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Comparison of the 'PetPace' smart health-monitoring collar to a Holter-ECG in terms of accuracy of heart rate and heart rate variability measurement

Thesis

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submitted by
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Abbreviations

ANS	autonomic nervous system
ARVC	arrhythmogenic right ventricular cardiomyopathy
aVF	augmented Voltage Foot
aVL	augmented Voltage Left
aVR	augmented Voltage Right
bpm	beats per minute
CMPS-SF	Short version of the Glasgow Composite Measure Pain Scale
DP	data points
ECG	electrocardiography
e.g.	exempli gratia (for example)
ETK	Ethics and Animal Welfare Committee
HPA	hypothalamic-pituitary-adrenal
HR	heart rate
HRV	heart rate variability
IASP	International Association for the Study of Pain
ISACHC	International Small Animal Cardiac Health Council
Max	Maximum
Min	Minimum
NN	normal-to-normal (interval of two normal consecutive QRS-complexes, without premature complexes)
NRS	Numerical Rating Scale
OA	osteoarthritis
RSA	respiratory sinus arrhythmia
SAM	sympatho-adrenal-medullary
SD	Standard Deviation
SDS	Simple Descriptive Scale
VAS	Visual Analogue Scale
VVTI	Vasovagal Tonus Index

1 Introduction

Because dogs cannot verbally communicate with humans, veterinarians must rely on the patients' medical history, abnormalities in vital signs like heart rate (HR), respiratory rate and body temperature determined by clinical examination and further diagnostics (e.g. electrocardiography, x-rays, ultrasonography). Many diseases, as well as stressful and painful conditions, can change a dog's behaviour and vital signs (Beerda et al. 1997, 1998, Short 1998, Eberspächer 2017). However, many dogs are generally more stressed in unfamiliar situations and environments, for example when they are examined at a veterinary clinic (Vial et al. 1979, Pagani et al. 1991, Beerda et al. 1997, Höglund et al. 2012, Bragg et al. 2015), which may lead to activation of the sympatho-adrenal-medullary (SAM) and the hypothalamic-pituitary-adrenal (HPA) system, which in turn causes alterations in clinical parameters (Moberg und Mench 2000). This creates the potential for misinterpreting these clinical findings as the body's response to pain or disease. In addition, under these circumstances, it is difficult to correctly interpret a dog's behaviour, especially for inexperienced individuals (Mich et al. 2010, Barletta et al. 2016, Doodnaught et al. 2017), because dogs may reveal their emotions to a lesser extent or act differently in a clinical setting/under observation (Mathews et al. 2014). Unfortunately, behavioural observations are essential for pain assessment (Mathews et al. 2014). There is a need for objectively evaluating and monitoring patients without disturbing them in any way or influencing their natural behaviour and vital signs. Activity monitors might be a solution to this problem. However, to establish a new medical instrument, it is always important to determine the quality of that tool by demonstrating its compliance with a gold standard. Therefore, the aim of this pilot study was to compare heart rate and heart rate variability measured by the smart health-monitoring collar 'PetPace' against the gold standard of HR and HRV measurements, a Holter-ECG. We hypothesised that the obtained data would demonstrate good agreement between the PetPace collar and the Holter-ECG in awake dogs.

1.1 Activity monitors

Activity monitoring appears to be growing in popularity among humans (Piwek et al. 2016) and it is only a matter of time before pet tracking is not only of scientific interest, but also becomes popular among pet owners. The development of small technical devices called accelerometers/activity monitors simplified tracking movements in dogs without the need for watching the animals or taking video recordings. These lightweight tools are usually mounted on collars that are placed around the animal's neck. Therefore, it is possible to detect even minor changes in the dogs' behavioural patterns without disturbing their natural demeanour. Each device uses specific sensors to collect raw acceleration data, which are processed by special algorithms developed by the respective companies and presented as traceable activity measurements. Belda et al. (2018) listed many activity-tracking devices for dogs, but to the author's knowledge, only a few collar-mounted monitors (Tab. 1) have been tested for validity and reliability in measuring physical activity in dogs so far.

Tab. 1. List of available validated activity monitors for dogs modified from Belda et al. 2018.

Activity monitor	Company and website	Validation study
Actical	Actical, Koninklijke Philips N.V., Amsterdam, Netherlands http://www.actigraphy.com/solutions/actical	(Hansen et al. 2007)
Actigraph	ActiGraph wGT3-X+, ActiGraph, LLC, Pensacola, FL, United States https://www.actigraphcorp.com/actigraph-wgt3x-bt/	(Yam et al. 2011, Belda et al. 2018)
Whistle	Whistle, Whistle Labs, Inc, San Francisco, CA, United States https://www.whistle.com	(Yashari et al. 2015)
PetDialog+	Powered by Oggii 3, Oggway Ltd., Tel Aviv, Israel; Partnered with Zoetis, Parsippany, New Jersey, United States https://oggii.com	(den Uijl et al. 2017)

PetPace	PetPace Smart-collar, PetPace, Burlington, MA, United States https://petpace.com/	(Belda et al. 2018, Ortmeyer et al. 2018)
Heyrex	Heyrex Limited, Karori, New Zealand http://www.heyrex.com/en/	(Mejia et al. 2019)

Commercially available activity trackers like PetPace, Whistle, Tractive, FitBark are advertised on their websites as helpful tools for e.g. physical activity analysis (what does my pet do and when – sitting, walking, running, lying), GPS tracking, weight controlling and health monitoring. Zamansky et al. (2019) analysed 81 questionnaires of FitBark users and revealed a couple of reasons for buying activity monitors. The most common reasons have been to track the dog's activity, increasing the overall activity of their dogs and themselves, improving general health, and controlling their unattended dogs when they are home alone. The authors conclude that these devices help people to find the motivation to take the dog out and exercise more (Zamansky et al. 2019). In addition, activity monitors are used for veterinary purposes like measuring physical activity (Dow et al. 2009, Michel und Brown 2011, Yam et al. 2011), estimating daily energy requirements (Michel und Brown 2011, Morrison et al. 2014), identifying pruritus-associated behaviour in allergic dogs (Nuttall und McEwan 2006, Plant 2008, Schwab-Richards et al. 2014, Griffies et al. 2018), detecting seizures in epileptic dogs (Muñana et al. 2020, PetPace. https://petpace.com/common-dog-diseases/epilepsy-in-dog/), assessment and pain management of osteoarthritis (OA) patients (Brown et al. 2010, Scott et al. 2017, Mejia et al. 2019) and estimation of stress levels in shelter dogs (Jones et al. 2014). Beside these scientific purposes, activity monitors may be valid tools for monitoring patients at home (Hansen et al. 2007) and for observing aggressive, anxious or hard to handle dogs at veterinary clinics.

Besides the Voyce sensor (Voyce®, One Health Group/i4C Innovations LLC, Chantilly, Virginia, United States, https://www.voyce.com), which is not available at the moment, the PetPace smart health monitoring collar (Fig. 1) is the only collar that is supposed to provide not only motion data but also real-time information about the dogs' health status. According to the manufacturer, the smart collar offers the possibility to measure non-invasively temperature, heart rate, respiratory rate, activity levels, calories, positions (e.g. sitting, lying, standing) and heart rate variability (PetPace. https://petpace.com/health-dashboard/). The smart collar is advertised as a tool for monitoring a pet's vital signs and warning the owners and potentially the vet when the collected parameters imply illness, stress, pain, or other health-related problems. Thereby the collar analyses the recorded data and concludes whether a changed vital sign is health relevant or not (PetPace. https://petpace.com/smart-sensing-collar/). The website indicates that the PetPace collar is ideal for every dog, no matter what age, breed, or health status; especially old, sick and at-risk pets would benefit from wearing this smart health-monitor. According to the manufacturer, the PetPace collar helps to detect and monitor common dog diseases like skin allergies (by monitoring the dog's activity level and posture patterns) (PetPace. https://petpace.com/common-dog-diseases/how-petpace-helps-dog-skin-allergies/), epilepsy (by determining activity levels and posture, pulse rate, respiratory rate, and temperature) (PetPace. https://petpace.com/common-dog-diseases/epilepsy-in-dog/) and heart disease (by measuring pulse rate, heart rate variability, respiratory rate, and activity levels) (PetPace. https://petpace.com/common-dog-diseases/heart-disease-in-dog/). Furthermore, it possibly supports detecting other diseases, which result in changed vital signs, activity levels, and postures, such as arthritis, gastroenteritis, pancreatitis, cancer, diabetes, etc. (PetPace. https://petpace.com/common-dog-diseases/).

Fig. 1. PetPace smart health monitoring collar around a dog's neck (PetPace. https://petpace.com/smart-sensing-collar/).

Integrated acoustic sensors register acoustic signals from blood flowing through large cervical arteries and count pulse waves at two-minute-intervals. Special algorithms determine the heart rate per minute (Scheinowitz and Lascelles 2017). The respiratory rate is recorded by detecting sinus arrhythmia during heart rate measurement (Ortmeyer et al. 2018). Since respiratory sinus arrhythmia is pulse rate dependent and usually occurs when the dog is relaxed and the pulse rate is below 100 bpm, the collar's respiratory rate detection may not be available at higher pulse rates.

The PetPace collar continuously records the animal's health data and sends them wirelessly to a gateway station at 2-, 15- or 30-minute intervals, depending on the type of subscription. The gateway station is connected to the user's modem via an Ethernet port and thus uploads it to the cloud. In this context, the 'cloud' is an internet-based provision of memory space by the use of the respective host's servers. The data in the cloud can be accessed from any web-enabled device at any time without having to save the files locally on this device.

The collar's measurements are displayed in a user-friendly way on PetPace website or in an app for Apple and Android smartphones. In addition, the app will send an alert if any of the pet's parameters changes to a worrying threshold, so the user can take immediate action. The PetPace collar has already been used in a number of studies to monitor activity and vital function (Ortmeyer et al. 2018, Ortmeyer und Robey 2019, Sundman et al. 2019). Moreover, there are two studies regarding the PetPace's validity. One of them compared the PetPace collar to the previously validated Actical accelerometer by assessing the correlation between the activity data outputs from the two devices. Overall, they found a moderate correlation between the PetPace collar and the Actical accelerometer. But after limiting the Actical activity counts to 50.000 per hour, as the authors of the Actical validation study (Hansen et al. 2007) did, a high correlation between the two activity monitors was noticed (Belda et al. 2018). Belda et. al (2018) did not compare the PetPace collar against the gold standard of activity monitoring (taking video recordings) but justified their study procedures with the fact that it was 'also appropriate to evaluate novel monitors against one that has been validated as a measure of activity in dogs'. The other study from Scheinowitz and Lascelles (2017) concluded, that the PetPace collar could measure HR with high accuracy in anaesthetised dogs by comparing the collar's HR data with the gold standard of HR measurement, an ECG. They ascertained a correlation of 0.68 between the PetPace collar and the ECG and found an overall difference between the heart rates of 5.7 % (± 11.4 %), ranging between -32 % and +26 %. However, this study showed some limitations, including the fact that the animals were under general anaesthesia. Therefore, more research is needed to determine whether the collar can monitor HR and HRV in awake patients as accurately as the gold standard method.

1.2 Electrocardiography

ECG recording is very commonly used as a non-invasive method for objectively measuring HR and HRV, for monitoring anaesthetised patients and for further heart diagnostics, in particular for the diagnosis of cardiac arrythmias. Clinical signs such as collapse, syncope, apathy and audible auscultatory arrhythmia are further indications for performing electrocardiography (Traub 2018).

The cardiac cycle consists of different phases, which are associated with electric voltage variations that can be measured with an electrocardiograph on the body surface. The ECG curve depicts these phases of the cardiac conduction system. The P-wave represents the depolarisation/contraction of the atrium, the QRS-complex the depolarisation/contraction of the ventricles and the T-wave shows the repolarisation/relaxation of the ventricles. The ECG assessment includes analysing the rhythm (sinus rhythm or abnormal rhythm), the heart rate (by counting the R-waves within a minute), the PQ-interval (detecting different types of AV-blocks) and the shape of the QRS-complex. (Harmeyer und Tobias 2010).

1.2.1 Brief historic background

In 1786, long before the invention of modern electrocardiographs, an Italian scientist called Luigi Galvani observed a connection between electric stimulation of the affecting nerve and muscle contraction by observing muscle spasms on a dissected frog leg (AlGhatrif and Lindsay 2012). The physicist Carlo Matteucci also experimented on frog legs and discovered in 1842 that each heartbeat is accompanied by an electrical current (Matteucci 1842, AlGhatrif and Lindsay 2012). The first human electrocardiogram was recorded by Augustus Desiré Waller in May 1887 with a mercury capillary electrometer (invented by Gabriel Lippmann in 1873), but it consisted of only two deflections (Waller 1887, Hurst 1998, Barold 2003). Willem Einthoven also experimented with Lippmann's capillary electrometer and was able to make some improvements to get four deflections instead of two, which he referred to as ABCD. With further research, he created a mathematical formula to correct the curves and generate one additional wave that resulted in labelling them as we know them today, PQRST (Hurst 1998). Einthoven developed the so-called string galvanometer to produce more accurate electrocardiograms and published short reports and detailed articles about his new invention and its ability to record human electrocardiograms (Einthoven 1901, 1902, 1903, Barold 2003, Rivera-Ruiz et al. 2008). To standardise ECG recording, he invented the three-axis, three-lead, bipolar system that is still in use today (Barold 2003). In 1924, he was awarded the Nobel Prize for Physiology and Medicine (Rivera-Ruiz et al. 2008, AlGhatrif and Lindsay 2012). In the following years, Sir Thomas Lewis, Frank Wilson and Dr. Emanuel Goldberger played a key role in the research and development of the ECG (Barold 2003, AlGhatrif and Lindsay 2012). The biophysicist Norman J. Holter developed the first ambulatory electrocardiograph in 1947, which weighed about 40 kg and was therefore not very practical for ambulatory use. Further research and inventions contributed to reducing the weight of the devices and developing improvements in the measurements (Barold 2005, Kennedy 2006). The first Holter-ECG recording was performed in 1954, and a few years later Holter-ECG technology was available to doctors and scientists in collaboration with Bruce Del Mar and Avionics Research Products Corporation (Kennedy 2006). In subsequent years, Holter electrocardiography was continuously developed and improved by many companies (Kennedy 2006).

1.2.2 Holter-ECG

The Holter-ECG is a special type of electrocardiograph. The composition and operating principle are basically the same as in the in-hospital version. The receiving unit is connected to four differently coloured cables (red, yellow, green, black) that are attached to four electrodes, which were previously attached to the dog's body. Compared to the routinely used electrocardiographs at veterinary clinics and practices, the Holter-ECG is a small, lightweight, portable box that allows monitoring the cardiac rhythm over a longer period of time without the need of hospitalisation and immobilisation of the canine patient (Petrie 2005). In the clinical setting it is mainly used to determine the cause of possibly heart-related signs of unknown origin, e.g. syncopes (Miller et al. 1999) and for the detection of special arrhythmias, e.g. in early-stage dilatative cardiomyopathy in Doberman pinschers (Calvert et al. 2000, Wess et al.

2017), or arrhythmogenic right ventricular cardiomyopathy (ARVC) in boxer dogs (Mõtsküla et al. 2013). Additionally, these possibly heart-related signs of unknown origin often do not occur in the short period of time during routine ECG recordings and may therefore be overseen (Petrie 2005, Wess et al. 2010). Further reasons are the assessment of the necessity and effectiveness of antiarrhythmic therapy (Petrie 2005, Gunasekaran and Sanders 2017) as well as the determination of HR (Pedro et al. 2018) and HRV (Stein et al. 1994) over a longer period of time. In our study, we only focused on the HR and HRV measurement.

1.2.3 Heart rate variability and VVTI in particular

The heart rate variability (HRV) is defined as the physiological variation of the time intervals between consecutive heart beats and describes the mammal's ability to autonomously adjust the heart rate in order to adapt to certain circumstances (American Heart Association Inc. 1996). The HR and therefore HRV is mainly regulated by the autonomic nervous system (ANS), which consists of two antagonistic components: the sympathetic and the parasympathetic nervous system. The ANS is influenced by various factors, including the cardiovascular and endocrine system (adrenal hormones), baroreceptors and chemoreceptors, circadian rhythm, stress, pain and psychologic issues (Harmeyer and Tobias 2010). The sympathetic nervous system uses the neurotransmitters adrenalin and noradrenalin to control the affected organs (heart, lacrimal and salivary glands, smooth musculature of blood vessels, bronchi, gastrointestinal tract and urinary tract), while the parasympathetic nervous system acts antagonistically to the same organs mediated by acetylcholine (Diener 2010). The parasympathetic tone predominates when the animal is at rest, has negative inotropic, chronotropic and dromotropic effects on the heart and is associated with a higher HRV (Harmeyer and Tobias 2010, Bergfeld et al. 2015). On the contrary, if the sympathetic nervous system is activated by a physical/psychological stressor or a nociceptive stimulus, positive chronotropic, inotropic, dromotropic and lusitropic effects on the heart are propagated and thus a lower HRV will be observed (Harmeyer and Tobias 2010, Bergfeld et al. 2015). There are many parameters related to HRV and various methods of calculating HRV, which are detailed in the Guidelines on HRV by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology (Task Force of The European Society of Cardiology and The North

American Society of Pacing and Electrophysiology 1996). Shaffer and Ginsberg (2017) also published an overview on HRV Metrics and Norms. A simplified overview is shown in Tab. 2.

Tab. 2. Overview of heart rate variability classification and parameters modified from The European Society of Cardiology and The North American Society of Pacing and Electrophysiology (1996)

Method classification		**HRV parameter examples**
Time domain methods	statistical measures	SDNN, SDANN, RMSSD, etc.
	geometric measures	HRV triangular index, TINN, Differential index, etc.
Frequency domain methods		ultra-low frequency, very low frequency, low frequency, high frequency, total power, etc.
Non-linear methods	Poincaré plots	S, SD1, SD2, ApEn, etc.

The PetPace collar uses the vasovagal tonus index (VVTI) to determine HRV. The VVTI is a time domain heart rate variability parameter, as it is derived from SDNN, which stands for 'standard deviation of the NN interval'. 'NN' refers to normal-to-normal, meaning all intervals between consecutive QRS-complexes in sinus rhythm are included in the calculation. VVTI is predominantly influenced by the parasympathetic nervous system and is therefore dependent on the vagal tone and gives information about high-frequency heart rate variability (Doxey und Boswood 2004). The VVTI is calculated with a simple formula ($VVTI = ln\,(SD_{NN})^2$), which was first mentioned in a veterinary context by Häggström et al. in 1996. To determine the VVTI, the natural logarithm of at least 20 (better 60 or more (López-Alvarez et al. 2014)) consecutive NN-intervals (in milliseconds) is calculated and squared. It is a relatively easy to acquire parameter, since only a short, non-invasive ECG recording is required. A disadvantage would be that it depends on a normal sinus rhythm and if any arrhythmia occurs, a reliable VVTI measurement will be impossible. It is a valuable cardiac parameter as it evidentially decreases in patients with various heart diseases or heart failure (Häggström et al. 1996, Pereira et al. 2008, López-Alvarez et al. 2014) and tends to increase when treatment is effective (Boswood und Murphy 2006). In addition, the VVTI is higher in brachycephalic dogs than in dogs of other breeds, and correlates negatively with the heart rate (Doxey und Boswood 2004).

According to the manufacturer's website, decreased HRV (VVTI) is 'associated with heart diseases, sepsis, diabetes, obesity, and more'. Additionally, they state that reduced HRV could be obtained in humans and lab animals suffering from chronic pain and stress. However, we could not find any studies that confirm the use of the VVTI for pain evaluation in human medicine, but heart rate variability generally tends to be decreased in humans suffering from chronic pain (Tracy et al. 2016) and stress (Kim et al. 2018). PetPace's manufacturer also claims that HRV is 'the first objective, remote, non-invasive, quantifiable marker for pain' (PetPace. https://petpace.com/hrv/).

In 1996, Häggström et al. found a significant correlation between VVTI and HR, cardiac size, and respiratory rate in 81 Cavalier King Charles Spaniels. VVTI was significantly lower in dogs with severe left atrial/ventricular dilatation, suggesting that this parameter is valuable in assessing the severity of mitral valve regurgitation and predicting decompensation. Further studies confirm the correlation between lower VVTI and increasing severity of various heart diseases (Pereira et al. 2008, López-Alvarez et al. 2014) and show a positive correlation between VVTI and survival time in heart failure class 2 and 3 (International Small Animal Cardiac Health Council) dogs (Pereira et al. 2008). In addition, López-Alvarez et al. (2014) proposed to determine VVTI by measuring the RR-intervals of significantly more than 20 consecutive QRS-complexes (e.g. 60 RR-intervals), in order to improve the validity of this biomarker. Unfortunately, this parameter did not serve as an appropriate biomarker for dogs in remission from canine multicentric lymphoma (Pecceu et al. 2017). Despite performing a thorough literature research, we did not find any studies demonstrating the utility of VVTI in assessing pain in dogs. Few studies could be found that looked at different heart rate variability parameters and pain. Hezzell et al. (2018) identified the number of animals required to conduct a study to verify the theory of decreased HRV in painful dogs. Another study investigated the effects of isoflurane with and without dexmedetomidine/remifentanil on HRV before and after nociceptive stimuli in six beagle dogs and questioned the usefulness of SDNN as a nociceptive indicator (Voigt et al. 2013). Bergfeld et al. (2015) concluded that the shortening of the RR-intervals is a potential indicator for nociception in anaesthetised dogs, but other

HRV-parameters appeared to be inadequate. Therefore, the utility of the VVTI as an appropriate pain indicator should be investigated in future studies.

1.3 Pain assessment

Since painful conditions in dogs are associated with lower activity levels, higher HR, lower HRV and changes in other physiologic parameters (Short 1998), pain assessment may be a potential purpose for using a smart health monitoring collar like PetPace. Currently, there is no satisfactory gold standard for measuring pain in veterinary medicine. It is still difficult to tell whether a dog is in pain or not because of its individual subjective character.

The International Association for the Study of Pain (IASP) defined human pain as *'An unpleasant sensory and emotional experience associated with actual or potential tissue damage or described in terms of such damage.'* (International Association for the Study of Pain). Today there is no doubt, that animals are able to feel pain. Therefore, there is a need to reliably recognise pain in animals in order to choose the right treatment and help them decrease their sensory and emotional suffering. As a result, in recent years, observing an animal's behaviour for pain assessment has been established as the method of choice (Mathews et al. 2014, Epstein et al. 2015), and several tools have been invented to make it easier and more objective. Various typical behavioural changes in painful dogs have been identified (e.g. posture, facial expressions, responses to palpation of a painful area, changes in appetite, and changes in human interaction) (Mathews et al. 2014) and possible factors affecting the perception of pain intensity, such as age and breed (Mathews et al. 2014, Reid et al. 2018) and even individual variations (Reid et al. 2018). With the introduction of simple uni-dimensional scales like the Simple Descriptive Scale (SDS), Visual Analogue Scale (VAS) and Numerical Rating Scale (NRS), the severity of pain could be assessed subjectively on a scale from pain-free to maximum pain based on the observer's estimation (Reid et al. 2018). However, studies by Holton et al. revealed a great variability of the estimated pain levels depending on the observer when using the uni-dimensional scales (Holton et al. 1998a, 1998b). A lack of standardisation, limited response options and no further details on the need for treatment are additional limitations (Reid et al. 2018). Multiparametric pain scales appear to be superior to the uni-dimensional scales in assessing pain because they provide more detailed response options and indicate whether intervention is required. At the moment there are five scales available for dogs to evaluate acute/postsurgical pain (Reid et al. 2018), which are listed in Tab. 3.

Tab. 3. Multiparametric pain scales for the assessment of acute pain in dogs modified from Reid et al. 2018.

Pain Scale	Validation study
University of Melbourne Pain Scale	(Firth und Haldane 1999)
Glasgow Composite Measure Pain Scale (CMPS)	(Holton et al. 2001)
Short version of the Glasgow Composite Measure Pain Scale (CMPS-SF)	(Reid et al. 2007)
4A-Vet	(Holopherne-Doran et al. 2010)
Colorado State Canine Acute Pain Scale	(not validated)

Although multiparametric pain scales are not as susceptible to personal influence as the uni-dimensional ones, the risk of variability between observers and inadequate pain management remains (Reid et al. 2018). In consequence, there is a need for tools that will enable an even more objective assessment of appropriate signs of acute pain in dogs. With that in mind, the PetPace collar might potentially fill that void.

1.4 Hypothesis

The aim of this study was to compare the heart rate and heart rate variability (VVTI) measurement of the PetPace smart health monitoring collar with the current gold standard, the Holter-ECG, to prove the validity of the collar's health parameters in order to reliably use it for clinical purposes. We hypothesised that the two methods would show good agreement in HR and HRV measurement.

2 Material and Methods

The study protocol was approved by the Ethics and Animal Welfare Committee (ETK) of the University of Veterinary Medicine, Vienna, and a written owner consent (see appendix) was obtained after full explanation of the study.

2.1 Study animals

Ten healthy dogs that belonged to employees of the Department of Anaesthesiology and Perioperative Intensive Care Medicine Unit at the University of Veterinary Medicine Vienna were enrolled in this study. Dogs were recruited after ensuring that all dogs were eligible for a ‘medium’ PetPace collar (neck circumference between 26–46 cm, body weight between 10–28 kg). The dogs were considered healthy by the owners and all dogs were used to wearing a neck collar and/or a chest harness and remaining in their owner’s office. Therefore, the participants were not unnecessarily stressed due to an unfamiliar study setting. The dogs stayed in the office during data collection (approximately 4 hours) and could do anything that came to their mind, like lying, standing, or walking around. They had free access to fresh water at any time.

2.2 Device setup

First, a new user account was created on the PetPace website, the gateway was plugged in and connected to the internet via the router at Anaesthesia Unit. Two medium-sized PetPace collars were set up and all dogs were randomly assigned to one of both collars. The specific information of the dogs (age, breed, name, sex, weight) was only stored on local computers due to data protection reasons. Prior to data collection, each dog was instrumented with a PetPace activity-monitoring collar according to the manufacturer’s instruction (PetPace. http://petpace.com/knowledge-base/basic-installation/). When putting it on, care was taken that the sensor was positioned ventrally on the neck and that there were at least two finger widths between the neck and the collar. Then the collar was turned on by pressing the ON/OFF button. The collar immediately started collecting data and automatically communicated with the gateway station.

After installing the PetPace collar, a Holter-ECG (Televet 100, Kruuse, Langeskov, Denmark) was applied. For this purpose, four ECG electrodes were attached to the dog's body: one electrode to the right and to the left of the chest at heart level, and one to the right and to the left between the last rib and knee crease approximately at the level of the greater trochanter. In order to improve the contact with the body surface and to ensure a more accurate measurement, even when the dog was moving, ultrasonic gel (Ultrasound Gel 500ml, Gello GmbH Geltechnik, Ahaus, Germany) was applied to each electrode and the electrode was additionally secured with adhesive tape (3M Durapore®, 3M Deutschland GmbH, Neuss, Germany). Then the telemetric ECG recording device 'Televet 100' (Kruuse, Langeskov, Denmark) was connected. In addition, the ECG recording device and the electrode cables were attached to a chest harness the dog was wearing so that the dog could move freely. A fully instrumented dog is shown in Fig. 2. The ECG recordings were sent directly to the computer via Bluetooth. After 4 hours of data collection both devices were removed from the dogs. No side effects were observed in any dog during the study procedures.

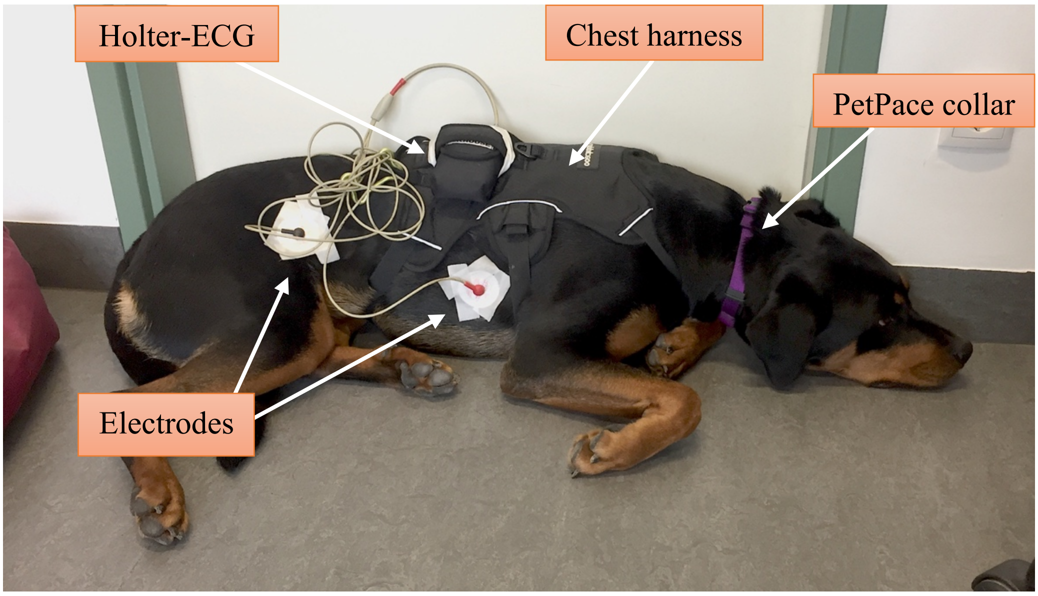


Fig. 2. A dog instrumented with a PetPace collar and a Holter-ECG.

2.3 Data collection and processing

We set the collection intervals of the PetPace collars to two minutes. The data were automatically transferred from the collar to the gateway station, which was connected to the internet and uploaded the recorded data to the cloud-based server. After logging in to the user account on PetPace's website (PetPace. https://petpace.com), it was possible to manage all collars, register new pets, look at summaries of the pet's activity and health parameters and view the different charts. We only focused on the HR and HRV charts. The data for each dog were downloaded separately from the website as CSV-files and converted into Excel-files (Microsoft® Excel, Microsoft Corporation, Redmond, Washington, USA).

We used Televet software (ECG Software Version 7.0.0, Engel Engineering Service GmbH, Heusenstamm, Germany) to manually mark each R-wave throughout the ECG recordings of all 10 dogs post hoc and export the RR-intervals to a text file. The Televet software surface is shown in Fig. 3.

Fig. 3. Televet software surface. ECG recording with six leads (Einthoven leads I, II, III and Goldberger leads aVL, aVR, aVF). The R-waves are marked with vertical black dotted and red lines.

To calculate mean HR and HRV, we used Kubios software (Kubios HRV standard, Kubios Oy, Kuopio, Finland), whose software surface is shown in Fig. 4.

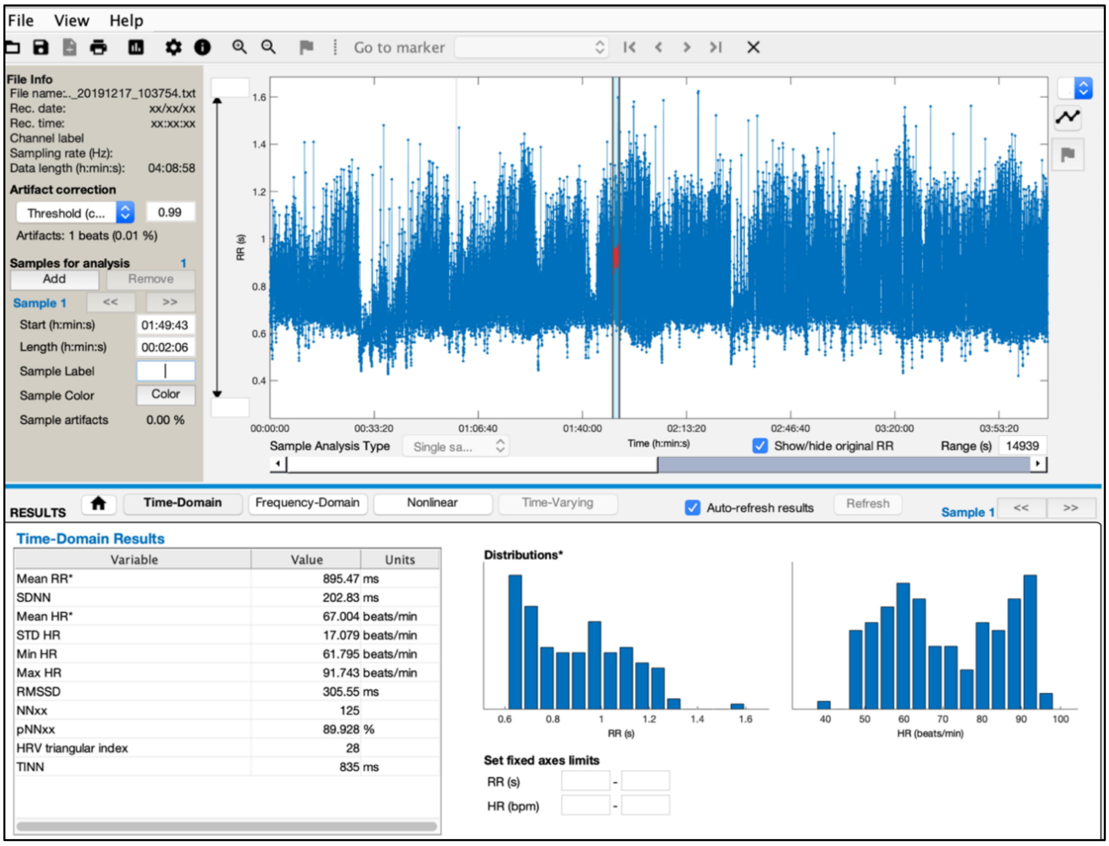


Fig. 4. Kubios software surface. At the top left are two boxes to insert start time and interval length. At the bottom left are the automatically calculated results for each specific time interval. In the ‘Time Domain Results’ column are the two parameters (SDNN, Mean HR) we used for further calculations.

Since it was not possible to start the HR and HRV measurements of the PetPace collar and the Holter-ECG simultaneously, we had to manually synchronise the data of the two methods with Kubios software in order to compare them accurately. Therefore, after importing the Televet files in Kubios we defined start time and time interval length for each measured data point of the PetPace collar. Kubios automatically provided all relevant time-domain, frequency-domain and nonlinear parameters. The two time-domain variables ‘Mean HR’ (Mean heart rate) and ‘SDNN’ (Standard deviation of the NN intervals) for each time interval from the ECG recording of each dog were downloaded into an Excel-chart and VVTI was calculated according to Häggström et al. (1996) with the formula: $VVTI = \ln(SDNN^2)$.

2.4 Sensitivity calculation

The sensitivity of a measuring instrument provides information about how accurate its measurements correspond to those of the gold standard. The sensitivity of the PetPace collar was calculated with the following formula modified from Parikh et al. (2008):

$$\text{Sensitivity} = \frac{\text{number of data points with} \leq 10\ \%\ \text{deviation}}{\text{number of data points with} \leq 10\ \%\ \text{deviation} + \text{number of data points with} > 10\ \%\ \text{deviation}}$$

2.5 Statistical analysis

The statistical analysis was performed using the NCSS 2020 software (NCSS 2020 v20.0.1., NCSS LLC, Utah, United States) and Microsoft Excel (Microsoft® Excel, Microsoft Corporation, Redmond, Washington, USA). Descriptive statistics were used to describe and summarise HR and HRV data. Data were tested for normality using a Shapiro-Wilk test and is presented as mean ± standard deviation (SD) or as median and minimum and maximum. Paired Student's t-tests and Bland-Altman plots were used to determine the accuracy of the PetPace's HR and HRV detection compared to the ECG measurements. Statistical significance was assumed at $p < 0.05$ for all tests.

3 Results

Six dogs were medium-sized mixed breeds (60 %), the other four included Golden Retriever, Rottweiler mix, Rhodesian Ridgeback and American Cocker Spaniel. There were six spayed females, one non-spayed female and three castrated males. Ages ranged from 1.9 to 14.9 years (mean age 9.17 years ± 4.67) and body weights were within the recommended range for the medium-sized PetPace collar (10–28 kg).

The data acquisition time ranged from 3 hours 30 minutes to 4 hours 30 minutes resulting in 593 data points each for HR and VVTI from the PetPace collars. In two dogs some ECG data were missing for unknown reasons. As a result, there were a total of 507 heart rate data points and 507 VVTI data points included for comparison with the Holter-ECG data. During the ECG recording time, the maximum possible amount of data points the PetPace collar should have collected (with the collection time set to two minutes) would have been 1163. This means 50.97 % of the potential data points have been obtained and the collar did not collect 570 data points for incomprehensible reasons. An overview of the data obtained by the PetPace collar can be found in Tab. 4.

Tab. 4. Data points obtained by PetPace of all ten dogs in absolute numbers and percentages.

	absolute numbers	**% of potential data points**
Total data points	593	50.97
Potential data points	1163	100
Comparable data points	507	43.59
Minimum obtained by one dog	24	19.92
Maximum obtained by one dog	104	80.54
Mean per dog (± SD)	59 (± 24.42)	50.97 (± 20.07)

SD = standard deviation

Overall, the mean HR and VVTI measured by the PetPace collar was 61 beats/minute (bpm) (39–165, SD 13.58) and 11.50 (8.89–12.3, SD 0.46), respectively. The mean HR from ECG recordings was 62 bpm (38–138, SD 11.88) and mean VVTI was 11.35 (5.86–12.89, SD 0.78). HR and VVTI are shown in detail in Tab. 5. The parameters of the PetPace collar compared to the Holter-ECG of each individual dog are listed in Tab. 6.

Tab. 5. Mean HR and VVTI measured by PetPace and Holter-ECG, SD, Minimum and Maximum of HR and VVTI of all ten dogs.

Method	Parameter	Mean	SD	Min	Max
PetPace	HR (beats/minute)	61	13.58	39	165
ECG		62	11.88	38	138
PetPace	VVTI	11.50	0.46	8.89	12.3
ECG		11.35	0.78	5.86	12.89

SD = standard deviation, **Min** = Minimum, **Max** = Maximum

Tab. 6. Obtained data points and potential data points of PetPace, mean HR and VVTI, SD, Minimum and Maximum of HR and VVTI of the individual dogs measured by PetPace and the Holter-ECG.

			HR			VVTI		
Dog ID	**Method**	**Data points (Potential DP)**	**Mean ± SD**	**Max**	**Min**	**Mean ± SD**	**Max**	**Min**
1	PetPace	76 (101)	44 ± 3	54	41	11.71 ± 0.25	12.17	11.09
	ECG		45 ± 5	65	38	11.72 ± 0.3	12.30	11.11
2	PetPace	43 (115)	59 ± 1	59	58	11.73 ± 0.16	11.89	11.57
	ECG		64 ± 2	66	62	11.65 ± 0.11	11.76	11.55
3	PetPace	24 (121)	67 ± 24	165	54	11.47 ± 0.37	11.83	10.06
	ECG		69 ± 8	86	55	10.53 ± 1.52	11.52	5.86
4	PetPace	73 (122)	55 ± 6	74	39	11.79 ± 0.26	12.30	10.92
	ECG		59 ± 7	84	51	11.80 ± 0.48	12.44	10.04
5	PetPace	104 (129)	67 ± 20	136	41	11.28 ± 0.72	12.24	8.89
	ECG		54 ± 6	88	45	11.42 ± 0.54	12.33	9.46
6	PetPace	55 (113)	54 ± 6	69	43	11.80 ± 0.21	12.16	11.21
	ECG		62 ± 7	81	51	12.04 ± 0.35	12.89	11.27
7	PetPace	36 (116)	71 ± 8	85	54	11.39 ± 0.22	11.78	10.84
	ECG		82 ± 10	117	68	11.14 ± 0.38	11.73	9.90
8	PetPace	30 (111)	60 ± 5	68	47	11.44 ± 0.28	11.88	10.84
	ECG		59 ± 6	75	47	11.35 ± 0.5	12.31	10.36
9	PetPace	78 (117)	59 ± 7	81	45	11.61 ± 0.2	12.00	10.97
	ECG		60 ± 12	138	49	11.43 ± 0.66	12.17	8.29
10	PetPace	74 (119)	65 ± 6	85	47	11.17 ± 0.26	11.70	10.63
	ECG		72 ± 5	97	65	10.39 ± 0.5	11.17	8.79

HR = heart rate (beats/minutes), **VVTI** = Vasovagal tonus index, **DP** = data points, **Potential DP** = Maximum possible data points that could have been collected during ECG recording time with the PetPace collection interval set to two minutes, **Min** = Minimum, **Max** = Maximum

3.1 Comparison of HR between PetPace and Holter-ECG

According to a paired Student's t-test, there was no statistically significant ($p = 0.182$) difference between the PetPace collar HR ·(61 ± 13.58 bpm) and the Holter-ECG HR (62 ± 11.88 bpm). Fig. 5 and 6 show the relationship between the HR of all ten dogs obtained by PetPace and Holter-ECG. The correspondence of the HR of each individual dog is shown in Fig. 7. The graph of Dog 2 differs from the graphs of the other dogs, because some ECG-data were missing and therefore only two data points for each, HR and VVTI, could be used for comparison. This resulted in two straight lines in the graphs of Dog 2 in Fig. 7 and 11.

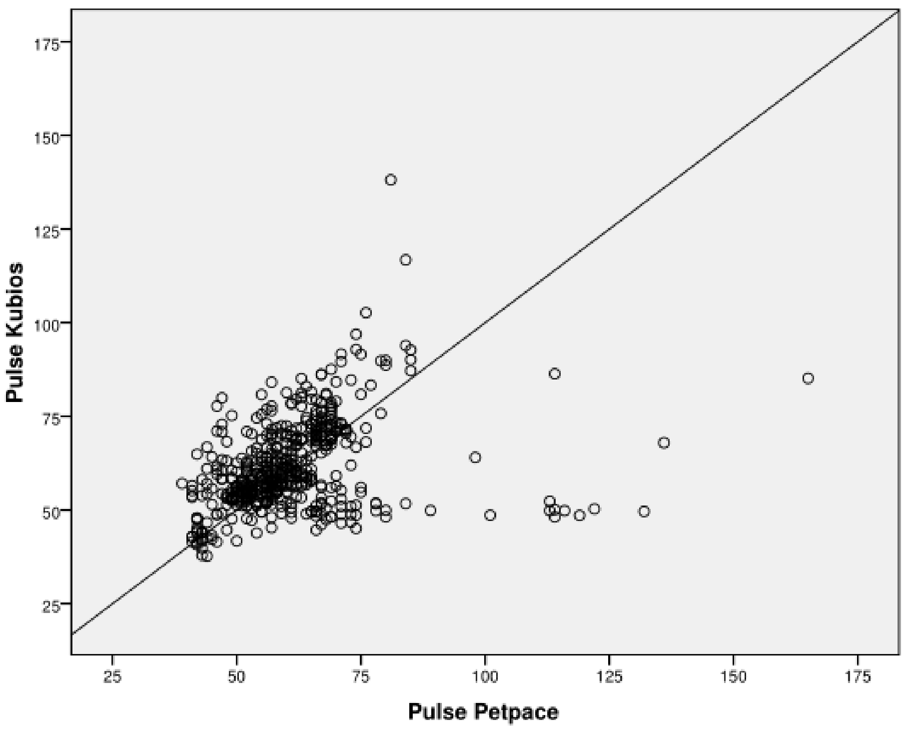


Fig. 5. Scatterplot of the heart rates recorded by PetPace (x-axis) and Holter-ECG (y-axis) with identity line.

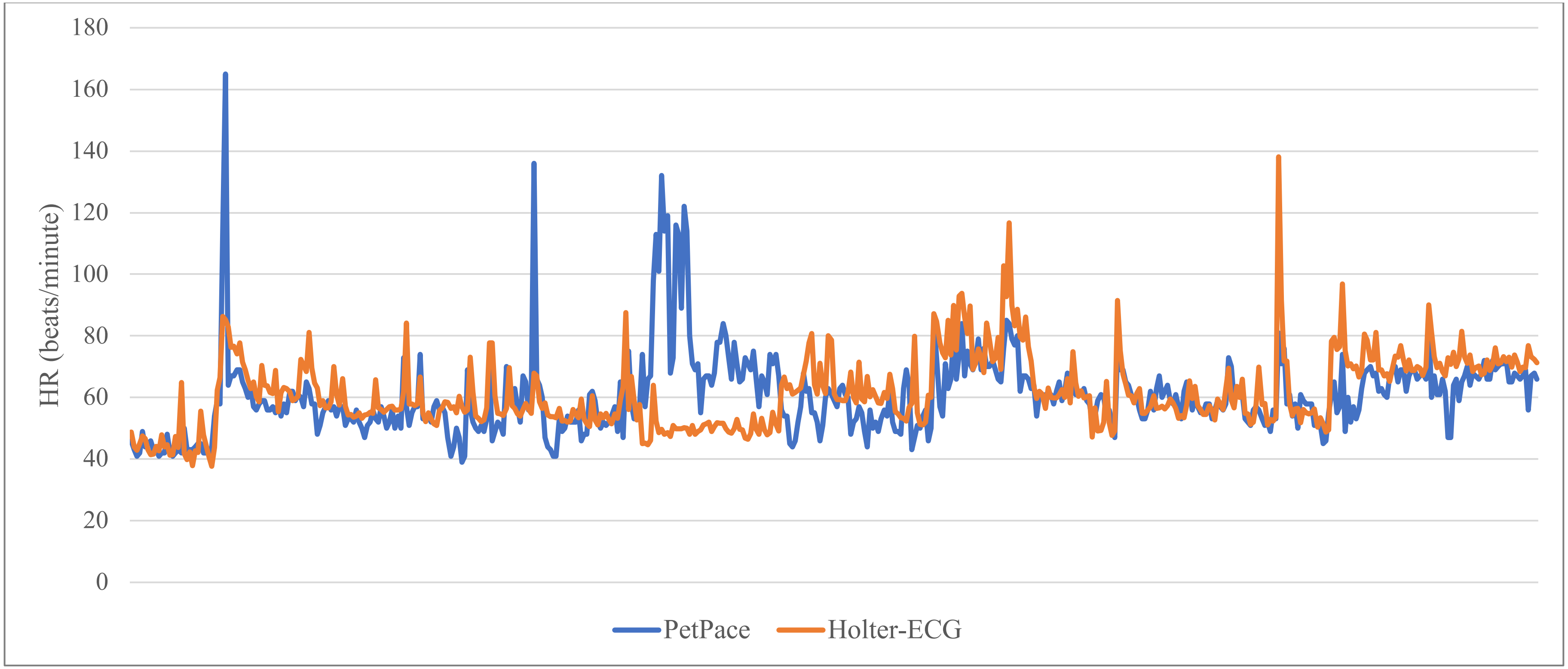
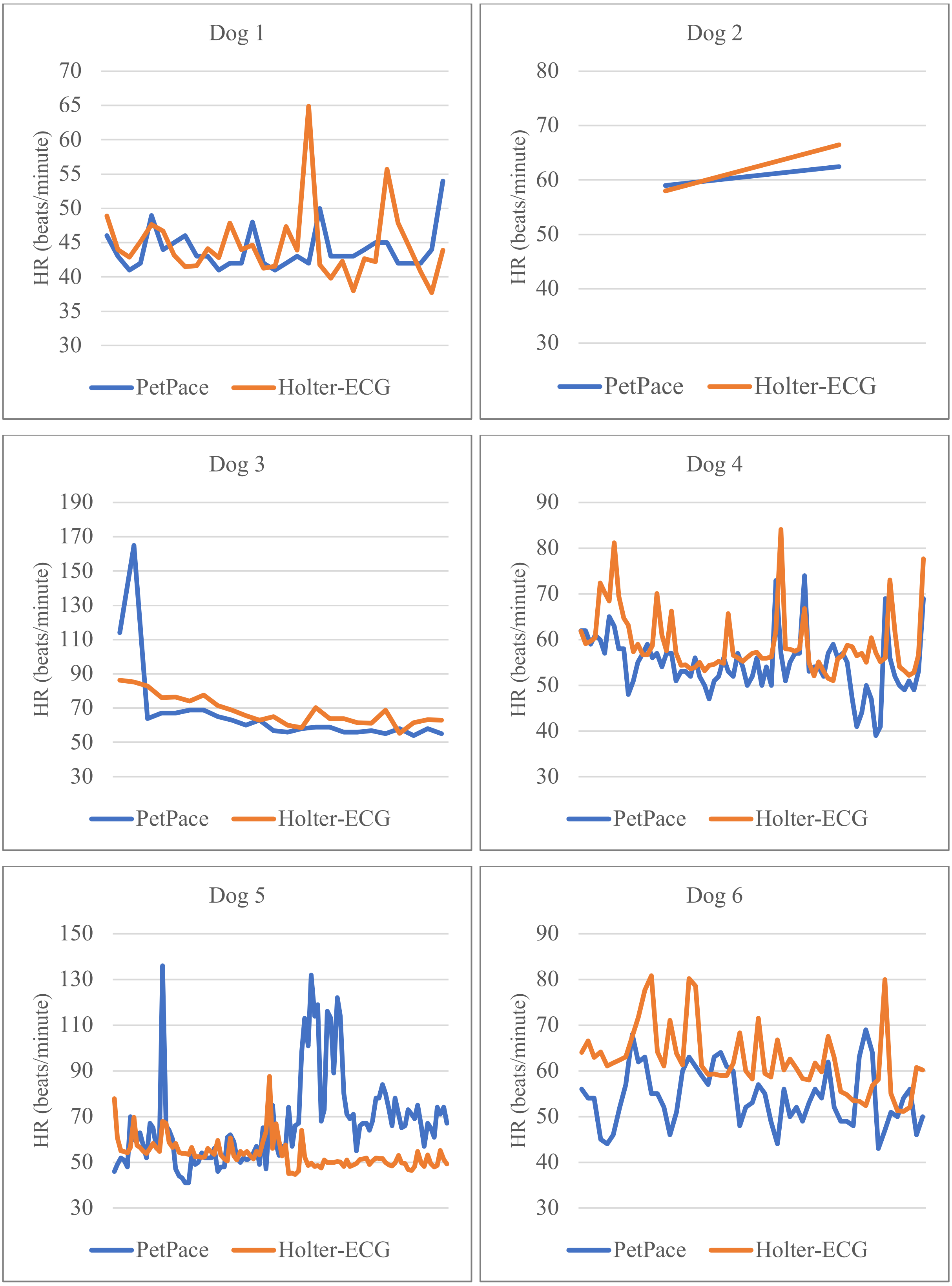


Fig. 6. The heart rates of all ten dogs recorded with the PetPace collar (blue line) compared to the Holter-ECG (orange line). The y-axis represents the heart rate in beats/minute. There is higher agreement between the two methods when the two lines are superimposed. Diverging lines mean poorer agreement.


Dog 1
70
65
60
55
50
45
40
35
30
HR (beats/minute)
PetPace
Holter-ECG
Dog 2
80
70
60
50
40
30
HR (beats/minute)
PetPace
Holter-ECG
Dog 3
190
170
150
130
110
90
70
50
30
HR (beats/minute)
PetPace
Holter-ECG
Dog 4
90
80
70
60
50
40
30
HR (beats/minute)
PetPace
Holter-ECG
Dog 5
150
130
110
90
70
50
30
HR (beats/minute)
PetPace
Holter-ECG
Dog 6
90
80
70
60
50
40
30
HR (beats/minute)
PetPace
Holter-ECG

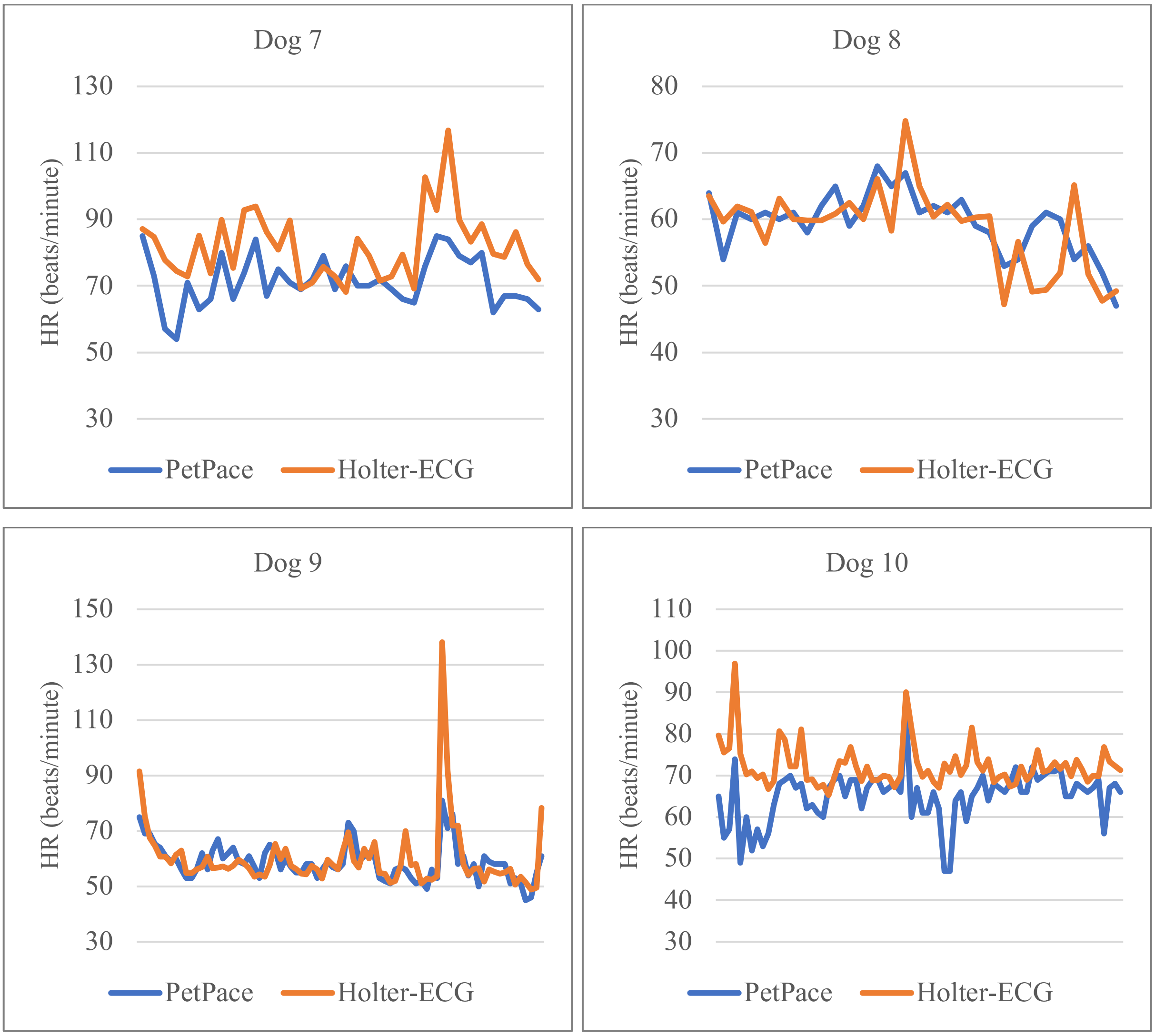


Fig. 7. The heart rates of every individual dog recorded with the PetPace collar (blue line) compared to the Holter-ECG (orange line). The y-axis represents the heart rate in beats/minute. As in Fig. 6 overlapping lines indicate a better agreement between PetPace and Holter-ECG. Dogs 5, 6 and 10 seem to have poorer agreement. Only a few statistical outliers can be identified with both methods. Missing ECG-data of Dog 2 led to only two comparable HR data points, which resulted in two straight lines.

The Bland-Altman plot (Fig. 8) shows an average difference between the PetPace collar measurements and the Holter-ECG of -0.88 (± 14.87) bpm. This means that the Holter-ECG measures an average of 0.88 bpm higher than the PetPace collar.

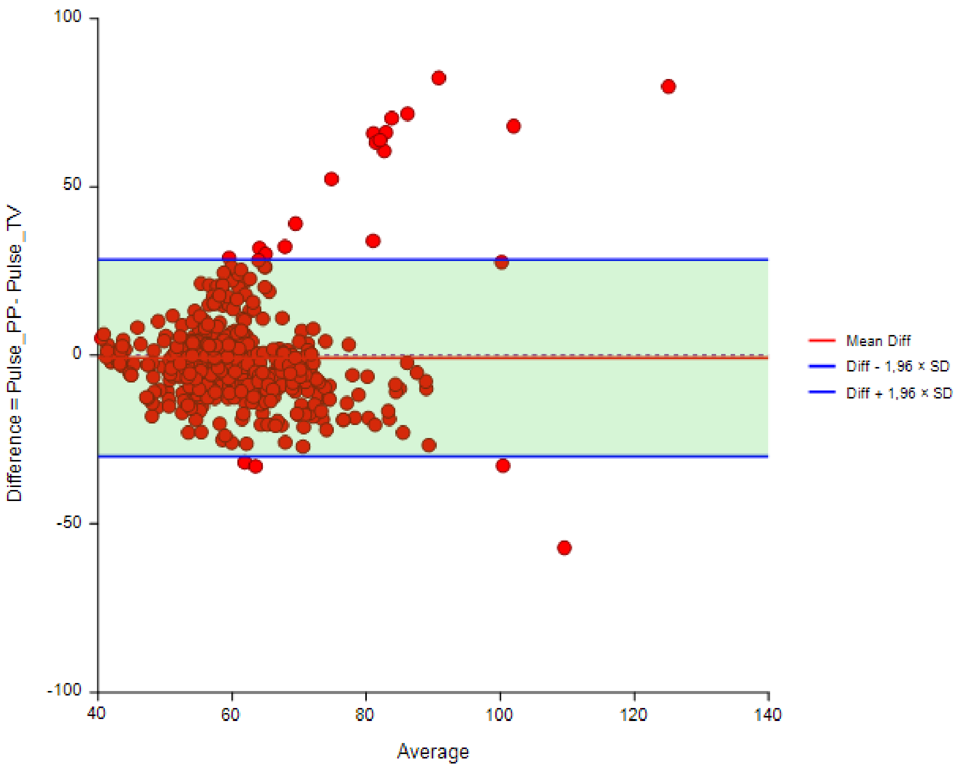


Fig. 8. A Bland-Altman plot of the PetPace collar and Holter-ECG HR measurements. The x-axis represents the mean of the heart rates of the two methods ($\frac{HR\ PetPace\ +\ HR\ Holter\text{-}ECG}{2}$), the y-axis represents the difference between the heart rates of the two methods (*HR PetPace - HR Holter-ECG*). The black dotted line (parallel to the x-axis) is the zero line, where no difference in measurements can be determined. The two blue lines are the limits of agreement, which are the *mean difference ± 1.96 x SD* (+28.27 and -30.03). 95 % of all data points are within these limits of agreement. The red line (parallel to the x-axis and the zero line) shows the actual mean difference of all measurements between the two methods, which in our case is at y = -0.88, which means that on average the Holter-ECG detects 0.88 bpm more than the PetPace collar.

When comparing PetPace's HR with the Holter-ECG HR measurements, 53.06 % of the data points show a deviation of less than 10 % from the Holter-ECG HR, 77.12 % a deviation of less than 20 %. 22.88 % of PetPace's HR values differ more than 20 % from Holter-ECG measurements. The sensitivity indicates a correct HR measurement in 53.06 % of all data points with the PetPace collar compared to the Holter-ECG.

3.2 Comparison of VVTI between PetPace and Holter-ECG

A statistically significant ($p < 0.001$) difference between the VVTI of the PetPace collar (11.50 ± 0.46) and the Holter-ECG (11.35 ± 0.78) was found using a paired Student's t-test. The relationship between the VVTI obtained by PetPace and Holter-ECG is shown in Fig. 9 and 10. The correspondence of the VVTI measured by the two methods of each individual dog is shown in Fig. 11.

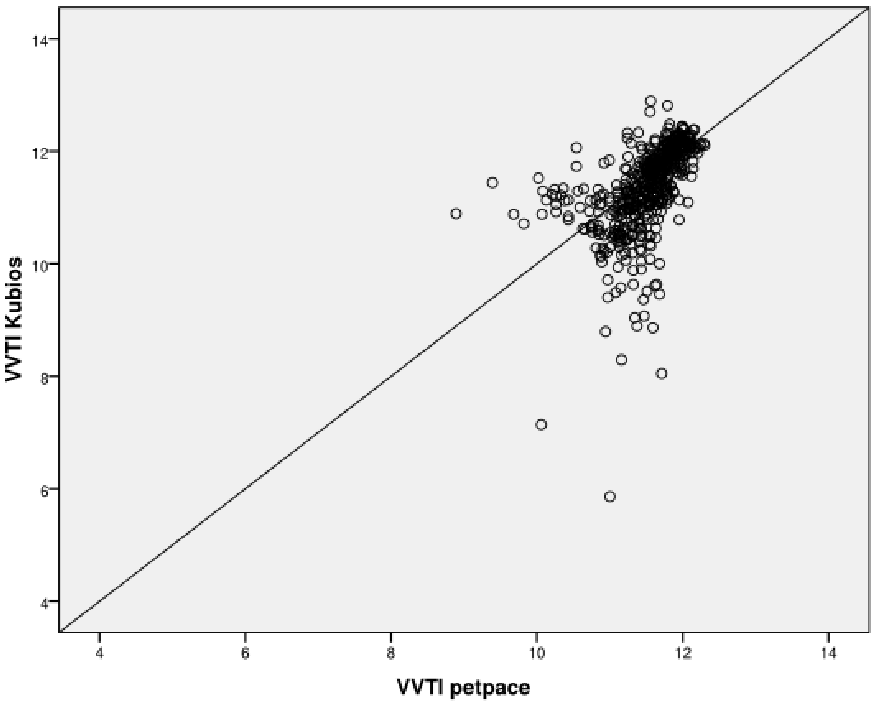


Fig. 9. Scatterplot of VVTI measured by PetPace (x-axis) and Holter-ECG (y-axis) with identity line.

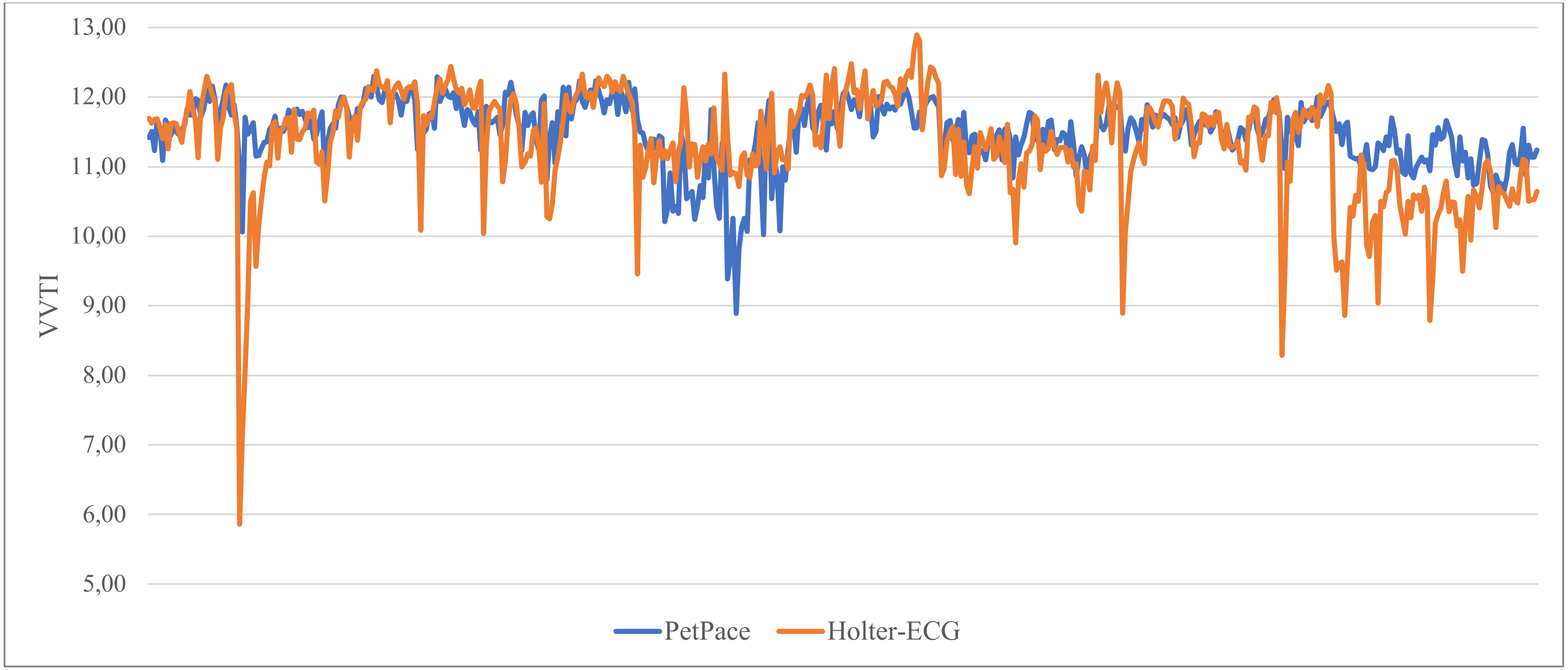
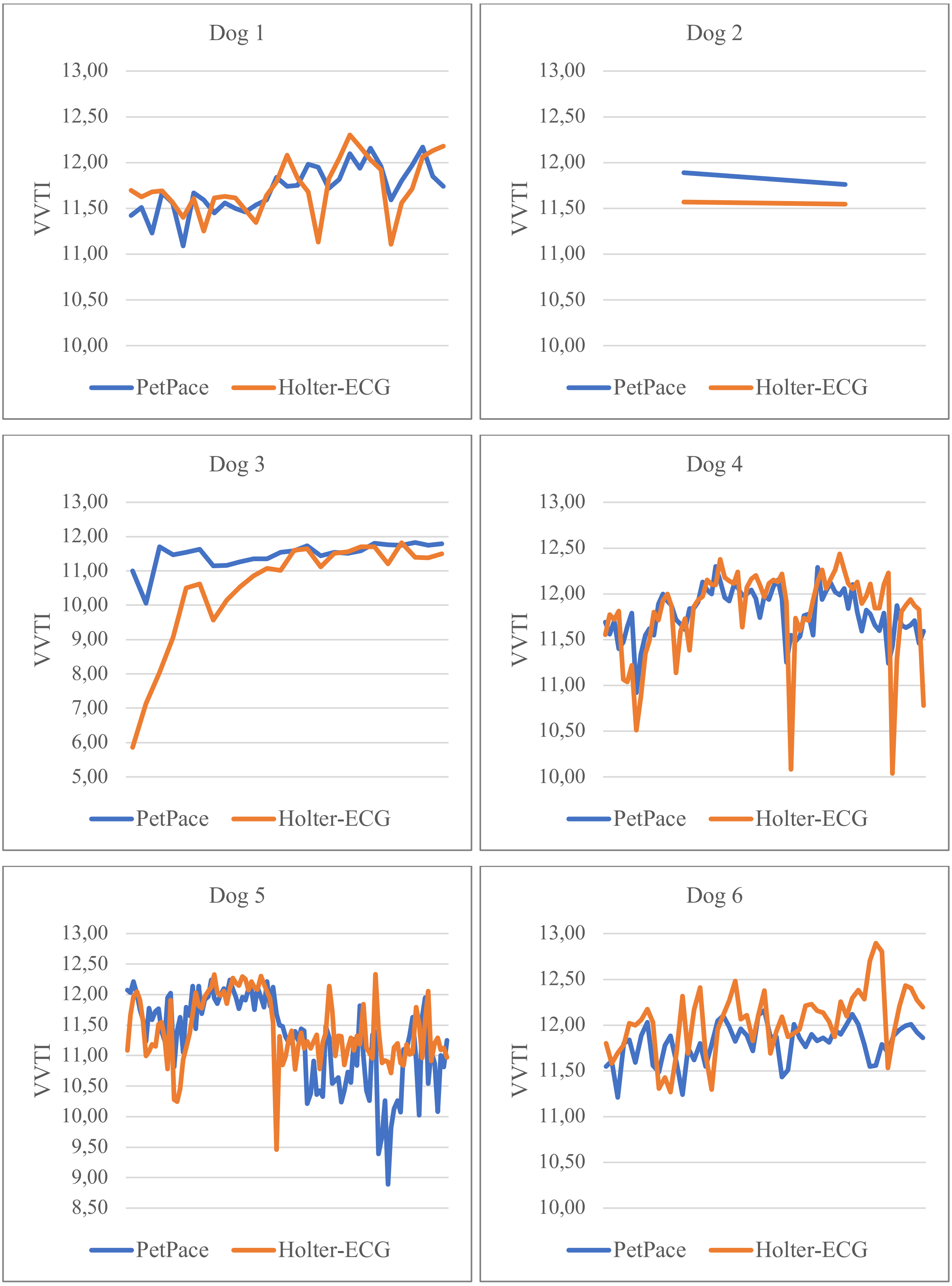


Fig. 10. The VVTI of all ten dogs recorded with the PetPace collar (blue line) compared to the Holter-ECG (orange line). The y-axis represents the VVTI. As in Fig. 6 and 7, the more the lines are superimposed, the higher is the agreement between the two methods.


Dog 1
13,00
12,50
12,00
11,50
11,00
10,50
10,00
VVTI
PetPace
Holter-ECG
Dog 2
13,00
12,50
12,00
11,50
11,00
10,50
10,00
VVTI
PetPace
Holter-ECG
Dog 3
13,00
12,00
11,00
10,00
9,00
8,00
7,00
6,00
5,00
VVTI
PetPace
Holter-ECG
Dog 4
13,00
12,50
12,00
11,50
11,00
10,50
10,00
VVTI
PetPace
Holter-ECG
Dog 5
13,00
12,50
12,00
11,50
11,00
10,50
10,00
9,50
9,00
8,50
VVTI
PetPace
Holter-ECG
Dog 6
13,00
12,50
12,00
11,50
11,00
10,50
10,00
VVTI
PetPace
Holter-ECG

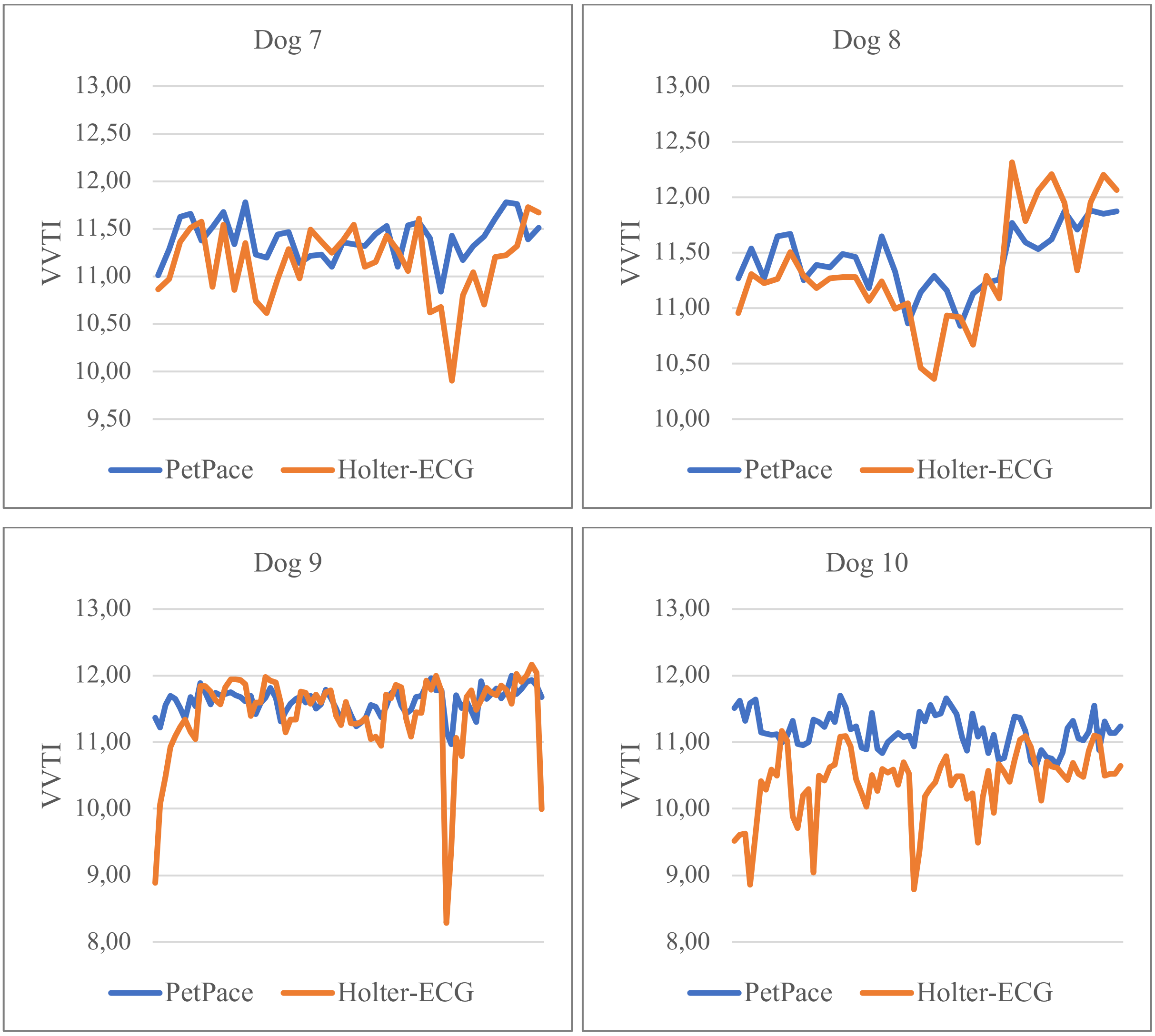


Fig. 11. The VVTI of each individual dog recorded with the PetPace collar (blue line) compared to the Holter-ECG (orange line). The y-axis represents the VVTI. Like the HR measurements, the VVTI measurements of dog 5, 6 and 10 seem to have poorer agreement between the two methods. As in Fig. 7, Dog 2 had only two comparable VVTI data points due to missing ECG-data, which resulted in two straight lines.

By using a Bland-Altman plot (Fig. 12), the mean difference between the VVTI calculated by the PetPace collar and the Holter-ECG is 0.15 ± 0.68. This means that the PetPace collar measures an average of 0.15 higher VVTI than the Holter-ECG.

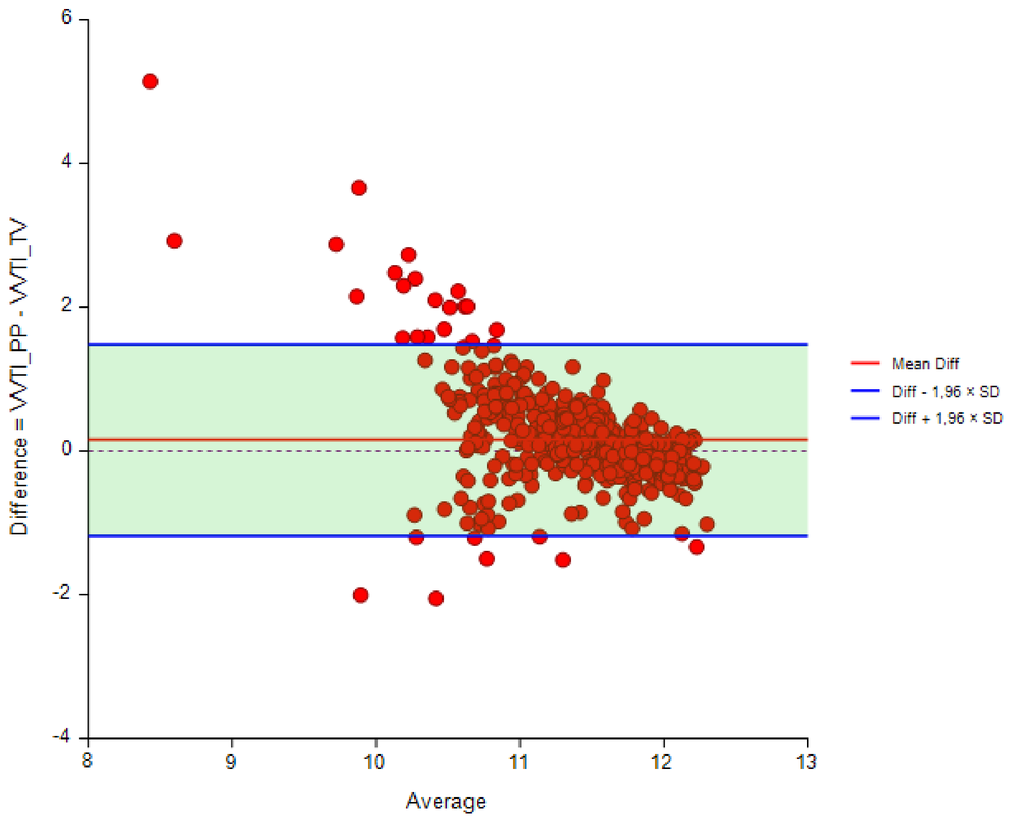


Fig. 12. Bland-Altman plot of the VVTI measurements of PetPace and Holter-ECG. The x-axis represents the mean VVTI of the two methods ($\frac{VVTI\ PetPace\ +\ VVTI\ Holter\text{-}ECG}{2}$), the y-axis represents the difference between the VVTI values of the two methods (*VVTI PetPace - VVTI Holter-ECG*). As in Fig. 8 the black dotted line is the zero line. The limits of agreement are at -1.18 and 1.48 (95 % of all VVTI data points are within these lines). The mean difference in VVTI measurements is at y = 0.15, which indicates, that the PetPace collar measures, on average, 0.15 higher VVTI than the Holter ECG.

4 Discussion

The PetPace Smart Collar is the only available health monitoring collar that, in addition to motion tracking, which is already offered by several other manufacturers, provides information on heart rate, respiratory rate, heart rate variability and body temperature. Two validation studies have been carried out so far. Belda et al. (2018) have proven the validity of the PetPace collar regarding the accuracy of its movement data by comparing it with the validated Actical accelerometer. They did not use the current gold standard (taking video recordings or observing the dog) of activity monitoring as their reference method. In our opinion, the comparison with a validated accelerometer does not seem sufficient to reliably validate another activity monitor but must be compared with an accepted gold standard method. Perhaps it would have been better if they additionally took video recordings of the dogs and compared the three activity monitors against each other and the current gold standard method. The second study on the validity of PetPace by Scheinowitz and Lascelles (2017), who compared the PetPace collar's HR measurements to the gold standard (ECG), found a clinically negligible overall difference in HR between PetPace and their reference method of 5.7 % (± 11.4 %), ranging between -32 % and +26 %, in anaesthetised dogs and cats. In addition, they found a correlation between the two methods of 0.68 and a Bland-Altman plot showed that most data points were within +/- 1 and 2 standard deviations.

In order to demonstrate the accuracy of the PetPace collar's HR detection in conscious dogs, whose behaviour is not influenced in any way, the aim of our study was to compare the data output of PetPace with the measurements of a Holter-ECG, the gold standard method of determining HR and HRV in dogs.

In order to introduce a new medical instrument, it is always important to determine the quality of that tool by demonstrating its compliance with the gold standard. According to Zaki et al. (2012), various statistical methods have been used in method comparing studies. The most frequently used methods in medicine, in descending order, were Bland-Altman Limits of Agreement, correlation coefficient (r), comparison of means/significant test, intra-class correlation coefficient, and comparison of slopes and/or sections. The most popular method, the Bland-Altman plot, was implemented in 1983 (Altman and Bland 1983). They claimed that their method of determining agreement between two different instruments was superior to other statistical calculations and coefficients. For example, they stated that the calculation of the

correlation coefficient *r* is sometimes misleading when determining the agreement between two methods of clinical measurement, because the correlation coefficient depends on the variation between and within individuals (Altman and Bland 1983) and evaluates only the linear association of two sets of observations (the closer it is to +1.0 or -1.0, the higher the linear relationship is). As a result, it depends on the choice of subjects and does not always reflect the degree of agreement (Altman and Bland 1983). Nevertheless, when comparing two different methods, there will always be deviations in the measurement results. However, what matters is how close the two values are to each other and whether this has consequences for clinical decisions or whether the two methods are possibly interchangeable (Bland and Altman 1999).
Using Bland-Altman plots, our study shows that the mean difference between the PetPace collar and the Holter-ECG HR measurement was 0.88 bpm. 95 % of the differences were within 2 standard deviations (between -30 and +28 bpm). A mean difference of less than one bpm does not seem to be clinically relevant. Additionally, no statistically significant difference between the mean values of both methods was found with a paired Student's t-test. Hence, we came to the conclusion that the PetPace collar's HR measurement is accurate enough to be used as a clinical parameter.
However, the HR detection sensitivity of the PetPace collar was only 53 %, which is obviously not satisfactory since a sensitivity of 100 % is considered optimal. However, we need to focus on what exactly an activity monitor is supposed to do and what the limits of this method are. It is a non-invasive, wireless and very easy-to-use method for collecting health data from dogs, which also offers the possibility of minimising stress in anxious and aggressive in-house patients by reducing physical contact. Since the purpose of using the PetPace collar is to assist the veterinary staff in continuously monitoring patients and no accurate cardiac evaluations are expected from this device, it seems acceptable to us to tolerate some degree of deviation from the ECG measurements. Due to the non-invasive character and its functionality, compromises in accuracy and increased susceptibility to interference (background noise, movement artifacts) can be accepted. In 53 % of the PetPace's HR measurements, the deviation from the ECG measurements was within 10 % and in 77 % it was less than 20 %, which in our opinion is still appropriate. The device is not intended to become the new gold standard in HR and HRV measurements but rather should indicate whether a dog's health status is currently stable, or anything has changed, and an intervention is required. We therefore perceive the PetPace collar

to be suitable for monitoring dogs and for follow-up examinations, if we are constantly aware of its limitations and the potential deviation from the actual health parameters.

The paired Student's t-test revealed a statistically significant difference between the mean VVTI values of the PetPace collar and the Holter-ECG. The Bland-Altman plot shows that the average difference is 0.15 with 95 % within 2 standard deviations (within +1.48 and -1.18). We conclude that the agreement between the two methods in measuring the VVTI is unsatisfactory because the bias appears too high. Still, there appears to be a trend in the right direction. As a consequence, the PetPace's VVTI data could be helpful for getting an initial overview of a patient's HRV status and for follow-up examinations. If a more accurate HRV parameter is required, we recommend using the Holter-ECG.

There are some limitations regarding this study. First, the sample size of 10 dogs is quite small and there were only 507 comparable data points. During this study, only 593 out of 1163 potential HR/VVTI values were obtained by the collar, which means it did not count 49 % of the potential data points. The PetPace collar ascertains pulse waves with integrated acoustic sensors that detect the acoustic signals of blood flowing through large cervical arteries (Scheinowitz and Lascelles 2017, Belda et al. 2018). Noises such as wheezing, barking or other loud ambient noises and a poor fit of the collar can cause the sensors not to count the pulse waves correctly or even fail to count them at all. In addition, at least 40 beats are required within two minutes to accurately calculate the heart rate (Ortmeyer et al. 2018) and not detecting the minimum of 40 beats results in obtaining no HR measurement. Furthermore, on average, the Holter-ECG counted more bpm than the PetPace collar, which could be due to the looser attachment of the collar to the dog's body compared to the ECG pads, which stick firmly to the dog's body surface and are therefore not that susceptible to interference from the dog's movements. That may lead to detecting more heart beats with the Holter-ECG than with the PetPace collar, which is biased more easily by the different mentioned factors. Moreover, when recording data, it was sometimes difficult for the PetPace collar to get a good signal even though we chose the correct collar size and placed it on the dog's neck according to the manufacturer's manual. In some dogs the signal seemed to be poorer than in others, perhaps because their fur was denser, although no correlation between fur length/texture and the PetPace signal could be observed with our study participants. Maybe the collar did not fit perfectly on some dogs, however, we could not find an explanation for this phenomenon. Further investigations with more dogs of different breeds and with different body shapes/sizes and fur length/texture are needed to identify the cause of the mentioned signal problems. Adjusting the collar sometimes resulted in receiving a better signal, but in some dogs, we could not find the perfect position for continuous HR and HRV tracking.

All dogs were considered healthy and more studies are needed to determine whether the collars work properly in dogs with health problems and can reliably differentiate healthy dogs from dogs with health issues. Besides, the study took place at the owners' offices where high-level activities (running, jumping) were not possible, and therefore we do not know if the collar would correctly collect HR and VVTI in these situations.

Since the PetPace collar is able to track a dog's movement pattern and reliably records HR, it can potentially detect minor changes and, as a result, be useful in pain recognition. Although PetPace's manufacturer claims the collar to be able to recognise pain (PetPace. https://petpace.com/hrv-pain-indicator/), future studies should evaluate the utility of activity monitors/smart collars as additional tool for pain recognition and assessment, because literature research did not reveal scientific proof of their statements. The perfect pain marker for dogs does not exist yet. The health and motion data of the PetPace collar are not specific indicators for pain either and can only provide indirect information about pain in dogs, since HR and HRV are both dependent on the autonomous nervous system and therefore are influenced by various factors (cardiovascular and endocrine system, baro- and chemoreceptors, the circadian rhythm, stress, pain, psychologic issues) (Harmeyer und Tobias 2010). In addition, we could not find a satisfactory agreement in VVTI measurement between PetPace and the Holter-ECG in this study. The applicability of PetPace's VVTI as a proper biomarker for pain remains questionable. Only a few studies focused on HRV parameters and pain recognition in dogs so far. Bergfeld et al. (2015) observed a shortening in RR-intervals after nociceptive stimuli in anaesthetised dogs and Voigt et al. (2013) questioned SDNN as a potential pain indicator. Therefore, more research is needed to investigate whether VVTI is even qualified as an indicator for pain assessment, as no study has addressed this issue to date.

Overall, the PetPace collar has great potential to be useful in clinical settings. It may be an additional tool that allows patients to be continuously monitored without disturbing them regularly. It could also be helpful for monitoring aggressive, anxious, or hard to handle animals as it can reduce the total amount of direct animal-veterinarian contact, which potentially avoids harmful incidents. Nevertheless, the collar would benefit from further improvements in its overall performance and how it fits the dogs to ensure continuous monitoring and more accurate measurements of health parameters for all dogs, regardless of their size, fur or body shape. In addition, the algorithm and/or the sensors of the PetPace collar may also need a few optimisations, because in our study the HR and HRV measurements sometimes were not as close to the ECG measurements as we expected. Furthermore, if one has to manipulate the patient and adjust the collar constantly because of fitting issues or limited measurement accuracy, the potential positive aspects of a non-invasive health monitor (e.g. reduction of animal-veterinarian contact, less time spent doing examinations when monitoring patients in-house, easier managing multiple patients simultaneously, easy monitoring patients at home wirelessly, allowing ill patients to rest more as they are not disturbed by regular clinical re-evaluations - especially during night) will no longer overweigh and clinical monitoring of each patient would be more practical. Since we could not determine exactly what caused the signal problems or why the HR and HRV measurements sometimes differed so much from the ECG-data, we cannot suggest any specific improvements. We hope that the manufacturer will strive for constant improvement. Once the issues are resolved and the HR and HRV (VVTI) measurements of the PetPace collar continuously show good agreement with the gold standard method (Holter-ECG), smart health monitoring collars like PetPace may find their way into veterinary clinics and practices someday. We might benefit from their advantages and would be able to reliably monitor canine patients wirelessly and use the health parameters for clinical purposes.

5 Summary

Since our pets cannot talk to us, the establishment of a diagnosis mainly relies on patient examination. The activity monitor PetPace promises not only the tracking of activity, but also the measurement of heart rate, respiratory rate, heart rate variability and body temperature. The aim of this study was to find out whether heart rate and heart rate variability measured by PetPace correspond to the measurements of the gold standard (Holter-ECG). Ten dogs were instrumented with a PetPace collar and a Holter-ECG at the same time and data were collected for four hours. The data obtained by the two methods were compared using Bland-Altman plots and paired Student's t-tests. The PetPace collar recorded an average heart rate of 61 bpm (± 13.58) and a VVTI of 11.50 (± 0.46) in all ten dogs. The Holter-ECG recorded an average heart rate of 62 bpm (± 11.88) and a VVTI of 11.35 (± 0.78). The paired Student's t-test revealed no statistically significant difference ($p = 0.182$) in mean heart rate values. A statistically significant difference ($p < 0.001$) was found between mean VVTI values. However, Bland-Altman plots showed that the average difference in heart rate measurements between the PetPace collar and the Holter-ECG was -0.88 (± 14.87) bpm and 95 % of all measurements were within two standard deviations. For the VVTI measurements, an average difference of 0.15 (± 0.68) was calculated. We conclude that the PetPace collar's heart rate measurements are reliable and could therefore be used for clinical purposes. VVTI, on the other hand, does not appear to be that accurate, but is still accurate enough to get an overview of a patient's VVTI-status or to perform follow-up examinations. If more accurate measurements are required, we recommend using the Holter-ECG. Further studies should investigate whether the PetPace collar provides accurate HR and VVTI measurements in animals with health problems and during high-level activities. Additionally, more research is needed on the utility of activity monitors like PetPace for pain recognition and assessment and the applicability of VVTI as a proper pain indicator should be investigated, as no study focused on this topic so far.

6 Zusammenfassung

Aufgrund der Tatsache, dass unsere Haustiere nicht mit uns sprechen können, müssen Tierärzte sie untersuchen, um die Ursachen für ihre Krankheiten herauszufinden. Der Aktivitätstracker PetPace verspricht nicht nur eine Aktivitätskontrolle, sondern auch die Messung der Herzfrequenz, Atemfrequenz, Herzratenvariabilität und Temperatur. Das Ziel dieser Studie war, herauszufinden, ob die von PetPace gemessene Herzfrequenz und Herzratenvariabilität den Messungen des aktuellen Goldstandards (Holter-EKG) entspricht. Dabei wurden zehn Hunden sowohl ein PetPace Halsband als auch ein Holter-EKG angelegt und über vier Stunden Daten erhoben. Diese Daten wurden dann mit Hilfe eines Bland-Altman-Diagramms und eines gepaarten Student's t-Test verglichen. Das PetPace Halsband zeichnete eine Herzfrequenz von durchschnittlich 61 Schlägen/Minute (± 13,58) und ein VVTI von 11,50 (± 0,46) auf, das Holter-EKG eine Herzfrequenz von 62 (± 11,88) Schlägen/Minute und ein VVTI von 11,35 (± 0,78). Der gepaarte Student's t-Test ergab dabei keinen statistisch signifikanten Unterschied ($p = 0.182$) der Herzfrequenzmittelwerte, jedoch wurde ein statistisch signifikanter Unterschied ($p < 0.001$) zwischen den VVTI-Mittelwerten gefunden. Mittels Bland-Altmann-Diagramm konnte gezeigt werden, dass die durchschnittliche Differenz der Herzfrequenzmessungen zwischen dem PetPace Halsband und dem Holter-EKG -0,88 (± 14,87) Schläge/Minute betrug und 95 % aller Messungen innerhalb von zwei Standardabweichungen lagen. Für den VVTI wurde eine durchschnittliche Differenz von 0,15 (± 0,68) ermittelt. Wir schließen daraus, dass die Herzfrequenzmessung des PetPace Halsbandes durchaus zuverlässig ist und somit für klinische Zwecke verwendet werden könnte. Der VVTI auf der anderen Seite, erscheint uns nicht genau genug, wobei der Wert für einen ersten Überblick über den VVTI-Status eines Patienten beziehungsweise für Verlaufskontrollen geeignet sein könnte. Wenn exaktere Messungen erforderlich sind, empfehlen wir die Verwendung des Holter-EKGs. Weitere Studien sollten untersuchen, ob das PetPace Halsband die Herzfrequenz und den VVTI auch bei Tieren mit gesundheitlichen Problemen und während starker Aktivitäten (Laufen, Springen, etc.) akkurat misst. Außerdem sind noch weitere Untersuchungen nötig, um herauszufinden, ob sich Aktivitätstracker wie PetPace eignen, Schmerzen bei Hunden zuverlässig zu erkennen. Darüber hinaus sollte der Nutzen von VVTI als geeigneter Schmerzindikator untersucht werden, da sich bisher keine Studie mit diesem Thema befasst hat.

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10 Appendix

10.1 Owner Consent

INFORMATION UND EINWILLIGUNG DER TIERHALTERIN / DES TIERHALTERS

WISSENSCHAFTLICHE STUDIE

Sie werden eingeladen, mit Ihrem Tier an einer wissenschaftlichen Studie teilzunehmen, die an der Veterinärmedizinischen Universität Wien (Vetmeduni) durchgeführt wird. Dabei sollen die unter Punkt 4. angeführten Maßnahmen vorgenommen werden. Sie werden ausdrücklich darauf hingewiesen, dass diese Maßnahmen aus veterinärmedizinischer Sicht nicht erforderlich sind, sondern der Verbesserung der medizinischen Behandlungsmöglichkeiten und der Erweiterung der wissenschaftlichen Erkenntnisse dienen. Die Durchführung der Studie wurde von der Ethik- und Tierschutzkommission der Vetmeduni positiv beurteilt.
Die Teilnahme an der Studie erfolgt freiwillig und unentgeltlich. Die Studie kann jederzeit beendet werden.

1. Titel der Studie
Vergleich des "PetPace" - Aktivitätsmonitor-Halsbandes mit einem Holter EKG in Bezug auf die Genauigkeit der Herzfrequenz- und Herzfrequenz-Variabilität-Messung

2. Fragestellung(en) und Zielsetzung(en) der Studie
Zurzeit gibt es zur Beurteilung akuter Schmerzen beim Hund verschiedene Schemata, die alle auf den Beobachtungen einer geschulten und erfahrenen Person basieren. Dabei wird besonderes Augenmerk auf das Verhalten, Gesichtsausdruck, Körperhaltung und die Bewegung des Tieres gelegt. Das Problem dabei ist, dass diese Form der Schmerzevaluierung nur eine Momentaufnahme ist und Tiere gewisse Verhaltensweisen/Schmerzäußerungen im Klinikumfeld bzw. unter Beobachtung nur in geringem Ausmaß zeigen oder sogar gänzlich unterdrücken. Dadurch wird es für den behandelnden Tierarzt schwierig, zuverlässig einschätzen, ob das Tier unter Schmerzen leidet oder nicht. Hinzu kommt, dass diese Schmerzbeurteilungs-Fragebögen immer einem gewissen persönlichen Einfluss unterliegen und so die Ergebnisse von Beobachter zu Beobachter unterschiedlich sein können. Das „PetPace“ ist ein

kleiner Sensor, der auf einem Halsband angebracht ist. Dieser zeichnet die Aktivität und die Herzfrequenz des Hundes auf, ohne diesen in irgendeiner Hinsicht zu stören. Die Daten werden dann am Smartphone oder am PC anschaulich dargestellt und sollen auf schmerzhafte Zustände aufmerksam machen. Da der Sensor die Daten sammelt, während der Hund in gewohnter Umgebung ist, kann dadurch u.U. eine bessere Aussage über seinen Schmerzen getroffen werden. Zusätzlich werden so persönliche (subjektive) Einflüsse auf die Beurteilung weitgehend verhindert, d.h. die Schmerzevaluierung wird objektiver. Allerdings gibt es bis dato noch keine Studien, die die Messungen der Vitalparameter und v.a. der Herzfrequenz und Herzfrequenz-Variabilität des „PetPace"- Halsbandes im Hinblick auf ihre Genauigkeit untersucht haben. Daher lautete unsere **Frage:** Gibt das „PetPace" – Halsband dieselben Werte bezüglich Herzfrequenz und Herzfrequenz-Variabilität wieder, wie der Goldstandard dieser Messungen (Holter EKG)?

3. Erwarteter Nutzen der Studie

Das Ziel der Studie ist, herauszufinden, ob der „PetPace" - Aktivitätsmonitor zuverlässig die Herzfrequenz und die Herzfrequenzvariabilität aufzeigen kann und ob diese ermittelten Werte mit der Goldstandard Messmethode, d.h. mittels Holter EKG übereinstimmt.

4. Beschreibung der geplanten Maßnahmen

Sie kommen am Tag der Studie mit Ihrem Hund an die Klinik für Kleintierchirurgie, in die Abteilung der Anästhesie und perioperative Intensivmedizin. In einem Büro bekommt ihr Hund von uns ein „PetPace"-Aktivitätsmonitor-Halsband gemäß Herstellerangaben (http://petpace.com/knowledge-base/basic-installation/) angelegt. Die Größe des Halsbandes wird abhängig vom Körpergewicht ihres Hundes gewählt, es sollten nach dem Anlegen aber mindestens 2 Fingerbreit Platz zwischen Nacken und Halsband sein und der Sensor sollte ventral am Hals aufliegen. Da das Halsband über einen Handelsüblichen Klickverschluss verfügt ist das Anlegen schnell, unkompliziert und stressfrei für ihren Hund. Danach folgt das Anbringen des Holter-EKGs. Hierzu werden vier EKG-Elektroden am Körper des Hundes platziert: jeweils eine Elektrode rechts und links am Thorax auf Herzhöhe, sowie rechts und links zwischen letzter Rippe und Kniefalte. Um den Kontakt mit der Körperoberfläche zu verbessern und um eine genauere Messung auch bei Bewegung des Hundes zu gewährleisten, wird auf jede Elektrode Ultraschallgel (Ultraschall Gel 500ml, Gello GmbH Geltechnik, Ahaus, Deutschland) aufgetragen und die Elektrode zusätzlich mit Klebebändern (3M Durapore®, 3M Deutschland GmbH, Neuss, Deutschland) am Hund befestigt. Eine Rasur der Körperstellen für das Anbringen des Holter EKGs ist nicht erforderlich. Anschließend wird dann telemetrische EKG-Messgerät Televet 100Ò

(Kruuse, Langeskov, Dänemark) angeschlossen. Sobald die Daten bezüglich Herzfrequenz und Herzfrequenz-Variabilität aufgezeichnet werden, startet die eigentliche Studie. Für die kommenden 4 Stunden verbleibt ihr Hund im Büro, hat freien Zugang zum Wasser und kann liegen, stehen und laufen, wie es ihm beliebt. Die gemessenen Daten werden automatisch vom Halsband und Holter EKG zur Datenempfangsstation bzw. Computer übertragen.

5. Mögliche Nebenwirkungen und Risiken

Im Zusammenhang mit dem Tragen des PetPace-Halsbandes und des Holter EKGs werden keine Nebenwirkungen erwartet.

6. Verwertung von Daten

Daten, Proben, Fotos und Videos Ihres Hundes, die im Rahmen der Studie gewonnen werden, dürfen in anonymisierter Form in der Lehre und Forschung der Vetmeduni verwendet und insbesondere auch publiziert werden.

Erklärung der Einwilligung

Ich bestätige hiermit, dass mir der Aufbau der Studie erklärt wurde und dass ich Gelegenheit hatte, Fragen zur Durchführung der Studie zu stellen. Ich habe die obenstehenden Informationen zur Kenntnis genommen und stimme der Vornahme der unter Punkt 4. angeführten Maßnahmen sowie der Verwendung der daraus resultierenden Daten zu:

Tier (Name, Art, TierNr. lt. TIS, Chip-Nr., falls vorhanden):

………………………………………………………………………………………………

TierhalterIn (Vor- und Zuname, Adresse, Tel.Nr.):

………………………………………………………………………………………………

Ort und Datum: **Unterschrift der Tierhalterin / des Tierhalters:**

……………………..… ……………………………………………………….

Studienverantwortliche/r:

……………………………………………….

Fragen / Kontakt: ………………… @vetmeduni.ac.at