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The AliveCor KardiaMobile ECG device allows electrocardiogram assessment in awake bonobos (*Pan paniscus*)

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OBJECTIVE
To determine the diagnostic utility of a smartphone-based ECG device (Alivecor KardiaMobile) in awake bonobos (*Pan paniscus*).

ANIMALS
7 adult bonobos in human care.

PROCEDURES
Bonobos were trained with positive reinforcement to hold 1 finger from each hand onto the KardiaMobile sensors for 30 seconds to obtain an ECG reading. Ten ECG tracings were recorded from each bonobo and evaluated by a veterinarian, a veterinary cardiologist, and a human cardiologist for tracing quality, tracing length, heart rate, identification of *P*-waves, and presence and quantification of premature ventricular or atrial contractions.

RESULTS
6 of the 7 bonobos were trained within 21 weeks to allow the collection of 10 diagnostic quality ECG tracings. The average heart rate recorded was 87 bpm (range = 60 to 118 bpm). Potential abnormalities identified by the KardiaMobile included premature ventricular contractions in 2 male bonobos and 1 premature atrial contraction in another male. There was strong agreement by reviewers in all ECG parameters except for the identification of *P*-waves.

CLINICAL RELEVANCE
The Alivecor KardiaMobile device has diagnostic utility as a screening tool for use in bonobos in human care. The training was accomplished to yield diagnostic ECG readings of acceptable duration in awake bonobos. Given the prevalence of cardiovascular disease in great apes, this technology may identify a subset of great apes who may benefit from early intervention and treatment in an effort to delay the progression of cardiac disease.

Bonobos (*Pan paniscus*) are 1 of 7 species included in the Hominidae taxonomic family, also known as the great apes. All great apes are endangered or critically endangered in their natural habitats in the wild. There are 5 species of great apes managed in human care within zoological institutions including western lowland gorillas (*Gorilla gorilla gorilla*), Bornean orangutans (*Pongo pygmaeus*), Sumatran orangutans (*Pongo abelii*) as well as Pongo hybrids, chimpanzees (*Pan troglodytes*), and bonobos (*Pan paniscus*). The most significant health concern for great apes maintained in human care is cardiovascular disease (CVD).[1] Adult male great apes show a greater predilection for developing CVD, although pathology has been diagnosed in aged females as well.[2] In 2019, the American Association of Zoos and Aquariums (AZA) Bonobo Species Survival Plan (SSP) Veterinary Advisor Annual Report listed CVD as the most common cause of mortality in male bonobos greater than 20 years of age and females greater than 30 years of age. The SSP report included a review of bonobo mortalities from the US and European zoos, concluding that 46% of all deaths in bonobos greater than 1 year of age were caused by CVD between 2004 and 2014.[3]

Most often, great apes do not exhibit overt clinical signs indicating the presence of CVD. Subtle signs might include social withdrawal, behavioral changes, appetite changes, weight loss, and mild to moderate lethargy.[1,4] In bonobos, occasional reports of nasal bleeding have been noted, possibly related to underlying hypertension.[4] In most instances of cardiovascular death, animals are found dead without premonitory clinical signs observed by caretakers.[1] The most common necropsy finding is myocardial fibrosis, with muscle fibers of the heart replaced with fibrous connective tissue.[2]

At this time, little is understood about the exact epidemiology and etiopathogenesis of cardiac disease in great apes and, therefore, limited information about diagnosis, treatment, and prevention.[2] In 2010, the Great Ape Heart Project (GAHP) was created to establish uniform strategies for the diagnosis, treatment, and prevention of CVD in great apes.[5] The GAHP supports institutions housing great apes by giving specific recommendations regarding the performance of awake and anesthetized echocardiograms[5] ECGs and instructions for the insertion of loop recorders for great apes in human care, and also provides advice from human and veterinary cardiologists and specialists regarding the management of clinical cases. Specific recommendations for the use of handheld ECG devices in great apes have not been published at this time.

The KardiaMobile™ by AliveCor (KM) is a mobile, clinical-quality ECG recorder that can be used with smartphones or tablets and is one of an ever-growing number of mobile devices used to track heart rhythm. For the KM device, the duration of recording can range anywhere from 30 seconds to 5 minutes, with 30 seconds being the default setting. The length of time recording can be set using the Kardia phone app. The software of the app allows for storing thousands of recordings on a smartphone or tablet.[6]

The accuracy of KM has been demonstrated in multiple studies in people and correlates well with gold standard rhythm assessment with 12-lead ECG.[7] The KM device has been utilized in a variety of human clinical contexts including to evaluate for arrhythmia recurrence after therapeutic interventions.[8] In this strategy, the device is used at regular intervals for arrhythmia screening and also on demand for symptoms.[8]

In addition to using in adult human patients, KM has also been used in the pediatric population with 1 study enrolling patients as young as 14 days with an average age of 8 years.[9] In contrast to adults, children required training and parental coaching or assistance to achieve optimal tracings, which were obtained in 90% of the participants.[9]

Several studies have been published evaluating the use of smartphone-based ECGs in veterinary species, including dogs and cats,[10] goats,[11] cows,[12] horses,[13] and water buffalo calves.[14] In 2020, Cloutier et al described training methodologies for use of the KM device in great apes.[15] However, the quality and diagnostic utility of the KM device has yet to be demonstrated in great apes.

The objective of this study was to determine the feasibility and utility of the KM device for the determination of heart rate and rhythm in awake bonobos in human care. We hypothesized that adult bonobos could be trained to use the KM device, that tracings would be of sufficient quality to allow calculation of heart rate and identification of premature atrial and ventricular contractions, and that interobserver variability for ECG parameters would be low.

Materials and Methods

This study protocol was performed in compliance with the Ape Cognition & Communication Institute Institutional Animal Care and Use Committee (IACUC) protocol 210305-1.

For this study, the KM monitor was attached to a wooden block **(Figure 1)** using a 3D-printed adapter to secure the monitor and prevent the bonobos from damaging the equipment. The wooden block was constructed from an 8-inch wide by half-inch thick piece of pine wood that was heavily sanded. Measurements of the KM monitor were taken and inputted into a computer-aided design (CAD) program. The mounting adapter was designed and modeled based on the gathered dimensions. The CAD model was converted into a stereolithography (STL) file and fed through a slicer program. The resulting g-code was used to 3D print a physical polylactic acid (PLA) model of the CAD design. The monitor was secured to the wooden block using 4 half-inch wood screws. The device was used in conjunction with a cellular phone that was placed directly behind the KM device on the wood block (Figure 1). The cellular phone needs to be within 6 inches of the KM device for accurate readings.

Figure 1—Photograph demonstrating the KardiaMobile device mounted to a wooden block and used during a training session with a male bonobo. As shown in the photo, a sterile lubricant was applied to the device sensors to increase conductivity. The ECG tracing is visible on the smartphone shown in this image. Completed ECG tracings were saved as PDFs and submitted to evaluators for review.

Each bonobo had been previously trained in protected contact with positive reinforcement techniques to present different body parts for inspection on cue. This training helps facilitate routine veterinary physical examination and wound care in conscious animals and can serve as a cornerstone for other types of husbandry, research, and veterinary procedures. For this study, 7 bonobos (3 females and 4 males) ranging in age from 11 to 40 years were trained with positive reinforcement with the goal of having the bonobo present 1 finger on opposite hands through the 2" X 2" metal mesh and hold

Table 1—The scoring system used to evaluate KardiaMobile ECG tracings from bonobos by evaluators in this study.

Score	Definition	1	2	3	4
Overall quality of tracing	Percentage of the tracing assessed as diagnostic quality.	75–100%	50–74%	25–49%	< 25%
P-wave	Percentage of the tracing for which *P*-waves were identifiable occurring before sinus QRS complexes.	75–100%	50–74%	25–49%	< 25%

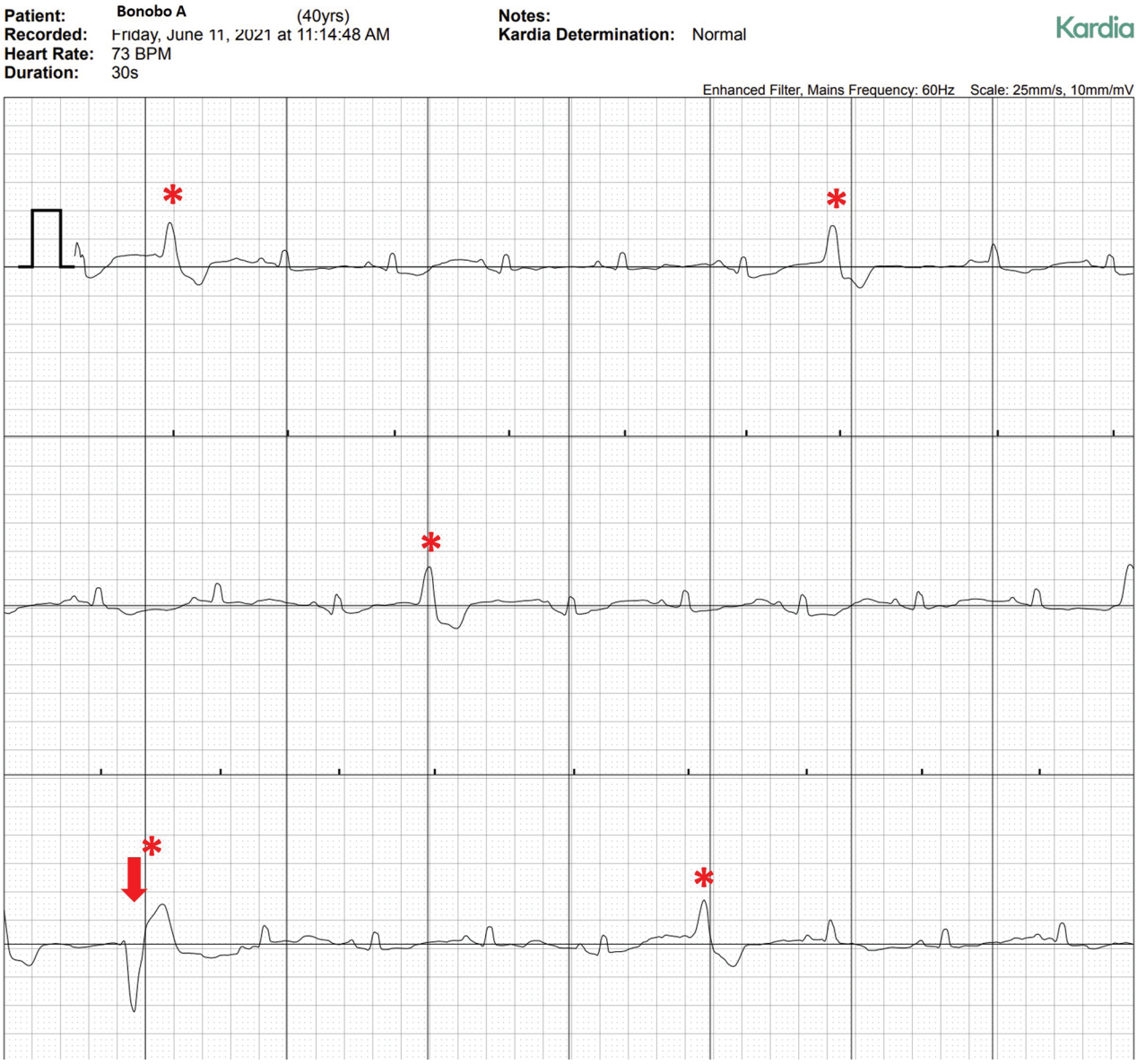

Figure 2—Example of a KardiaMobile ECG tracing obtained from a 40-year-old male bonobo. In this tracing, 5 ectopic complexes (red asterisks), indicative of premature ventricular contractions, were identified from all 3 evaluators in this study. A polymorphic complex is also identified (red arrow and red asterisk). Also noted in this particular tracing are clearly identified *P*-waves before every non-ectopic complex. Note also that the Kardia determination for this ECG was "normal." This demonstrates that practitioners should not rely on the algorithm of the program for interpretation of HR or rhythm abnormalities but should critically evaluate each tracing.

the finger pad on the KM sensor for 30 seconds (Figure 1). Sterile lubricant or 70% ethyl alcohol hand sanitizer gel was applied to the KM sensors to increase conductivity.

ECG tracings were recorded by trainers and uploaded as PDFs to a shared file. The ECG tracings were first evaluated by a non-veterinarian (S.H.) for determination of usability before submission to the 3 evaluators. Ten of the best tracings obtained per bonobo, based upon acceptable duration and lack of significant movement artifact, were submitted to evaluators. Submitted tracings were evaluated by a boarded veterinary cardiologist, a boarded human cardiologist, and a first-year veterinarian who had received instruction in ECG interpretation from the human cardiologist. The ECG strips were evaluated for (1) the quality of tracing, (2) the length of tracing in seconds, (3) the heart rate in beats per minute, (4) the number of premature ventricular contractions (PVCs), (5) the presence of identifiable *P*-waves, and (6) the presence of any atrial arrhythmias. The scoring system used to assess the tracing quality and presence of *P*-wave is shown **(Table 1)**.

If deemed clinically necessary, a 12-lead ECG was performed under general anesthesia using previously described techniques for chimpanzees.[16]

Statistical Analysis

Continuous data (tracing duration, heart rate, and ECG quality scores) are presented as the median and interquartile range (IQR). Interobserver agreement was analyzed using the PROC MIXED procedure of SAS (Version 9.4, SAS Institute). Differences of least-squares means are presented and differences were considered significant at $P < .05$.

Results

Six of the 7 bonobos were successfully trained during the period of this study to obtain 10 ECG tracings of diagnostic quality. The 7th bonobo (a 12-year-old female) was too active during the 30-second interval, such that the KM device could not obtain a tracing of sufficient duration. For that bonobo, 17 training sessions performed over 21 weeks produced only 2 tracings nearing diagnostic quality, both less than 13 seconds in length. Therefore, this bonobo was eliminated from the study. For the remaining bonobos, training to obtain the 10 diagnostic quality tracings took up to 21 weeks, depending upon the availability of the trainers and the

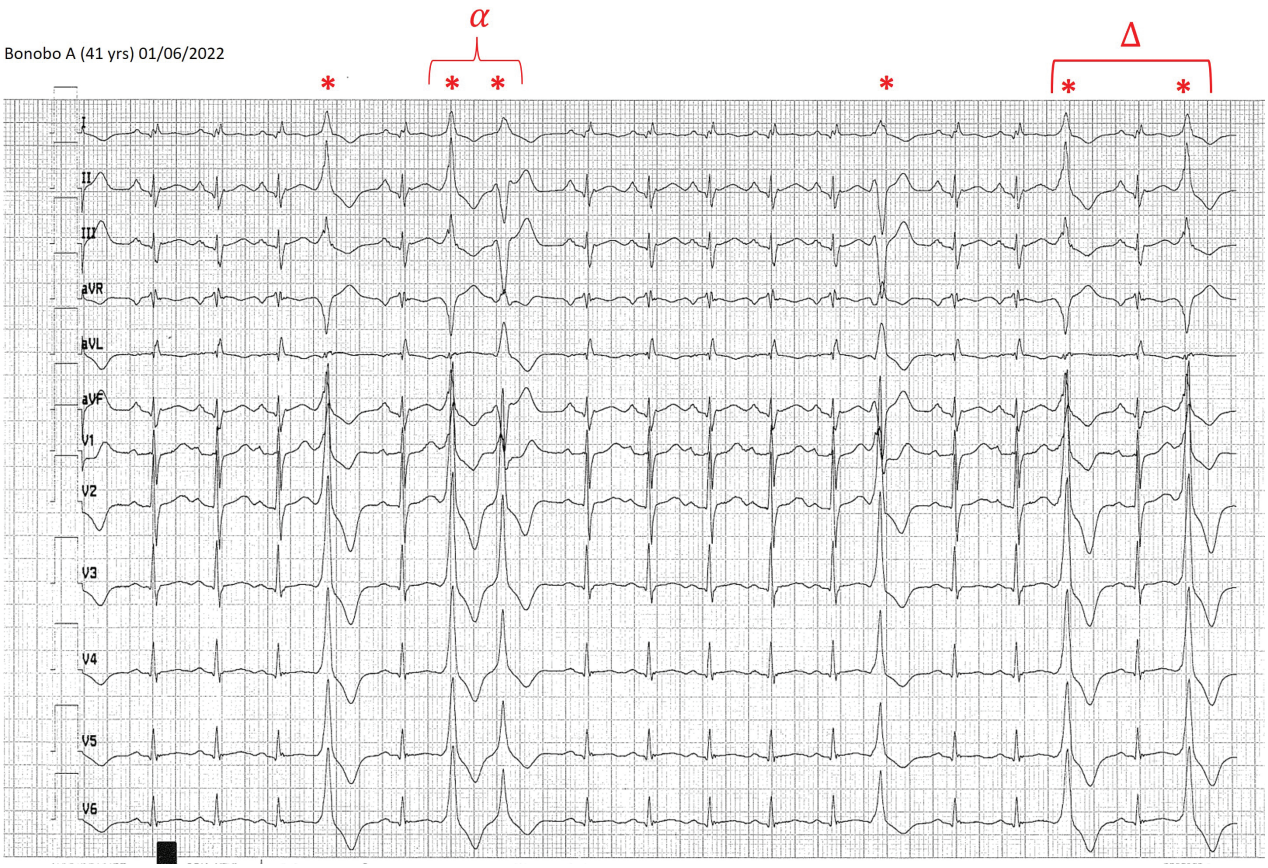

Figure 3—A 12-lead ECG performed at the standard paper speed in the same 41-year-old male bonobo, taken 6 months after the KardiaMobile ECG shown in Figure 2. The rhythm is normal sinus with a ventricular couplet (α) and ventricular bigeminy (Δ), and best noted in the inferior leads as well as lead aVR. The dominant premature ventricular contraction (PVC) morphology (red asterisks) has a right bundle branch block configuration with an inferior axis. This would imply a PVC origin superiorly within the left ventricle, probably around the mitral annulus.

individual bonobo. The fewest number of training sessions performed to obtain the 10 diagnostic tracings was 17 (n = 3 bonobos). The highest number of sessions performed to obtain the 10 diagnostic tracings was 32, in one 40-year-old male and one 13-year-old female. After the 10 diagnostic quality tracings were obtained from each bonobo, training continued to maintain the behavior as part of the veterinary repertoire, but new tracings were not included for evaluation in this study.

The 10 selected tracings for each bonobo were submitted for assessment by all 3 evaluators, using the scoring system outlined (Table 1). The median duration of all tracings evaluated was 30 seconds (IQR, 5 seconds). The median heart rate was 85 bpm (IQR, 13 bpm). The median overall quality score for all tracings was 1.67/4 (IQR 1), indicating that greater than 50% of the tracing duration was considered diagnostic quality by the evaluators. Tracings were considered diagnostic quality if the amplitude and morphology of QRS complexes were clearly visible without significant motion artifacts of the baseline. Two male bonobos had PVCs detected in multiple tracings **(Figure 2)** and another male had a single PAC detected in 1 tracing. There were no rhythm abnormalities detected in the 2 female bonobos with ECG tracings evaluated. There was no statistical difference between evaluators in the assessment of tracing quality (P = .23), tracing length (P = .20), heart rate (P = .94), the presence of PVCs (P = .29), or the presence of atrial arrhythmia (P = .40). The median P-wave score was 2.33/4 (IQR 1.67). For the presence of P-waves, least squared means testing detected a difference among observers (P = .0043), which was determined to reflect significant differences between the veterinary cardiologist and both the first-year veterinarian (P = .005) and human cardiologist (P = .014). The veterinary cardiologist scores were higher, indicating less frequent identification of P-waves. There was no difference in P-wave identification between human cardiologist and the first-year veterinarian (P = .99).

Two male bonobos in this study had PVCs identified with the KM device. Because of the finding of frequent PVCs in the oldest bonobo (Figure 2), further formal evaluation including 12-lead ECG as well as echocardiography was performed under anesthesia **(Figure 3)**. Simultaneous echocardiographic evaluation of this bonobo demonstrated left ventricular dysfunction (LVEF 35%) with no regional wall motion abnormalities or valvular dysfunction.

Discussion

In this study, 6 of 7 bonobos were successfully trained to utilize the KM device and diagnostic quality ECGs were obtained. Heart rate and rhythm were successfully assessed with an excellent interobserver agreement. Overall, the ECG tracings produced in this study by the KM device were easily interpreted by all 3 evaluators with a strong agreement. This study supports the use of the AliveCor KardiaMobile™ ECG technology in awake bonobos for interpretation by a veterinary practitioner or in consultation with specialists. The KM device is an inexpensive and easily accessible technology for veterinarians to use as a screening tool for the assessment of cardiac health in the bonobo, and great apes in general.

Previous studies demonstrating the usefulness of smartphone-based ECG applications in veterinary patients have used methods requiring thoracic contact with the device to obtain ECG readings.[10–14] For great apes, thoracic contact may not be practical or safe in a non-anesthetized patient. Because the KM device has been created to be used with human fingers, it works well for use in great apes. Although the instructions for humans are for the placement of two fingers on each sensor, the size of the bonobo fingers allowed only the use of 1 finger from each hand, but diagnostic tracings were still obtained. Mounting the device (Figure 1) prevents the ability of apes to cause damage to the device and the smartphone in close proximity. In this study, 3D-printing technology was used to create the mounting system used, but less technically advanced solutions to mounting could also be used. The majority of the bonobos in this population were trained within 21 weeks to present fingers and hold to the KM device sensors for nearly 30 seconds to obtain diagnostic ECG tracings.

The bonobos used in this study are trained to participate in cognitive and communication studies, often involving the use of touch-screen devices and pointing; therefore, transitioning the previously trained behaviors to participation in this study may have been easier for this population than for other apes in human care. These animals also experience frequent positive-reinforcement training sessions for veterinary examination as a normal daily practice. Had there been more trainer time available, this data may have been acquired within a faster timeline, but there was individual bonobo variation in participation and satisfactory ECG tracing acquisition. The major obstacle to training was convincing the bonobo to sit quietly and maintain contact with the KM sensors without movement for 30 seconds. The main reason for tracings being rejected for consideration was significant motion artifacts or short tracing duration. Since the completion of this study, the 12-year-old female that was initially eliminated from data collection has been successfully trained for KM tracing acquisition, but tracings continue to be brief (< 20 seconds), demonstrating how individual variation in compliance can affect results. Brief tracings (< 30 seconds) will reduce the diagnostic accuracy and full rhythm assessment. Similar to what has been observed when using the KM device in small children, as well as in previous literature, the KM is sensitive to motion artifacts (muscle tremor, arm movement, and muscle tension) and background noise.[9] These parameters are difficult to control in both a pediatric and zoological setting. Limitations of staffing, as well as the trainability of individual great apes within other facilities, may require longer training periods to obtain similar results.

Two male bonobos in this study had PVCs identified with the KM device. PVCs in humans demonstrate

a wide QRS (> 120 milliseconds) and often a compensatory pause. Frequent ventricular ectopy often serves as a marker of underlying pathologic conditions such as hypertensive heart disease, dilated cardiomyopathy, and ischemic heart disease. The oldest individual in this study group had frequent PVCs with multiple 30-second tracings showing between 2 to 3 ectopic beats (Figure 2). As shown, the Kardia determination for this ECG was "normal." This demonstrates that practitioners should not rely on the algorithm of the program for interpretation of HR or rhythm abnormalities but should critically evaluate each tracing.

The morphology of PVCs on a 12-lead ECG (left vs right bundle branch block morphology, the axis in the frontal plane, and transition point across the precordium) can serve as useful clues as to the origin. In humans, the 12-lead ECG assessment of likely PVC origin is frequently used as a rough guide during radiofrequency ablation procedures.[17] As demonstrated in the 12-lead ECG of the 41-year-old bonobo (Figure 3), the QRS morphology is consistent with the right bundle branch block (indicating a left ventricular origin). The frontal and precordial axis suggests that the dominant PVC originated from the mitral annulus. In this case, the high PVC burden identified by the KM device likely reflects underlying cardiac disease and is not an isolated finding. Given previous studies documenting left ventricular fibrosis as a common post-mortem finding in great apes,[2,4] frequent PVCs could provide a convenient clue to underlying structural abnormalities.

While there was an acceptable agreement between all evaluators for the majority of the ECG parameters in this study, there was a statistically different interpretation between evaluators for the presence of *P*-waves. This finding is not surprising given that the *P*-wave represents the most diminutive of the inflections recorded by the ECG, and there were some limitations with contact and artifact which might make visualization of the *P*-wave more challenging in this setting. There may also be individual differences in the threshold for confidence in the identification of the *P*-wave. In this study, the human cardiologist instructed the first-year veterinarian in ECG interpretation, and this may have increased agreement between these 2 evaluators.

Simultaneous 12-lead EKG recordings were not performed at the time of KM tracings of bonobos to confirm the heart-rate determinations to be accurate, but the amplitude and morphology of QRS complexes obtained using KM indicated that there were no "missed beats" during the recording. In humans, KM has been proven accurate with simultaneous 12-lead ECG recording.[7]

The results of this study demonstrate that awake bonobos can be trained to use the KardiaMobile™ ECG device as a screening and diagnostic tool for the detection of cardiac rhythm abnormalities. Diagnostic quality tracings were obtained in 6 of 7 bonobos allowing assessment of heart rate and rhythm. The ventricular ectopy diagnosed with the KM device was confirmed with the anesthetized cardiac examination in 1 male bonobo. Similar interpretations of ECG tracings by all 3 evaluators in this study indicate that this technology is accessible to general practitioners, and the tracings produced can be easily shared with specialists for additional interpretation. Assessment of heart rhythm is only 1 component of cardiac assessment. Normal cardiac rhythm does not necessarily exclude underlying structural or functional abnormalities. Therefore, KM technology should be considered part of the toolbox for great ape health monitoring. Echocardiograms and 12-lead ECG should be considered the gold standard for the diagnosis of underlying CVD. The authors recommend institutions housing great apes include training for KM as a routine screening tool for the early identification of subclinical cardiac disease in great apes.

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