Pulse-wave analysis during routine blood pressure measurement shows potential to distinguish between sinus and nonsinus rhythm

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OBJECTIVE
To investigate whether pulse-wave analysis (PWA) performed by trained evaluators facilitates detection of nonsinus rhythm.

ANIMALS
Same-day, high-definition oscillometry pulse-wave data and ECG results of 155 animals (144 dogs and 11 cats) were analyzed.

METHODS
In this cross-sectional study, we enrolled 18 participants from various backgrounds, all of whom received PWA training. The ability to distinguish between sinus and nonsinus rhythms was assessed using receiver operating characteristic curve analysis. The pulse-wave datasets were divided into 5 ECG categories. Agreement between ECG diagnoses and PWA-based arrhythmia detection was evaluated using Cohen \( \kappa \) values, and the correlation between the academic year of veterinary students and their \( \kappa \) values was assessed.

RESULTS
All cardiology researchers demonstrated satisfactory accuracy in distinguishing pathological rhythms using PWA (area under the curve, 0.704 to 0.761), with the highest accuracy in detecting atrial fibrillation (area under the curve, 0.811 to 0.845). Fair agreement with ECG categorization was achieved by all 3 cardiology researchers, 2 of 5 general practitioners, and 3 of 10 veterinary undergraduates. The veterinary undergraduates’ years of study were correlated with their diagnostic performance (Spearman \( \rho = 0.658; P = .019 \)).

CLINICAL RELEVANCE
PWA during routine noninvasive blood pressure measurement showed significant potential for the detection of pathological arrhythmias, notably atrial fibrillation. This approach yielded improved effectiveness when it was used by veterinarians with cardiology experience. Thus, introducing hands-on training courses, particularly those focused on cardiology and interactive workshops, may enable frontline veterinarians to promptly identify arrhythmias using PWA, facilitating timely ECG examinations or referrals.

Keywords: atrial fibrillation detection, cardiology training, high-definition oscillometry, noninvasive blood pressure measurement, veterinary medicine

Pulse palpation has been a cornerstone of veterinary physical examinations since the time of traditional Chinese human medicine, dating back over 2,000 years.¹,² This method offers vital insights into patient health, notably by revealing arrhythmias through pulse deficits or variable pulse strengths. Traditionally, the graphical representation of an animal’s pulse required an invasive arterial line. However, contemporary advancements in noninvasive blood pressure (NIBP) monitoring technology have allowed for the visualization and categorization of pulse oscillations detected by a pressure cuff,³ thereby providing a vital, recordable snapshot to interpret pulse quality during veterinary physical examinations. Pulse-wave analysis (PWA), which captures and documents the regularity and intensity of the pulse, may be useful in the early detection of arrhythmias.

Given their user-friendly nature, wide availability, and ease of access, NIBP monitors are frequently...

Received October 18, 2023
Accepted February 12, 2024
doi.org/10.2460/ajvr.23.10.0233

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favored over direct blood pressure monitors and Doppler ultrasonic flow detectors. Thus, NIBP measurements can play crucial roles in diverse clinical scenarios, including the monitoring of patients with cardiac disease and hypertension secondary to hyperthyroidism or chronic kidney disease and assisting with the differentiation of left ventricular hypertrophy.\(^2\)\(^3\) When equipped with high-definition oscillometry (HDO) technology, particularly the Memo Diagnostic Pro monitor (S+B MedVet), which was established as the noninvasive blood pressure reference for cats in 2013, a real-time pulse-wave display can be obtained.\(^3\) During the deflation process, as the pressure in the cuff decreases, the monitor records the oscillations generated by each pulse in the cuff, forming a pulse-wave pattern. Such real-time visualization of individual pulse waves yields substantial insights into cardiac rhythm and output variations.\(^3\) Additionally, examination of the peak amplitude offers indirect information on variations in pulse pressure, a parameter linked to cardiac output. For instance, the effect of premature beats on cardiac output and ventricular filling depends on the coupling interval between sinus and ectopic beats and the instantaneous heart rate. In some cases, the interval of ectopic beats may be similar to that of sinus beats. The origin of the ectopic beat can affect ventricular filling, especially if it lacks the atrial contribution, which typically constitutes 20% to 25% of ejected blood. In pronounced sinus arrhythmia, the proximity of T and P waves can decrease the diastolic relaxation time, consequently reducing ventricular filling volume. These variations in cardiac dynamics are evident in the pulse-wave morphology, such as a reduced peak amplitude due to insufficient ventricular filling caused by premature beats.\(^3\)

Peculiar changes in pulse-wave morphology potentially indicating arrhythmias have been anecdotaly observed during routine blood pressure measurements at the cardiology department of the National Chung Hsing University Veterinary Teaching Hospital. However, insufficient scientific evidence has been published to substantiate such correlations. Hence, we aimed to assess the practicality of the abovementioned observations in the evaluation of arrhythmias. To this end, we conducted a cross-sectional study to evaluate the capability of participants with varying clinical experience to use PWA after the training. The participants were grouped according to their professional backgrounds. “Cardiology researchers” included contributors to cardiovascular research, such as cardiology postgraduate students and residents; “general practitioners” comprised veterinary professionals with at least 1 year of clinical experience in areas mostly outside of cardiology; and “veterinary students” comprised currently enrolled undergraduates.

### Methods

#### Participant recruitment

Recruitment was conducted via Facebook, taking advantage of its wide network. We posted a Google Form in targeted Facebook groups, reaching out to veterinarians at the National Chung Hsing University Veterinary Teaching Hospital, department alumni, and the university’s undergraduate students. Interested individuals were invited to a Facebook group specifically created for the study, which served as a platform for detailed discussions on the research agenda and regular updates on its progress. Our recruitment criteria were inclusive and open to students at any academic level and to veterinary professionals, regardless of their years of practice or specialty areas. The only exclusion criterion was the inability to participate in the training course or to complete PWA after the training. The participants were grouped according to their professional backgrounds. "Cardiology researchers" included contributors to cardiovascular research, such as cardiology postgraduate students and residents; “general practitioners” comprised veterinary professionals with at least 1 year of clinical experience in areas mostly outside of cardiology; and “veterinary students” comprised currently enrolled undergraduates.

The recruitment process and study methodology were exempt from ethical review owing to the minimal risk it posed and not including vulnerable populations, as per the Ministry of Health and Welfare’s guidelines dated July 5, 2012. More details are available at https://dep.mohw.gov.tw/doma/fp-2782-9538-106.html.

#### Data collection, categorization, and anonymization

As this study involved a cross-sectional, observational analysis of existing clinical data with no new or invasive procedures performed on animals, it fell outside the purview of the Institutional Animal Care and Use Committee. The investigator, trained as a veterinary cardiologist under the direct supervision of a board-certified veterinary cardiologist, was responsible for the retrieval and collation of data from patients with both ECG and HDO blood pressure data collected during the same outpatient visit from March 2019 to January 2021. Our study’s primary inclusion criterion was data collected during a single outpatient visit from March 2019 to January 2021. We did not exclude patients with hypertension or other diseases. This approach allowed for a diverse range of clinical cases in our study sample. The investigator anonymized all of the data to maintain confidentiality and data integrity.

The ECG diagnoses were categorized into 5 groups according to the electronic medical records: sinus rhythm/sinus arrhythmia, premature complexes (including supraventricular and ventricular), heart block (including second- and third-degree atrioventricular blocks and nodal dysfunction), atrial fibrillation/flutter, and “others” (categories outside the preceding 4). All identifiable patient data were anonymized, and a unique alphanumeric identification code was assigned to each subject. The HDO data were processed using the HDO software suite (High Definition Oscillometry MDSWin; S+B MedVET) and made accessible to the study participants.

#### Training session

The training session was designed and led by the investigator, who had been utilizing HDO for blood
pressure measurements in a wide range of settings, including on conscious, sedated, and anesthetized animals across various species, for 11 years at the start of this study. The investigator further enriched his expertise by participating in practical training courses offered by the HDO system manufacturer 5 years before this study started.

All participants attended a 60-minute lecture delivered by the investigator, focusing on the interpretation of pulse-wave data. The topics covered in the lecture included the characteristics of sinus rhythms on ECG and PWA, the oscillometric method spanning from inflation to deflation, the correlation between regularity and amplitude height in cardiac output, and the morphology of various types of arrhythmias in PWA. A normal sinus rhythm exhibits a typical bell-shaped pattern in PWA, with a gradual increase and decrease in amplitude at equal intervals. Sinus arrhythmia manifests as clusters of multiple pulse peaks forming subpeaks within a larger bell-shaped pattern, reflecting the cyclic heart rate characteristic of this condition. Premature contraction manifests as unexpectedly lower amplitude spikes that are randomly dispersed, often followed by a longer-than-normal pause. Heart block manifests as unpredictably wider intervals followed by higher-than-expected pulse peaks. Atrial fibrillation manifests as irregular intervals and the lack of a gradual rise and fall in pulse amplitude (Figure 1).

**Result classification**

Upon completing their training, the participants were blinded to patient information, medical history, medication records, physical examination findings, and other variables.
and other relevant factors. The participants then performed 2 tasks; first, they engaged in a binary classification of the PWA results into sinus rhythms (including normal sinus rhythm and sinus arrhythmia) and non sinus rhythms (including pathological arrhythmias). Subsequently, they divided the results into 5 predefined categories corresponding to the ECG diagnostic groups to achieve a more detailed classification. All data were subsequently entered into a commercially available spreadsheet program (Google Sheets; Google LLC) by the participants.

**Statistical analyses**

For the statistical analyses, we primarily utilized IBM SPSS Statistics for Windows, version 24.0 (IBM Corp). First, we evaluated the diagnostic performance of PWA in differentiating sinus from non-sinus rhythms, designating the ECG results as the independent variable and the HDO PWA results as the dependent variable. This setup enabled us to calculate the area under the receiver operating characteristic (ROC) curve (area under the curve [AUC]) for the detection of nonsinus rhythms, such as premature complexes, heart block, and atrial fibrillation. The AUC was utilized to gauge the diagnostic accuracy of PWA in identifying these arrhythmias. The AUC values were interpreted as follows: poor, 0.5 to 0.6; fair, 0.6 to 0.7; good, 0.7 to 0.8; very good, 0.8 to 0.9; and excellent, 0.9 to 1.0.

Subsequently, we determined the agreement between the participants’ pulse-wave interpretations and the confirmed ECG diagnoses by using the Cohen κ coefficient values. The κ values were interpreted as follows: slight, κ ≤ 0.20; fair, 0.21 ≤ κ ≤ 0.40; moderate, 0.41 ≤ κ ≤ 0.60; substantial, 0.61 ≤ κ ≤ 0.80; and almost perfect, κ > 0.80. In addition, we evaluated the correlation between the academic year of the veterinary students and their κ values using a non-parametric Spearman rank correlation coefficient.

Finally, we used ROC curve analysis to identify the arrhythmia category most accurately identified through pulse-wave pattern identification, which reflected the overall discriminative power of PWA in detecting specific types of arrhythmias. The predetermined statistical significance level was set at P < .05.

**Results**

The participants in this study spanned various levels of expertise. The cardiology researchers group consisted of 2 veterinarians who had recently completed a 2-year cardiology-focused master’s program and a second-year cardiology resident, all of whom had made substantial contributions to and published papers in the field of cardiovascular research. The general practitioners’ group comprised 5 practicing veterinarians. Finally, the veterinary students’ group consisted of 10 undergraduate students at various stages of their academic journey, with 1 second-year student, 2 third-year students, 5 fourth-year students, and 2 final-year students in their clinical year.

Between March 2019 and January 2021, 155 datasets that met the inclusion criteria were analyzed. These datasets corresponded to 144 dogs across 23 different breeds and 11 cats. In the canine cases, the most frequently represented breed was the Maltese (30 cases; 20.8%), followed by the Toy Poodle (21 cases; 14.6%), mixed breeds (20 cases; 13.9%), Cavalier King Charles Spaniel (12 cases; 8.3%), Miniature Schnauzer (10 cases; 6.9%), Dachshund (8 cases; 5.6%), and Shiba Inu (7 cases; 4.9%). The remaining cases were distributed among other breeds, such as the Siberian Husky, Japanese Spitz, Chihuahua, Shih Tzu, Japanese Chin, Golden Retriever, Beagle, and Pomeranian. In the feline dataset, Chinchilla breeds were the most prevalent, accounting for 3 cases (27%). American Shorthair and Persian Longhair breeds, as well as mixed-breed cats, were also notably represented, each contributing 2 cases (18%). Both domestic and British Shorthair breeds were less common (3 case [9%] each).

Diagnostic ECG results (Figure 2) classified most datasets as sinus rhythm/sinus arrhythmia (81 cases; 52.3%), followed by premature complexes (23 cases; 14.8%), heart block (16 cases; 10.3%), atrial fibrillation (8 cases; 5.2%), and others (27 cases; 17.4%). The “others” category included mostly pacin rhythm (15 cases; 55.6%) of all “others” cases. Sick sinus syndrome and accelerated idioventricular rhythm were identified in 3 cases each (11.1% each of “others” cases). Atrial fibrillation mixed with ventricular premature complexes was identified in 2 cases (7.4% of “others” cases). Single ventricular ectopic, inverted P wave, supraventricular tachycardia mixed with high-grade atrioventricular block, and isorhythmic atrioventricular dissociation were each identified in 1 case, each representing 3.7% of the “others” category.

Agreement between ECG diagnoses in PWA-based assessments was evaluated using κ values

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**Figure 2**—A classification chart of the ECG data. AIVR = Accelerated idioventricular rhythm. APC = Atrial premature complexes. AVB = Atrioventricular block. HR = Heart rate. IAVD = Isorhythmic atrioventricular dissociation. LAD = Left axis deviation. LAFB = Left anterior fascicular block. RAD = Right axis deviation. RBBB = Right bundle branch block. SVT = Supraventricular tachycardia. VPC = Ventricular premature complexes. VT = Ventricular tachycardia.
Among the veterinary undergraduates, 7 showed “slight agreement,” while 3 showed “fair agreement.” Among the practicing veterinarians, 3 showed “slight agreement,” and 2 showed “fair agreement.” The cardiology researchers all showed “fair agreement.” A significant correlation was found between the year of study and $\kappa$ values ($Spearman \rho = 0.658; P = .019$).

The ability to detect nonsinus rhythms was evaluated using AUC values (Figure 3; Supplementary Table S1). Veterinary students exhibited detection capabilities that ranged from poor to fair (AUC values, 0.471 to 0.628). In contrast, practicing veterinarians achieved better detection abilities, with AUC values ranging from 0.525 to 0.702. Cardiology researchers achieved the highest levels of proficiency among all groups, with AUC values ranging from 0.704 to 0.761.

In the ROC curve analysis, atrial fibrillation detection had the highest overall AUC values across all participant groups. A fourth-year veterinary undergraduate achieved the highest AUC value (0.898). The cardiology resident achieved an AUC value of 0.845, whereas another fourth-year veterinary undergraduate and the 2 cardiology postgraduates achieved AUC values of 0.814, 0.811, and 0.821, respectively. A third-year veterinary undergraduate recorded the lowest AUC value (0.313; Figure 3; Supplementary Table S1).

**Discussion**

Ours is the first cross-sectional study to determine whether PWA can be used to detect arrhythmias during routine NIBP measurements. As hypothesized, PWA holds promise as a potential method for the differentiation of sinus rhythm from pathological arrhythmias, particularly atrial fibrillation. Participants from diverse veterinary medicine backgrounds documented varying results when applying PWA. Notably, its application during routine blood pressure measurements appeared to yield optimal results when the participants possessed a background in cardiology.

Arrhythmia is an abnormal heart rhythm that can range from a harmless to a potentially serious condition.10–12 For frontline veterinary practitioners without a strong background in ECG interpretation, differentiation between sinus and nonsinus rhythms is crucial. Veterinarians typically use auscultation, pulse palpation, and variations in pulse strength to detect potential arrhythmias or pulse deficits that may necessitate further ECG investigation. In our study, participants used the changes in cardiac output and pulse characteristics caused by arrhythmias along with an NIBP-measuring device that recorded pulse-wave data for each measurement. This approach demonstrated impressive performance, particularly in distinguishing atrial fibrillation, and yielded the largest consistency in identifying sinus rhythms and various arrhythmias among participants with extensive cardiology experience. This result may be due to all 3 cardiology researchers having hands-on experience in using the HDO for NIBP measurements and receiving clinical feedback for those assessments. Moreover, structured practice and feedback-based learning can significantly improve ECG interpretation skills,13,14 a concept that likely also applies to the PWA used in our study.

Different arrhythmias can have varying impacts on hemodynamics and do not always result in clinical symptoms; they are often discovered incidentally. In our study, the data consist of a 53.5% proportion of pathological arrhythmias, which is higher than previous prevalence rates, ranging from as low as 2.6% in an ECG data bank to as high as 39.9% in the cardiology department of another referral veterinary hospital.15–17 Several methods can be used to enhance the identification of pathological arrhythmias, including extended auscultation, prolonged ECG recordings,
and the incidental detection of arrhythmias via simultaneous ECG during echocardiography. Additionally, our cardiology department routinely employs the HDO blood pressure machine for every cardiology outpatient, recording pulse-wave data with each measurement. This practice often leads to the incidental detection of arrhythmias in asymptomatic patients. Furthermore, pet owners frequently agree to additional ECG examinations when arrhythmias are first suspected during NIBP measurements using PWA.

In our study, even the best-performing veterinarians with cardiology experience achieved only fair agreement in distinguishing between different types of nonsinus pathological arrhythmias. This might be due to several reasons. For instance, certain arrhythmias, such as ventricular premature complexes with compensatory pauses, intermittent heart block, and sinus arrhythmias, have similar presentations; all 3 exhibit a wider interval followed by a higher pulse peak after the pause due to increased time for left ventricular filling. The distinction among these conditions depends on the detection of a premature beat, appearing as a lower amplitude spike on the PWA at the start of this wider interval. Moreover, with its cyclical characteristics, sinus arrhythmia presents as a regular recurrence of multiple pulse peaks with a higher pulse rate (shorter interval on PWA) followed by a slower one (wider interval). The high prevalence of sinus arrhythmia in our dataset (32.9%) may be explained by multiple factors. Our patient sample comprised many more dogs (n = 144) than cats (11), and cats in a hospital environment typically experience sympathetic activation, reducing the prevalence of sinus arrhythmias in cats compared to that in dogs. Additionally, breed predispositions (particularly in brachycephalic dogs), changes in behavioral states that affect autonomic tone, and various underlying health conditions might also have contributed to the high prevalence of sinus arrhythmias in our study. Furthermore, blood pressure measurements in conscious animals are demanding, with movement, panting, and shaking potentially causing substantial baseline artifacts resembling a series of fluctuating pulse waves, thereby complicating interpretation. Particularly for less-experienced interpreters, distinguishing between these artifacts and actual pulses can be confusing, a problem akin to that faced in the interpretation of ECGs.

Atrial fibrillation, the most prevalent pathological arrhythmia, is characterized by fast and irregular heartbeats that can be readily identified during physical examination through auscultation and palpation.\textsuperscript{11,18-21} The irregular and inconsistent cardiac output is distinct in PWA and typically manifests as a series of high- and low-pulse peaks with irregular intervals between them. In our study sample, atrial fibrillation and atrial flutter were less common than other conditions (n = 8; 5.2%). Moreover, among these 8 patients, 5 had been receiving anti-arrhythmia medications (diltiazem, digoxin, and atenolol) for at least a week, which stabilized their hemodynamic performance. Despite these conditions, even the less-experienced participants managed to distinguish atrial fibrillation relatively well, indicating its high recognizability with PWA. In recent years, wearable devices to aid in identifying atrial fibrillation have emerged in human medicine\textsuperscript{22,23}; however, similar equipment is not currently available for small animals. As an ECG machine is not standard equipment in general practice and as using NIBP monitors to measure blood pressure is more common than using ECG, integration of PWA into NIBP measurements for patients with substantial cardiac remodeling who are at an increased risk of arrhythmia, especially atrial fibrillation,\textsuperscript{24} could facilitate timely referrals in the case of concerns.

Nevertheless, the overall performance of all study participants varied, and those with cardiology experience exhibited a superior ability in screening patients for nonsinus rhythms and further categorizing the type of arrhythmia. This may stem from these participants’ comprehensive understanding of the Wiggers diagram,\textsuperscript{25} cardiovascular physiology, and pathophysiology, as well as their clinical experience. Similar research\textsuperscript{26-28} has indicated that specializing in cardiology after graduation markedly enhances auscultation skills and ECG interpretation abilities. This suggests that acquiring new skills, such as using PWA, necessitates strategic learning methods,\textsuperscript{14} such as a combination of interactive workshops involving the actual use of HDO with traditional lecture-style classes. Interestingly, similar proportions of general practitioners and veterinary undergraduates achieved similar levels of agreement. This result suggests that more clinical experience, other than that in the field of cardiology, does not necessarily enhance a veterinarian’s proficiency in PWA compared to that of students. A likely reason is that obtaining and analyzing pulse-wave data through NIBP measurements is a relatively new concept that is not typically covered in veterinary education, resulting in a similar starting point for most participants regardless of their clinical experience. Ultimately, we hope this approach will prompt more frontline veterinarians to suspect arrhythmia during routine NIBP measurement and subsequently refer such patients for ECG examinations.

Despite offering valuable insights, this cross-sectional study had several limitations. First, the participants were disproportionately recruited. The participants included relatively few cardiology researchers in comparison to veterinary students, as is expected in the field of veterinary medicine. Although this disparity was inevitable, it might have influenced our findings. Second, ECG and routine blood pressure measurements were performed sequentially, not simultaneously. The short window for gathering pulse-wave data, exclusively during cuff deflation, yielded less data than ECG, influencing their comparative analysis. Third, participants were not assigned a specific timeframe in which to complete their PWA interpretation posttraining, and accuracy may diminish over time after training.\textsuperscript{14} Importantly, ECG remains the gold standard for the diagnosis of arrhythmias and should precede clinical
decision-making. The principal aim of the use of PWA is for early screening, not as a replacement for ECG examinations. The utility of this method lies in its potential to facilitate early detection of arrhythmias, prompting timely ECG referrals. Finally, our study did not exclude cases receiving pharmacotherapy for arrhythmia or those fitted with a permanent pacemaker. Further, it did not distinguish sinus arrhythmia from the sinus rhythm category, which may influence the capabilities of PWA.

This study underscores the potential of PWA in detecting pathological arrhythmias, especially atrial fibrillation. Enhanced training for veterinarians, particularly those specializing in cardiology, may improve the clinical application of PWA. The strengthening of continuing education programs may empower general practitioners to better identify arrhythmias, facilitating timely ECGs or referrals. Further studies are needed to evaluate whether cardiology-focused training and workshops can enhance the use of PWA in clinical practice. Crucially, prospective studies are necessary to thoroughly evaluate the influence of blood counts, echocardiographic features, ECG characteristics, and hemodynamic results on pulse-wave morphology, improving our understanding of potential relationships and underlying causes. Such research should be focused on establishing the baseline pulse-wave characteristics in healthy dogs and investigating the impact of common diseases, such as myxomatous mitral valve disease, as well as factors such as age, weight, sex, and sedation status, on PWA results. Such studies are vital for a deeper comprehension of the role of PWA in various clinical settings.

Acknowledgments
We are grateful to ANIWARE Co, Ltd for supporting the submission costs.

Disclosures
The authors have nothing to disclose. No AI-assisted technologies were used in the generation of this manuscript.

Funding
The authors have nothing to disclose.

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**Supplementary Materials**

Supplementary materials are posted online at the journal website: avmajournals.avma.org