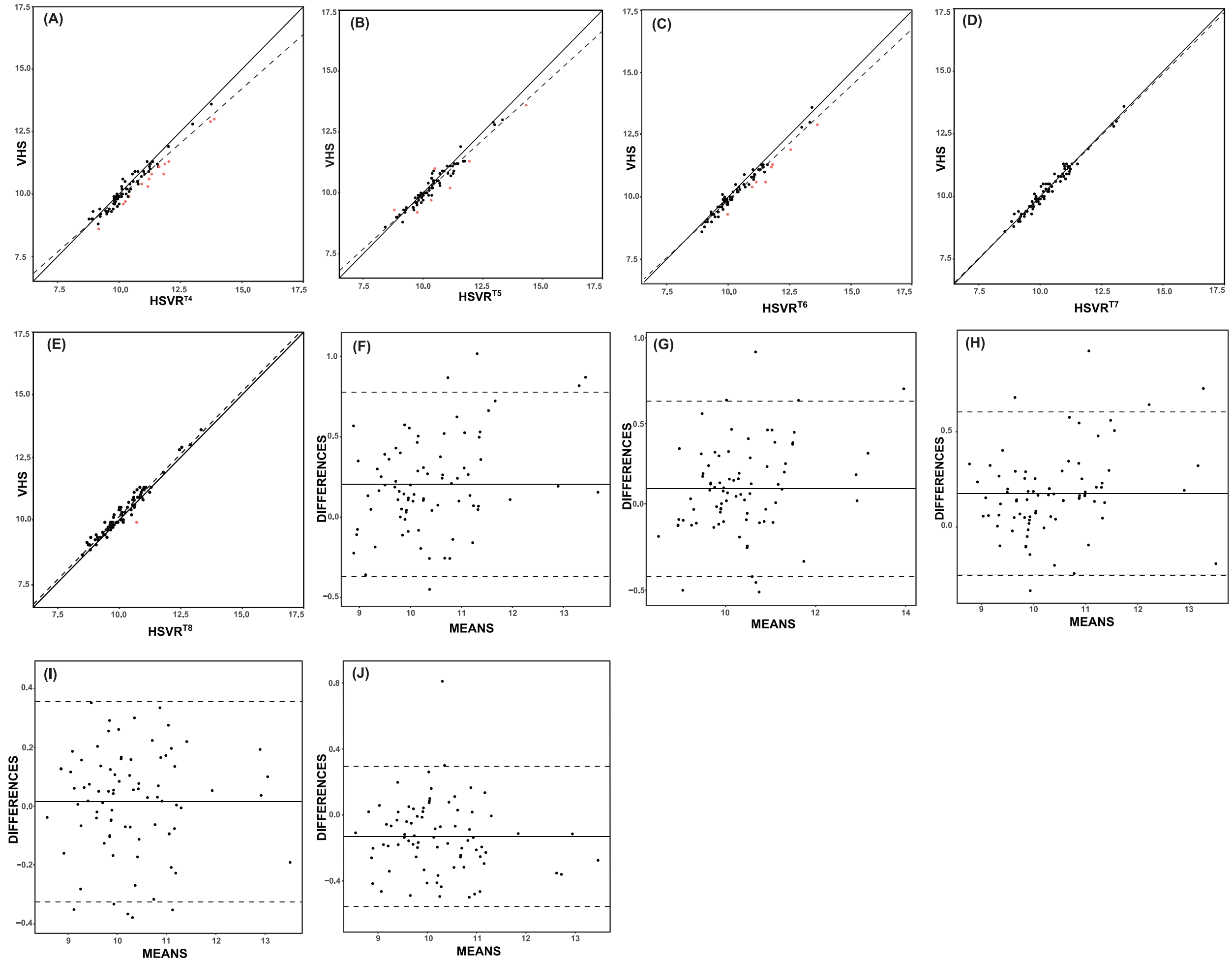

FIGURE 2 Lin's concordance correlation coefficient (CCC) and related Bland–Altman plots. (A–E) Lin's CCC comparing VHS with HSVRI determined using T4 (A), T5 (B), T6 (C), T7 (D), and T8 (E). The *y*-axes show the VHS index, and the *x*-axes show the HSVR. The continuous lines represent the lines of perfect agreement (i.e. the ideal condition where HSVR equals VHS), the dashed lines represent the estimated least squares lines, and the red dots represent outliers. (F–J) Bland–Altman plots comparing VHS with HSVR obtained using T4 (F), T5 (G), T6 (H), T7 (I), and T8 (J). The *x*-axes show the mean of both measurements, the *y*-axes show the difference between the two measurements, the dashed lines represent the 95% confidence intervals, and the continuous lines represent the bias [Color figure can be viewed at wileyonlinelibrary.com]

to 0.38), 0.11 for $HSVR^{T5}$ (±0.27; 95% CI −0.42 to 0.63), −0.13 for $HSVR^{T8}$ (±0.22; 95% CI −0.57 to 0.30), 0.18 for $HSVR^{T6}$ (±0.21; 95% CI −0.24 to 0.60), and 0.20 for $HSVR^{T4}$ (±0.30; 95% CI −0.38 to 0.70) (Figure 2F–J). The MAE for the comparison between HSVR and VHS was lowest for $HSVR^{T7}$ (0.14; 95% CI 0.12–0.16) followed by $HSVR^{T8}$ (0.20; 95% CI 0.16–0.23), $HSVR^{T6}$ (0.22; 95% CI 0.18–0.26), $HSVR^{T5}$ (0.22; 95% CI 0.23–0.33), and $HSVR^{T4}$ (0.28; 95% CI 0.23–0.33). The ICC showed good to excellent inter-observer (Table 2; $P = .000$) and intra-observer (Table 3; $P < .001$) agreement for all measurements.

4 | DISCUSSION

The primary aim of this study was to describe a new objective method for radiographic assessment of cardiac silhouette dimensions in patients where VHS cannot be determined owing to alterations affecting the thoracic vertebral bodies or intervertebral disc spaces.

TABLE 2 Intraclass correlation coefficients for inter-observer agreement among the three observers

	ICC (n = 80)	95% CI
VHS	0.92	0.86–0.95
$HSVR^{T4}$	0.88	0.82–0.92
$HSVR^{T5}$	0.90	0.86–0.93
$HSVR^{T6}$	0.88	0.81–0.92
$HSVR^{T7}$	0.87	0.81–0.92
$HSVR^{T8}$	0.89	0.85–0.93

Abbreviations: CI, confidence interval; $HSVR^{T4}$, heart to single vertebra ratio determined using the fourth thoracic vertebra; $HSVR^{T5}$, heart to single vertebra ratio determined using the fifth thoracic vertebra; $HSVR^{T6}$, heart to single vertebra ratio determined using the sixth thoracic vertebra; $HSVR^{T7}$, heart to single vertebra ratio determined using the seventh thoracic vertebra; $HSVR^{T8}$, heart to single vertebra ratio determined using the eighth thoracic vertebra; ICC, intraclass correlation coefficient; VHS, vertebral heart size index.

TABLE 3 Intraclass correlation coefficients for intra-observer agreement between the three observers

	ICC (95% CI) (n = 30)		
	Observer 1	**Observer 2**	**Observer 3**
VHS	0.96 (0.93–0.98)	0.96 (0.93–0.98)	0.93 (0.87–0.96)
$HSVR^{T4}$	0.98 (0.97–0.99)	0.95 (0.90–0.97)	0.92 (0.85–0.95)
$HSVR^{T5}$	0.98 (0.96–0.99)	0.96 (0.92–0.98)	0.90 (0.83–0.95)
$HSVR^{T6}$	0.88 (0.78–0.93)	0.95 (0.91–0.97)	0.92 (0.85–0.95)
$HSVR^{T7}$	0.99 (0.97–0.99)	0.88 (0.79–0.94)	0.90 (0.82–0.95)
$HSVR^{T8}$	0.97 (0.94–0.98)	0.87 (0.78–0.93)	0.94 (0.89–0.97)

Abbreviations: CI, confidence interval; $HSVR^{T4}$, heart to single vertebra ratio determined using the fourth thoracic vertebra; $HSVR^{T5}$, heart to single vertebra ratio determined using the fifth thoracic vertebra; $HSVR^{T6}$, heart to single vertebra ratio determined using the sixth thoracic vertebra; $HSVR^{T7}$, heart to single vertebra ratio determined using the seventh thoracic vertebra; $HSVR^{T8}$, heart to single vertebra ratio determined using the eighth thoracic vertebra;ICC, intraclass correlation coefficient; VHS, vertebral heart size index.

The secondary aims of the study were to assess the level of agreement between the new method and VHS, including intra- and inter-observer agreement. Findings from our study supported our hypotheses. The HSVR was a simple, quick, and reliable method with an excellent agreement with the VHS and substantial intra- and inter-observer agreement. Congenital alterations of the thoracic spine, of uncertain clinical relevance, are present in many dogs, particularly brachycephalic breeds,[31] and this means it is impossible to correctly determine VHS.[11] Similarly, acquired spinal alterations (e.g. severe *spondylosis deformans*) tend to worsen with age and make VHS unreliable for follow-up of the cardiac silhouette in the same patient. Eventually, these alterations hinder the ability to predict the onset of potentially serious disorders such as pulmonary edema.[26,27,32] Determining HSVR by comparing the cardiac axes with a single thoracic vertebra overcomes this intrinsic limitation of VHS and represents a more objective evaluation of cardiac silhouette dimensions, even in patients with alterations involving some thoracic vertebrae between T4 and T8. In the present study, we decided to calculate the VHS and vertebral length, including the respective caudal intervertebral disc space, since its absence would have led to an overestimation of HSVR when compared to VHS. Indeed, multiple intervertebral disc spaces are implicitly included when the cardiac LA and SA are transposed over the spine for VHS estimation. Finally, not considering the intervertebral disc space in determining the VHS will lead to erroneously obtain the same VHS value when the transposed cardiac axis reaches either the caudal endplate of one vertebra or the cranial endplate of the following vertebra.[22] In the present analyses, $HSVR^{T7}$ showed substantial agreement with VHS, together with low bias and mean error between the methods. The results of the present analyses also indicate that, when it is not possible to determine $HSVR^{T7}$, it is possible to use the other ratios in the following order of preference: $HSVR^{T8}$, $HSVR^{T5}$, and $HSVR^{T6}$. Although these indices showed slightly lower agreement with VHS than did $HSVR^{T7}$, they still showed substantial agreement and low bias. Of the five ratios evaluated, $HSVR^{T4}$ is perhaps least favorable because it showed the lowest, although still acceptable, level of agreement with VHS and relatively higher bias compared with HSVR calculated using the other thoracic vertebrae. The method's reliability is also supported by the high correlation between VHS and HSVR despite the broad heterogeneity of the study sample, which mostly comprised mixed-breed dogs and a variety of pure-breed dogs of different sizes and thoracic conformations. Furthermore, the presence or absence of an underlying cardiac disease was not considered in order to increase the randomness of the sample, making it more representative of the dog population in clinical settings. The good to excellent inter- and intra-observer agreement confirms the reliability of this new method, probably due to the easier method of calculating the cardiac silhouette dimensions in vertebral units and the clear anatomical landmarks. In fact, as previously described, the inter- and intra-observer agreement for VHS is related to individual variations in the identification of the anatomical landmarks used to track the cardiac axes and converting the length of the cardiac axes into vertebral units.[14,15,17,19,22,23,25,27,33] Similar to the objective VHS proposed by Sánchez et al.,[33] the cardiac axes measured for HSVR are normalized for the vertebral length without transposing the cardiac axes over the thoracic spine and without the need to span the conversion of the cardiac axis in vertebral units, thus reducing the method's susceptibility to differing inter-observer interpretation.[12,22] In this way, it is possible to avoid some of the limiting factors, such as inter-observer variation in the interpretation of VHS, and may allow more objective evaluation of cardiac silhouette dimensions.[22,33] However, unlike the above-mentioned objective VHS, HSVR is determined using a single vertebral body rather than the entire T4–T8 distance. Therefore, HSVR is suitable for the objective evaluation of cardiac dimensions in patients with thoracic spine alterations. Furthermore, HSVR is quicker and easier to determine than VHS because it is not necessary to transpose the cardiac axes on the thoracic spine. These advantages of HSVR could increase the clinical applications of quantitative radiographic evaluation of the cardiac silhouette, which is difficult to interpret, and may reduce the risk of erroneous subjective interpretation.[33]

Some limitations of this study include the following: the relatively high experience of the three observers. Although previous studies of VHS have demonstrated that the difference between observers is more strongly linked to identification of the anatomic landmarks than to the observer's experience,[14,15,17,19,22,23,25,27,33] further studies involving inexperienced observers would be useful to verify its use. Another possible limitation of the HSVR is the need to use breed-specific cut-off values, the same as VHS, because there is intrinsic variability in the ratio between the heart size and vertebral body length among different breeds. In conclusion, HSVR is a simple and reliable modality for assessing the cardiac silhouette size in dogs with thoracic spine alterations. Given the simplicity of determining HSVR, as there is no need to transpose the cardiac axes on the thoracic spine, non-specialists could benefit more than radiologists in using this method.

LIST OF AUTHOR CONTRIBUTIONS

Category 1

a. Conception and Design: Costanza, Meomartino
b. Acquisition of Data: Meomartino, Greco, Piantedosi, Costanza, Pasolini, Coluccia, Castiello, Baptista
c. Analysis and Interpretation: Bruzzese, Costanza

Category 2

a. Drafting the Article: Costanza, Meomartino
b. Revising the Article for Intellectual Content: Greco, Piantedosi, Bruzzese, Pasolini, Coluccia, Castiello, Baptista

Category 3

a. Final Approval of the Completed Article: Costanza, Greco, Piantedosi, Bruzzese, Pasolini, Coluccia, Castiello, Baptista, Meomartino

Category 4

a. Agreement to be Accountable for all Aspects of the Work in Ensuring that Questions Related to the Accuracy or Integrity of any Part of the Work are Appropriately Investigated and Resolved: Costanza, Greco, Piantedosi, Bruzzese, Pasolini, Coluccia, Castiello, Baptista, Meomartino

CONFLICT OF INTEREST

The authors declare no conflict of interest.

PREVIOUS PRESENTATION OR PUBLICATION DISCLOSURE

Portions of this study were presented as an oral communication at the 74th SISVET Online Congress, 23–26 June 2021.

EQUATOR NETWORK DISCLOSURE

The authors followed the GRRAS checklist for reporting of studies of reliability and agreement.

DATA ACCESSIBILITY STATEMENT

Available from the Corresponding Author upon reasonable request

ORCID

Dario Costanza https://orcid.org/0000-0001-7310-0246
Adelaide Greco https://orcid.org/0000-0001-6841-1963
Diego Piantedosi https://orcid.org/0000-0001-8745-7959
Dario Bruzzese https://orcid.org/0000-0001-9911-4646
Maria Pia Pasolini https://orcid.org/0000-0002-9045-7770
Pierpaolo Coluccia https://orcid.org/0000-0003-3244-4135
Erica Castiello https://orcid.org/0000-0003-1941-9138
Cláudia Sofia Baptista https://orcid.org/0000-0002-8158-4743
Leonardo Meomartino https://orcid.org/0000-0002-7290-3108

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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