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Assessment of Mitral Regurgitation Severity by Doppler Color Flow Mapping of the Vena Contracta in Dogs

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Background: Quantitative and semiquantitative methods have been proposed for the assessment of MR severity, and though all are associated with limitations. Measurement of vena contracta width (VCW) has been used in clinical practice.

Objective: To measure the VCW in dogs with different levels of MR severity.

Animals: Two hundred and seventy-nine dogs were classified according to 5 levels of MR severity.

Methods: This was a retrospective study. EROA and regurgitant volume calculated by the PISA method, were measured and indexed to BSA. Descriptive statistics were calculated for VCW and VCW index for all categories of MR severity. Spearman's rank correlation coefficients (ρ_s) were calculated to compare the results of the different methods (VCW and VCW index vs RV PISA, RV PISA index, EROA, EROA index), and between VCW and VCW index versus MR severity.

Results: All Spearman's rank correlation coefficients were significant ($P < .001$). The median values of VCW resulted of 2.9 mm (IQR 3.4–2.5) and of 4.6 mm (IQR 5.4–4.1) in the groups previously classified as mild-to-moderate and moderate-to-severe, respectively. The median values of VCW index resulted of 4.4 mm/m^2 (IQR = 5.5–4.2) in mild-to-moderate MR and of 10.8 mm/m^2 (IQR = 12.8–9.4) in moderate-to-severe MR.

Conclusion and Clinical Importance: This is not a validation study against any previously validated invasive gold standard, the VCW method has proved easy to employ and it might be an additional tool in quantifying disease severity that supports, rather than replace, data coming from other techniques in daily clinical practice and research.

Key words: Congestive heart failure; Degenerative mitral valve disease; Vena contracta width.

The diagnosis of mitral regurgitation (MR) caused by degenerative mitral valve disease (MVD) is frequently straightforward, because the clinical and echocardiographic findings are often obvious and in agreement. However, there is currently no "gold standard" for reliably determining MR severity.[1] However, quantification of MR severity is essential for clinical decision making, and many studies have indicated the importance of assessing MR severity for monitoring the progression of MVD, evaluating the effect of treatments, and predicting patient outcomes.[2–6]

Various semiquantitative methods by using color flow Doppler (CFD) mode (eg, area of regurgitant jet area signal to left atrium area ratio (ARJ/LAA), and quantitative methods (eg, proximal isovelocity surface area method (PISA), also called flow convergence) have been proposed for detecting MR severity in humans and dogs.[1–3,7–17] However, all these methods have some limitations, and none of them are simple enough to be universally recognized and safely applied without restrictions.

To overcome some of the limitations of these techniques, semiquantitative vena contracta width (VCW) analysis was introduced into clinical practice. VCW, as determined by transthoracic CFD mapping, has been introduced into human medicine as a simple

Abbreviations:

2-D	2-dimensional
ARJ/LAA	ratio area of the regurgitant jet area signal to left atrium area
BSA	body surface area
CFD	color flow Doppler
CV	coefficient of variation
EROA index	effective regurgitant orifice area index
EROA	effective regurgitant orifice area
IQR	interquartile range
K_m	constant (10.1 for dog)
LA	left atrium
L	mild
LM	mild-to-moderate
M	moderate
MR	mitral regurgitation
MS	moderate-to-severe
MVD	mitral valve disease
PISA index	proximal isovelocity surface area index
PISA	proximal isovelocity surface area
RV	regurgitant volume
S	severe
VCW index	vena contracta width index
VCW	vena contracta width
V	mitral valve regurgitation jet velocity
VTI	mitral valve velocity time-integral
ρ_s	Spearman's correlation coefficient

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echocardiographic marker of MR severity. VCW can predict the angiographic severity of MR and correlates well with catheterization-derived regurgitant volume (RV) and transesophageal CFD mapping.[1,5,6,9,10,18]

Hemodynamically, VCW represents a contraction in the edges of the flow streamlines as they move through an orifice.[18–20] The method directly measures the diameter of the vena contracta, defined as the narrowest cross-sectional area of the jet, just downstream from the regurgitant orifice. The VCW is the area of the jet as it leaves the regurgitant orifice; it thus reflects the regurgitant orifice area and has been shown to be related directly to the severity of the regurgitant lesion, and with both RV and the effective regurgitant orifice area (EROA).[1,6,7,13,21]

Using a canine animal model, Zhou et al. compared measurements of VCW with indicators of eccentric MR severity, as determined by electromagnetic flow meters, and obtained good correlations between VCW and RV, as well as regurgitant fraction (RF), the percentage of stroke volume ejected into the left atrium (LA) during systole.[22]

The VCW is generally easy to measure in clinical settings, though an extra zoom lens may be required to assess the size of the regurgitant jet with greater accuracy.[22,23] It should be noted that any errors in measurement will result in either over- or underestimation of MR severity, because of the small diameter of the jet in the regurgitant orifice.[23]

Various echocardiographic views can be used to measure VCW in humans, but measurements are usually made from the parasternal long axis and from the apical 4-chamber view.[6,7,13,18]

The VCW method is widely used in human medicine but is not applied in veterinary medicine, though to the best of our knowledge a range of measures of VCW is not available in large canine populations.[2,8,10,11,22,24,25]

The goal of this study was to measure the VCW in a population of dogs with MVD and different levels of MR severity graded by other noninvasive quantitative and semiquantitative techniques.

Materials and Methods

In this retrospective study, medical records for 896 privately owned dogs that underwent cardiologic examination from January 2007 to February 2011 were reviewed. The records were selected according to the following inclusion criteria: diagnosis of MVD; complete medical records referring to the first visit; thoracic radiography in presence of clinical signs[2,11]; electrocardiographic examination[2,11]; complete data for echocardiographic and Doppler examinations as recommended by the authors to achieve grading of MR severity (ARJ/LAA ratio), mitral inflow pattern analyzed by pulsed wave (PW), signal intensity (jet density) of the continuous wave (CW), and envelope of the MR jet assessment of MR severity achieved by quantitative PISA and semiquantitative methods.[1,8,11,21,22,24,26] We first graded the disease by means of quantitative methods and semiquantitative methods (different from VCW) and then observed how VCW values were distributed among different grade of MR severity (average based on $\geq$ 3 measurements for each parameter).[1–3,10–13]

Exclusion criteria included presence of congenital heart disease; presence of atrial fibrillation, any other arrhythmias, or both that severely altered the beat to beat time interval[11]; VCW, PISA, or both not clearly visualized[11]; presence on CFD imaging of more than 1 mitral regurgitant jet evidenced through accurate recording at the time of the examination.[8]

Hemodynamic Measurements

EROA and RV were calculated by using the PISA method (EROA (cm^2) = flow rate (mL/s)/V (cm/s); RV (mL) = EROA (cm^2) × VTI cm) [2,11] (Fig 1). To take account of animal size, the parameters were indexed according to body surface area (BSA $m^2 = K_m \times BW_{gr}^{0.67}/10^{-4}$) to give EROA index (measured as cm^2/m^2) and RV index (measured as mL/m^2).[27,28]

Vena contracta width was determined in each subject from the left parasternal apical 4- and 5-chamber views. The narrowest sector angle that allowed visualization of the MR jet was used to maximize the color flow imaging frame rate.[18] The transducer was angled to optimize visualization of the area of proximal flow acceleration, the VCW and the downstream expansion of the jet. For each echocardiographic window, zoom mode was used to optimize the visualization of VCW (mm), and an average value was calculated based on its largest diameter during systole measured for at least 3 cardiac cycles.[14,22,23,29,30] To take account of the effect of body weight on the intrinsic dimensions of the valvular apparatus, VCW was indexed for BSA to give the VCW index (mm/m^2).[27]

All the echocardiographic examinations were performed on awake dogs by the same experienced investigator (MDM), by using standardized thoracic imaging planes, in accordance with the recommendations of the American Society of Echocardiography, and by using two-dimensional (2-D), M-mode, and CFD and spectral Doppler.[14] The gain settings for CFD and spectral Doppler were adjusted as required to optimize the signal, and the settings were not changed when recording the images and measuring VCW.

All dogs were examined using a vet echocardiograph with 2.5–3.5 MHz, 3.5–5 MHz, and 7.5–10 MHz mechanical phased array transducers.[a] MR severity was graduated on the basis of the area of the regurgitant jet projecting into the left atrium, the jet

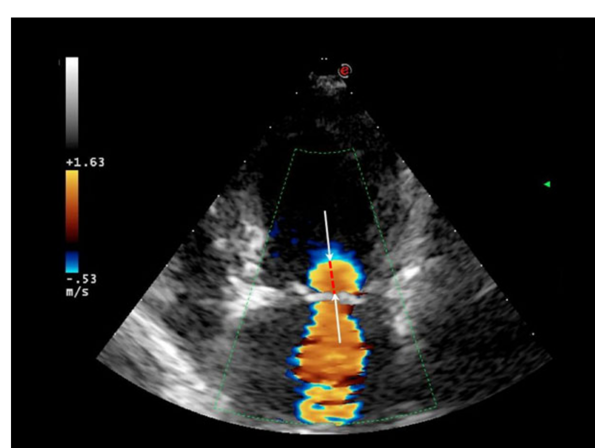

Fig 1. Apical 4-chamber view. Color flow Doppler image showing the semicircle of flow of convergence on the left ventricular side of the mitral valve. The radius of the proximal isovelocity region (dotted line) should be measured from the ventricular side of the mitral valve leaflets to the edge of the hemisphere (arrows).

density of the CW Doppler signal, the mitral inflow pattern analyzed by PW Doppler, and EROA dimensions.[1,7,8,10–12,21,22,24,31] The grade of MR was classified as mild (L), mild-to-moderate (LM), moderate (M), moderate-to-severe (MS), or severe (S).[6,10,14–16,21,32]

Within-day and between-day intraobserver variability in the studied parameters were determined by reanalysing the parameters measured by the same observer (MDM) 3 times after the first measurement on a subset of 10 randomly selected exams from the database.

Statistical Analysis

Statistical analysis was performed by using SPSS (v. 17). The normal distributions of the measurements of interest (RV PISA, RV PISA index, EROA, EROA index, VCW, VCW index) were tested using the Shapiro-Wilk test. Means, standard deviations, medians, and Interquartile Ranges were calculated for VCW and VCW index for all categories of MR severity (L, LM, M, MS, S). If the distribution was not normal, the significance of the differences among categories were calculated using the Kruskal-Wallis test ($P < 0.001$).[33]

Spearman's rank correlation coefficients (ρ_s) were calculated to compare the results of the different methods (VCW and VCW index vs RV PISA, RV PISA index, EROA, EROA index). The relationships between VCW and VCW index, and MR severity were also evaluated.

Results

A total of 279 dogs were selected. The mean age was 11.4 ± 2.9 years and the mean weight was 11.7 ± 10 kg. Most of the dogs were mongrels (44%) and among the breeds, the most common were Poodles (13%), Yorkshire Terriers (8%), and Shih-tzus (5%).

The study population was classified into 5 groups on the basis of MR severity.[24,26,29,34–36] Most dogs had severe MR (97 dogs), followed by moderate (78 dogs), and moderate-to-severe (47 dogs), mild (30 dogs) and mild-to-moderate (27 dogs) MR (Figs 2–4).

The intraobserver coefficients of variation (CV range in %) were <10% for each tested variable.

There were significant correlations between VCW and VCW index and other quantitative and semiquantitative parameters (Table 1). The highest correlation coefficients occurred among dimensionally similar parameters (indexed values with indexed values, and nonindexed ones with nonindexed ones). Semiquantitative MR severity correlated better with VCW ($\rho_s = 0.76$) than with VCW index (Table 1). All Spearman's rank correlation coefficients were statistically significant ($P < 0.001$).

Regression analysis demonstrated positive relationships for RV PISA, RV PISA index, EROA, EROA index to VCW and VCW index. The best relationships were between VCW IX and RV PISA IX and EROA IX ($\rho_s = 0.836$ and 0.857, respectively) (Figs 5–8).

The indexed and unindexed VCW were calculated with respect to the semiquantitative method in subjects with different classes of MR severity (Figs 9, 10).

A proportional increase in VCW and VCW index was observed with worsening mitral insufficiency. Even in the event of an overlap among adjacent categories, there was no overlap between the medians and IQR values for mild-to-moderate and moderate-to-severe MR in terms of VCW and VCW index, and the differences among the classes of MR severity resulted statistically significant ($P < 0.001$).

The median values of VCW, irrespective of body size, resulted of 2.9 mm (IQR 3.4–2.5) and of 4.6 mm (IQR 5.42–4.08) in the groups previously classified as mild-to-moderate and moderate-to-severe, respectively (Table 2, Fig 10).[21,31,32]

The median values of VCW index resulted of 4.4 mm/m^2 (IQR 5.5–4.1) in dogs with mild-to- moderate mitral insufficiency and of 10.8 mm/m^2 (IQR 12.8–9.4) in dogs with moderate-to-severe MR (Table 2; Fig 9).

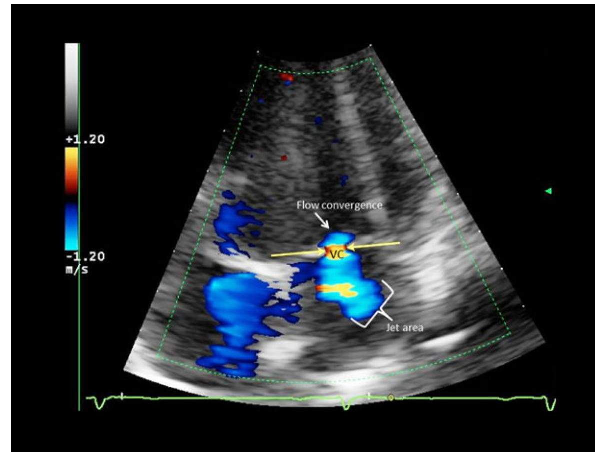

Fig 2. Apical 4-chamber view. Semiquantitative assessment of mitral regurgitation severity using vena contracta width (VC) in a dog with mild mitral regurgitation. Color Doppler at the level of the mitral valve during systole. The components of the regurgitant jet (flow convergence zone, vena contracta, jet turbulence) were obtained.

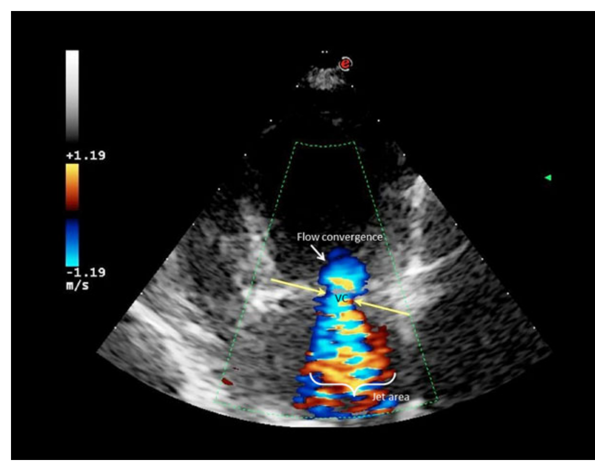

Fig 3. Apical 4-chamber view. Semiquantitative assessment of mitral regurgitation severity using vena contracta width (VC) in a dog with moderate mitral regurgitation. Color Doppler at the level of the mitral valve during systole. The components of the regurgitant jet (flow convergence zone, vena contracta, jet turbulence) were obtained.

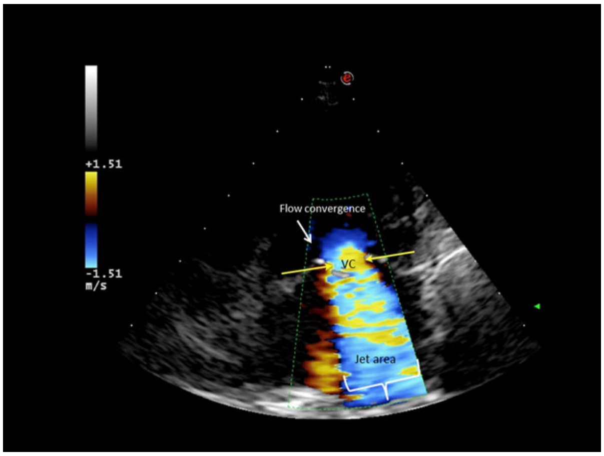

Fig 4. Apical 4-chamber view. Semiquantitative assessment of mitral regurgitation severity using vena contracta width (VC) in a dog with severe mitral regurgitation. Color Doppler at the level of the mitral valve during systole. The components of the regurgitant jet (flow convergence zone, vena contracta, jet turbulence) were obtained.

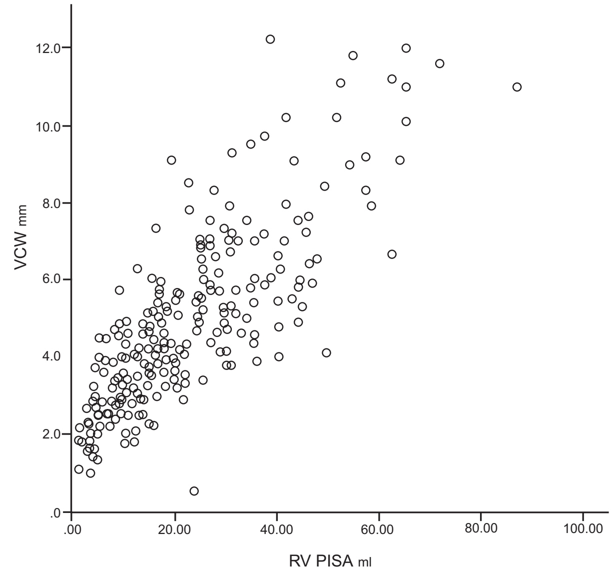

Fig 5. Scatter plot showing positive, direct, and significant relationship between vena contracta width (mm) and regurgitant volume (mL) by the proximal isovelocity surface area method ($\rho_s = 0.82$; $P < .001$).

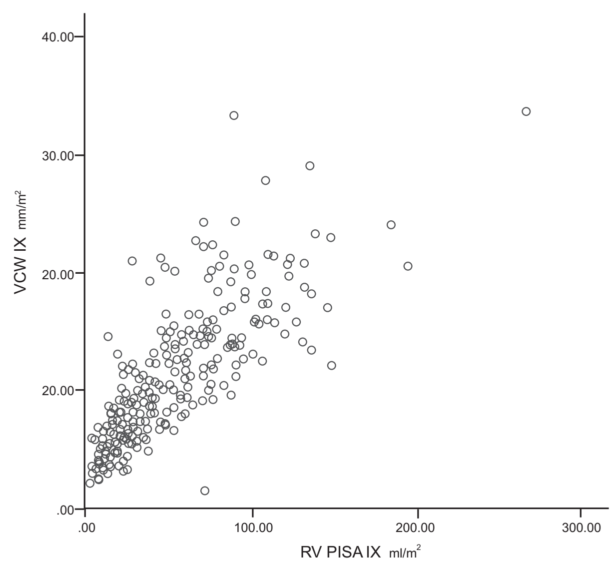

Fig 6. Scatter plot showing positive, direct, and significant relationship between vena contracta width indexed (mm/m^2) and regurgitant volume indexed (mL/m^2) by proximal isovelocity surface area method ($\rho_s = 0.84$; $P < .01$).

Discussion

The combination of 2-D and Doppler echocardiography represents an important method for the noninvasive detection and evaluation of the severity of MR.[2,22] Calculation of the ARJ/LAA ratio using CFD mapping is commonly used as a noninvasive method for assessing the severity of MR in veterinary medicine.[2,12] The major advantages of this method are its rapidity and the ease of data acquisition.[1] However, jet area evaluation is limited by a variety of hemodynamic (eg, systemic hypertension, ventricular-atrial pressure gradient reduction, loading conditions, left atrial compliance) and technical factors (eg, gain setting, angle between the jet and the ultrasound beam, orientation of the jet).[1,11,13,22] Doppler color flow mapping may also markedly underestimate the severity of MR in eccentric jets: a flow jet directed against the atrial wall appears smaller than a central jet of the same regurgitant volume (Coanda effect), which could lead to an underestimation of the severity of MR.[1,6,11–13,18,22,31,37]

Other proposed semiquantitative methods in human and veterinary medicine include the CW Doppler evaluation of jet characters and intensity, the PW Doppler mitral inflow pattern, and the estimation of variables

Table 1. Spearman's correlation coefficients (ρ_s) measure the association between 2 scale of variables ($P < .000001$).

	RV PISA (mL)	RV PISA Index (mL/m^2)	EROA (cm^2)	EROA Indexed (cm^2/m^2)	Severity of MR
VCW (mm)	0.82	0.65	0.82	0.66	0.76
VCW indexed (mm/m^2)	0.59	0.84	0.66	0.86	0.73

VCW, vena contracta width; VCWIX, vena contracta width indexed; RV, regurgitant volume; PISA, proximal isovelocity surface area; PISA, proximal isovelocity surface area index; EROA, effective regurgitant orifice area; EROA index, effective regurgitant orifice area index.

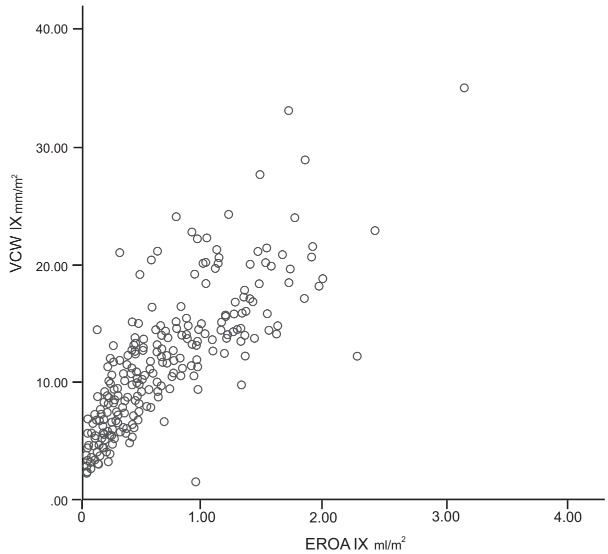

Fig 7. Scatter plot showing positive, direct, and significant relationship between vena contracta width indexed (mm/m^2) and EROA index (mL/m^2) ($\rho_s = 0.86$; $P < .01$).

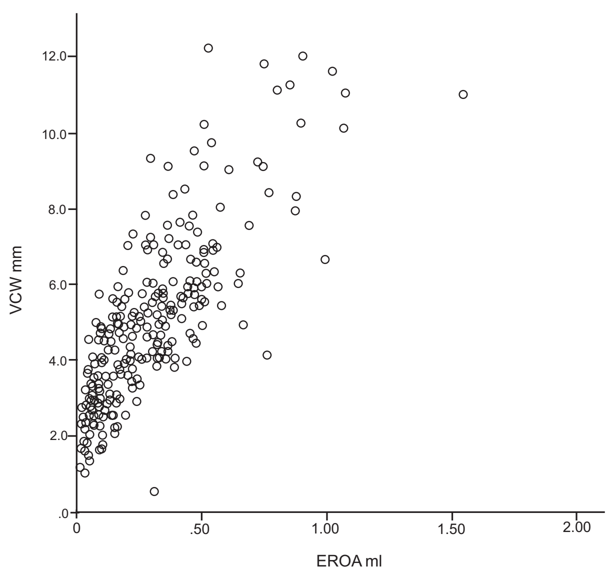

Fig 8. Scatter plot showing positive, direct, and significant relationship between vena contracta width (mm) and EROA (mL) ($\rho_s = 0.825$; $P < 0.01$).

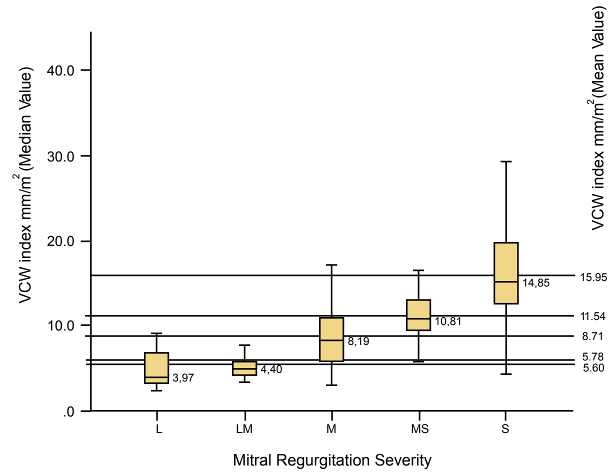

Fig 9. Box and whisker plot showing median, mean, and interquartile ranges of VCW index (mm/m^2) in the 5 different classes of mitral regurgitation severity. The ends of the box are the 25th and 75th quartiles. The line across the box identifies the median sample value. VCWIX, vena contracta width indexed; L, mild (30 dogs); LM, mild-to-moderate (27 dogs); M, moderate (78 dogs); MS, moderate-to-severe (40 dogs); S, severe (97 dogs).

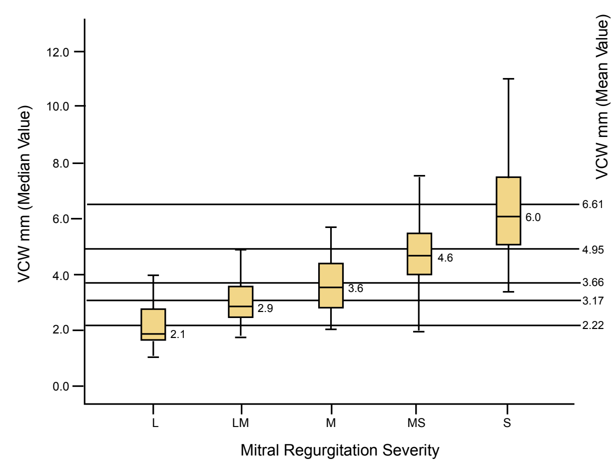

Fig 10. Box and whisker plot showing mean, median, and interquartile ranges of vena contracta width (mm) in the 5 different classes of mitral regurgitation severity. The ends of the box are the 25th and 75th quartiles. The line across the box identifies the median sample value. VCW, vena contracta width; L, mild (30 dogs); LM, mild-to-moderate (27 dogs); M, moderate (78 dogs); MS, moderate-to-severe (40 dogs); S, severe (97 dogs).

related to the compensatory changes in the heart secondary to MR such as pulmonary artery pressure by tricuspid regurgitation velocity, pulmonary venous inflow pattern, and left atrial size.[2,15,22] However, these techniques have several limitations: the interpretation of CW Doppler patterns of MR can be highly operator dependent, thus blurring the distinction between moderate and severe disease, and eccentric jets tend to underestimate whereas central jets overestimate the severity of MR.[32]

Quantitative Doppler echocardiographic assessment of MR severity is based on the evaluation of RV and RF realized by the volumetric and PISA methods, as the product of EROA and RV integral.[3,6–8,10,11,14,37–39] Several veterinary studies have quantified MR severity using PISA and compared the results with those obtained by using the volumetric method, as well as highlighting their relevance for follow-up evaluations.[2,10,11,25] The volumetric method has limitations: it is time-consuming, is unable to distinguish between the severity of MR and that of aortic regurgitation in patients with both lesions, and it is not effective in the presence of mitral stenosis, aortic stenosis, and intraventricular septal defects.[1,9,10,19]

Table 2. Mean, standard deviation, median, and interquartile range of vena contracta width and vena contracta width indexed in the 5 different classes of mitral regurgitation severity.

Mitral Regurgitation Severity	VCW			IQR	VCW IX			IQR
	Mean	±SD	Median	75°–25° VCW	Mean	±SD	Median	75°–25°
L	2.22	0.85	2.1	2.65–1.63	5.78	4.31	3.97	6.59–3.33
LM	3.17	1.01	2.9	3.4–2.5	5.6	2.28	4.40	5.55–4.16
M	3.66	1.34	3.6	4.3–2.90	8.71	3.64	8.19	10.79–6.09
MS	4.95	1.76	4.6	5.42–4.08	11.54	4.16	10.81	12.81–9.45
S	6.61	2.1	6	7.5–5.1	15.95	5.24	14.85	19.66–12.7

VCW, vena contracta width; VCWIX, vena contracta width indexed; IQR, interquartile range; SD, standard deviation.

The PISA method is currently the most common method for quantifying MR severity in dogs.[2,7,9–11] However, this method also has limitations: it is time-consuming, requires multiple measurements, and the evaluation of the variables is subjected to both method- and operator-dependent errors (intra- and interobserver variability are high), and it requires the skill of a well-trained operators.[2,3,9,10,12,36] The PISA method is more accurate for regurgitations with circular rather than noncircular orifices, and it may be difficult to judge the precise location of the orifice and the flow convergence shape.[1,2,6–8] Lastly, PISA is more accurate for central than for eccentric jets, and the presence of multiple regurgitant jets, which can occur in dogs with severe MVD, precludes the use of the PISA method.[2,7,8]

Measurement of VCW is less technically demanding than the previously mentioned methods and is relatively independent of instrument settings.[7,18,35] Determination of VCW can be easily performed by a trained operator, and is feasible in a high percentage of subjects (>98%) in our experience, with the exception of poorly compliant patients or under poor imaging conditions. Unlike PISA, VCW measurements have been validated in human beings for assessing eccentric jets, which are a common characteristic of mitral valve prolapse or flail leaflets in dogs.[18] However, opinions on how the position of the jets influences the VCW evaluation vary: some authors state that VCW has been validated for assessing both central and eccentric jets and its value is proportional to the effective orifice area.[13,40] The correlation between VCW and EROA, both indexed or not, was significant in our study ($\rho_s = 0.825$ and $\rho_s = 0.857$). Others, however, have suggested that VCW may be overestimated in the case of eccentric jets, and in cases with a non-concentric regurgitant area, the VC diameter obtained in M-mode and 2-D echocardiographic views may over- or underestimate the regurgitant area.[40,41]

The VCW is considered to be relatively unaffected by flow rate and driving pressure within the clinically encountered flow range.[22] This technique may have a limited ability to obtain reliable measures with multiple regurgitant jets; in the case of multiple MR jets, the fact that the respective widths of the VC are not additive must be taken into account, and in these cases the use VCW method is not recommended.[21,31,42]

Our results showed a high correlation between VCW and the semiquantitative and quantitative evaluating methods of mitral insufficiency as seen in human patients, and the values for mild and severe regurgitant jets are also similar.[1,5,20] The absolute values of VCW we found in dog are consistent with the results from human studies, where a VCW <3–4 mm is associated with mild mitral insufficiency, whereas values >4–6 mm are associated with severe mitral insufficiency.[21,28,31] In dogs, as in children, VCW indexed to account for BSA appears to be also an useful measure of MR severity, as shown by its high correlation with semiquantitative and quantitative stadiation.[43,44]

However, the analysis of regurgitant area based on VCW has some limitations relating to the difficulty in identifying the plane perpendicular to the MR flow, the narrowest neck of the jet in any imaging plane available from the transthoracic windows may cut obliquely across the flow stream and include portions of the expanding jet, thus overestimating the VCW.[20] Three-dimensional color Doppler echocardiography has recently been suggested for the direct measurement of VCW and may overcome some of the limitations of the 2-D echocardiographic techniques.[21,40,41]

Even if direct relationships exist between VCW index and RV index and PISA index, the scatter is so wide that VCW determination alone seems unsuitable for assessing the severity of mitral insufficiency. Its results should be confirmed by other methods,[5,8] including qualitative (ie, ARJ/LAA ratio, CW signal density of MR jet), semiquantitative (ie, VCW, mitral inflow, pulmonary vein flow), and quantitative parameters (eg, PISA method, EROA, RV) for grading MR severity.[8,21] In dogs, as in humans, it should be possible to develop a score of MR severity suitable for use in daily clinical practice and research.[1,16,19,21] The evaluation of MR severity should therefore be recommended in dogs with MVD to identify and track alterations over time and to detect worsening of the disease.[8]

This was a retrospective study, and although the inclusion and exclusion criteria were very strict, some errors may have occurred. The reliabilities of the analyses of VCW and VCW index were not tested when multiple regurgitant jets were present, which could represent a limitation of this study. It may be advisable to avoid using the technique under these circumstances until further studies have been performed. Many of the dogs in this study had received medical treatment for heart failure (eg, furosemide, spironolactone, angiotensin converting enzyme inhibitors), which might have interfered with the studied variables. Prospective and invasive studies are needed to evaluate and compare the sensitivity, specificity, and predictive values of the VCW method with other methods, and examine differences in the regurgitant volume before and after therapies.

Conclusions

Characterization of the severity of regurgitant lesions is among the most difficult problems in valvular heart disease. The search for a suitable quantitative technique for evaluating MR severity has led to the development of many tools, however no "gold standard" has yet been established.[5] Cardiac computed tomographic angiography slightly overestimates mild MR and slightly underestimates severe MR.[45] At the moment, a "stand-alone" technique for accurate quantification of mitral insufficiency is not available neither in human nor in veterinary medicine. The intention of the authors was to introduce the technique as an additional tool in quantifying disease severity that supports, rather than replace, data coming from other techniques.

Even if the present study is not a VCW validation study, as the technique was not assessed against any previously validated invasive gold standard in dog, and although the VCW method alone is not adequate and has some limitations, it appears to provide a valuable tool for the rapid identification of belonging to a group of moderate-to-severe mitral insufficiency (VCW = 4.6 mm; IQR = 5.4–4.1 and VCW IX = 10.8; IQR = 12.8–9.4) and of mild-to-moderate insufficiency (VCW = 2.9 mm; IQR = 3.4–2.5 and VCW IX = 4.4; IQR = 5.5–4.2), while intermediate VCW values need further confirmation.

Vena contracta width analysis should thus be considered as a helpful tool for the evaluation of MR severity in light of its ease of use which makes it valuable for determining MR severity when other semi-quantitative techniques cannot be applied.[23]

Footnote

[a] Pie Medical 300S Pandion: Esaote, Florence, Italy

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Conflict of Interest Declaration: Authors disclose no conflict of interest.

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