University of Veterinary Medicine, Budapest
Doctoral School of Veterinary Sciences

Digital phonocardiography in the diagnosis and education of canine cardiac arrhythmias

Ph.D. Thesis

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List of Abbreviations

AV Block	atrioventricular block
CS	conventional acoustic stethoscope
dB	decibel
DPCG	digital phonocardiogram
DSPG	digital spectrocardiogram
ECG	electrocardiogram
ES	electronic stethoscope
ms	millisecond
mV	millivolt
PSA	physiological sinus arrhythmia
PVT	paroxysmal ventricular tachycardia
S1	first heart sound
S2	second heart sound
S3	third heart sound
s	second
SR	sinus rhythm
TiHo	University of Veterinary Medicine Hanover Foundation (Stiftung Tierärztliche Hochschule Hannover)
UVMB	University of Veterinary Medicine Budapest
VES	ventricular extrasystole

Summary

Cardiac auscultation is an important part of the physical examination in both human and veterinary medicine. Not only is it safe, cheap, and quick to perform, but it can also indicate other, more advanced diagnostic imaging methods, such as echocardiography, electrocardiography, and thoracic radiography. However, with the ever-increasing accessibility of these diagnostic imaging methods, both the clinical use and education of cardiac auscultation is on the decline – even despite several publications demonstrating diseases that cannot be effectively diagnosed without this examination method. One of the reasons perceived behind this decline is the low sensitivity and specificity of conventional stethoscopes. Namely, both parameters depend greatly on experience, and the hearing capacity of the examiner, the latter decreasing with age. Electronic, sensory type stethoscopes have largely solved these limitations with the ability to filter and enhance selected frequency intervals. The ability to record and transfer the cardiac sounds to a computer allows further filtering and amplification with dedicated software. From the sound files, phonograms can be created (in this case digital phonocardiograms- DPCGs) providing the ability to visualize heart sounds, adding further diagnostic value to auscultation. Some electronic stethoscopes also allow to record ECG-s simultaneously on DPCGs.

In the first part of this work, the efforts of our research group are presented to adapt the technique developed for the recording of canine heart murmurs to cardiac arrhythmias. In our scientific work, two different methods to create DPCGs were evaluated, the first, using the Welch Allyn Meditron Analyzer electronic stethoscope, which provides the option to synchronously record electrocardiograms and present them in the same sound file. This type of stethoscope greatly facilitates the creation of good quality phonocardiograms. It also allows to recognize the electronic systole and diastole on the ECG part which helps to identify the parts of the cardiac sounds on the phonocardiograms. However, this stethoscope is very hard to obtain as it is no longer manufactured. During the second method, a commercially available electronic stethoscope, the 3M Littmann 3200 was used. This device does not have the option to simultaneously record electrocardiograms, thus, a wireless Holter ECG was used, and the phono- and electrocardiograms were edited together after the examination. When comparing the two techniques, phonocardiograms recorded by the 3M Littmann 3200 stethoscope were less reliable for analyzing arrhythmias, because the artifacts produced with this stethoscope made it difficult to differentiate them from cardiac arrhythmias. On the other hand, the device seemed easier to be used due to its wireless nature. For teaching and clinical research of

pathological arrhythmias, the Welch Allyn Meditron system is more suitable because of its capability of synchronous ECG recordings on the digital phonocardiograms. A further benefit of device is its reduced background noise due to on-device noise filtering. Due to its limited availability, and the fact that a controlled environment is required for optimal sound recording and DPCG creation due to its wired nature, the use of the Welch Allyn Meditron system is not feasible in an everyday clinical setting.

The second part of the doctoral thesis focuses on the utilization of the digital phonocardiograms created in the first study in the education of cardiac auscultation. There have been previous studies dealing with the utilization of DPCGs for teaching heart murmurs in human cardiology. Our research group firstly published on the same topic regarding canine cardiac murmurs and veterinary cardiology not being part of this thesis. When searching through the literature, we did not find previous articles in veterinary medicine evaluating the value of digital phonocardiography in the education of arrhythmias in dogs. In our study, forty-two veterinary students participated in this research, all in their clinical training (3^{rd} to 5^{th} year). The students were divided into three groups and were first asked to listen to 10 heart sounds (pretest, containing 2 physiologic heart sounds, 4 heart murmurs and 4 arrhythmias) and make a diagnosis on them. Then the first group underwent training using a self-study website utilizing DPCGs including, but not limited to DPCGs of the sounds of the pre-test, group 2 was asked to participate in an online webinar demonstrating DPCGs, whereas group 3, the control group had no training. After a 48-hour washout period, a post test using the same sound files was performed (without DPCGs). Our results showed significant improvement in both training groups, whereas no improvement in the control group.

This doctoral thesis demonstrates the methodology for proper DPCG recording of cardiac arrhythmias in veterinary medicine not published before. The study also demonstrated the value of DPCGs in the education of cardiac auscultation regarding canine arrhythmias for the first time in veterinary medicine. This work creates a valuable basis for further research, either as a template for evaluating newer devices for DPCG creation or the use of DPCGs in veterinary education.

Összefoglalás

A szív hallgatózásos vizsgálata fontos részét képezi a humán és az állatorvosi klinikai diagnosztikának. Nemcsak biztonságos, olcsó, és gyorsan elvégezhető módszer, de indikációjaként szolgálhat különböző modern képalkotó diagnosztikai eljárásoknak, mint például az echokardiográfia, az elektrokardiográfia és a mellkas röntgenvizsgálata. Ennek ellenére, az utóbbi képalkotó eljárások egyre szélesebb körben való elérhetőségének következtében fokozatosan csökken e vizsgálómódszer klinikai alkalmazása, valamint az oktatásban játszott szerepe is. Mindez igaz annak ellenére, hogy több közleményben mutattak be olyan, akár halálos kimenetelű kardiológiai betegségeket, amelyeket hallgatózás nélkül nem lehet felismerni. Egy másik oka a vizsgálómódszer hanyatlásának a hagyományos, analóg fonendoszkópok alacsony szenzitivitása és specifitása. Mindkét paraméter nagyban függ a vizsgáló tapasztalatától és hallásától – utóbbi az életkor előrehaladtával fokozatosan csökken. Az elektronikus, szenzoros sztetoszkópok nagyrészt megoldást kínálnak ezekre a korlátozó tényezőkre, többek között a különböző frekvenciatartományok szűrésének vagy hangosításának segítségével. Ezek az eszközök lehetőséget nyújtanak továbbá a szívhangok felvételére és számítógépre való átvitelére, ahol további szűrésre és szelektív erősítésre van lehetőség az ilyen eszközökhöz tartozó számítógépes programok segítségével. A rögzített hangokból fonogramok (ebben az esetben digitális fonokardiogramok, DPCG-k) készíthetők, melyek segítségével a hangjelenségek vizualizálhatók, további diagnosztikai értéket adva a szív hallgatózásos vizsgálatának.

A *dolgozatom első fejezetében* a kutatócsoportunk által korábban kutyák szívzörejeinek rögzítésére kifejlesztett metodika adaptálását mutatjuk be szívritmuszavarok felvételére. Két különböző eszközt is értékeltünk, az első, a már korábbi kutatásainkban is használt Welch Allyn Meditron Analyzer elektronikus sztetoszkóp, amely alkalmas szinkron elektrokardiogramok rögzítésére is. A DPCG és az EKG ezt követően ugyanabban a file-ban és ábrán jeleníthető meg, jelentősen megkönnyítve a jó minőségű, szinkron EKG-val ellátott fonogramok készítését, valamint a kamrai systole és diastole elkülönítését, megkönnyítve a szívhangok összetevőinek azonosítását. Ugyanakkor ez a fonendoszkóp kifejezetten nehezen beszerezhető, tekintettel arra, hogy a gyártását beszüntették. A második eszköz a jelenleg (az értekezés írásakor) is kereskedelmi forgalomban elérhető elektromos sztetoszkóp, a 3M Littmann 3200. Az utóbbi eszköz nem képes szinkron EKG rögzítésére, ezért egy vezeték nélküli Holter EKG (Innobase Pico) készüléket használtunk, majd az így készített fono- és elektrokardiogramokat a vizsgálat után, számítógép segítségével szerkesztettük egy egységes videóvá.

A két módszer összehasonlításakor a 3M Littmann 3200 fonendoszkóp által készített fonokardiogramokon jelentősen nehezebb volt az eszköz által rögzített műtermékek elkülönítése a kóros ütésektől, és ezáltal a szívritmuszavarok megállapítása is. Másrészt e fonendoszkóp használata jelentősen könnyebb, tekintettel a vezeték nélküli kialakítására, így kifejezetten jól használható a mindennapi klinikai munkában. A kóros szívritmuszavarok oktatására és klinikai kutatására a Welch Allyn Meditron rendszer tűnik alkalmasabbnak, köszönhetően a szinkron EKG-készítés lehetőségének, valamint a háttérzaj szűrésének. Ez utóbbi eszköz korlátozott elérhetősége, valamint a tény, hogy a jelentős mennyiségű kábel miatt csak kontrollált környezetben lehet vele optimális felvételeket készíteni, jelentősen gátolja a mindennapi klinikai életben való alkalmazhatóságát.

Dolgozatom második fejezetében az első részben készített DPCG-k alkalmasságát tanulmányoztuk a szív hallgatózásos vizsgálatának oktatásában. Több korábbi kutatás is foglalkozott a DPCG-k használatával a humán kardiológia oktatásában. Kutatócsoportunk az állatorvoslásban elsőként írta le a technológia használatát kutyák szívzörejei tekintetében. A közlemények nem képezik ezen dolgozat részét. Az állatorvosi szakirodalom áttekintése során nem találtunk a digitális fonokardiográfia a kutyák szívritmuszavarainak kórjelzésével és oktatásával foglalkozó publikációt. A szakirodalom tanulmányozása során nem találtunk olyan állatorvosi közleményeket, amelyekben a digitális fonokardiográfia alkalmazásáról számoltak be a kutyák szívritmuszavarainak oktatását illetően. A kutatásunkban 42 állatorvostan-hallgató vett részt. Az önkéntes alapon jelentkezett hallgatókat három csoportra osztottuk, majd 10 szívhangot hallgattattunk meg velük (2 fiziológiás hangfelvételt, 4 szívzörejt és 4 ritmuszavart), amelyeket azonosítaniuk kellett. Ezt követően az első csoportnak egy önképző, az előtesztben bemutatott szívhangokat is bemutató weboldallal kellett foglalkozniuk. A második csoport egy DPCG-ket bemutató interaktív webináron vett részt, míg a harmadik, kontrollcsoport nem részesült semmilyen tantervi oktatáson kívüli képzésen. A képzést, valamint egy 48 órás felejtési, más kifejezéssel „ürülési" periódust követően ugyanazt a 10 szívhangot hallgatták meg, és kellett azonosítaniuk mindegyik csoportban. Eredményeink szignifikáns fejlődést mutattak mindkét, képzésben résztvevő csoport eredményeiben, míg a kontrollcsoportéban nem mutatkozott javulás.

Disszertációmban elsőként mutatom be a megfelelő minőségű DPCG-k készítésének metodikáját a kutyák szívritmuszavarait illetően. Ugyancsak úttörő kutatásnak számít az, hogy az állatorvoslásban először tanulmányoztuk a DPCG-k szerepét a kutyák szívritmuszavarainak oktatásában.

Introduction and aims of the study

Cardiac auscultation plays a significant role in both human and veterinary cardiology, even despite the rapid development and wide use of diagnostic imaging techniques. It commonly helps to identify cardiac murmurs and arrhythmias. The auscultatory findings can prompt further, more advanced diagnostic techniques, e.g., thoracic radiography, echocardiography, and electrocardiography. Auscultation is safe, cheap, easy, and quick to perform, thus providing an excellent screening test for most dogs and cats. Furthermore, clinicians can gain valuable information about the underlying disease process and its severity based on auscultatory findings (Ljungvall et al., 2014; Caivano et al., 2017; Rishniw, 2018). Along the conventional (acoustic) stethoscopes (CS), the so called sensory, electronic stethoscopes (ES) have been gaining popularity among clinicians. Use of the latter brings several benefits compared to acoustic devices, as well as unlocking new avenues to successfully diagnose and teach cardiac diseases via digital phonocardiography.

Auscultation as a diagnostic method

Auscultation is an important part of clinical diagnostics both in the veterinary and human medical fields. Along aiding the diagnosis of various respiratory, and occasionally gastrointestinal pathology, the examination method is exceptionally useful in identifying cardiac murmurs and arrhythmias.

Conflicting opinions have developed in the last decades regarding the usefulness of cardiac auscultation in medical literature. Several authors have questioned the usefulness of the method, claiming that the increasing availability of non-invasive diagnostic imaging methods, such as echocardiography, electrocardiography and thoracic radiography can and will replace the auscultation in clinical cardiology (Nassar, 1998; Markel, 2006).

Multiple counter opinions have been published in the recent decades, emphasizing the importance of cardiac auscultation in the diagnosis of heart diseases, while acknowledging its limitations, such as the low sensitivity and specifity. The former parameter proved to be 70% while the negative predictive value to be 92% when evaluating the method's diagnostic value in asymptomatic valvular defects of human patients (Roldan et al., 1996). Other authors were not able to show significant difference between the sensitivity of appropriately performed cardiac auscultation and echocardiography in differentiating innocent and pathologic heart murmurs, even aside the lower sensitivity of the method. This latter research yielded the conclusion that preferring ultrasonography instead of the cheaper and easier performed auscultation is not warranted (Shub, 2003). The importance of cardiac auscultation was also emphasized in a case study, where ignoring the left arm pulse deficit identifiable by auscultation led to the incorrect diagnosis of coronary thromboembolism. This mistake costed the patient's life, who actually suffered from an aortic dissection (Jauhar, 2006).

Based on medical research, electronic stethoscopes successfully overcome the above-mentioned limitations of auscultation, and provide further diagnostic values via their roles in digital phono- and spectrocardiography, while still retaining the above-mentioned benefits of conventional stethoscopes, like the ease of use and low cost (Tavel, 1996, Tavel, 2006). Murphy (2008) demonstrated the importance of auscultation and phonendoscopes on multiple physiologic and pathologic sound recordings created during thoracic examination of several patients. These sounds where then used to create a collection of sound phenomena that need to be recognized by the clinician, otherwise a correct diagnosis might not be achievable even with knowing the findings of modern diagnostic imaging methods.

The tools of auscultation

Auscultation is traditionally performed with acoustic (or conventional) stethoscopes. These devices can be easily and cheaply acquired, their sensitivity however is not always sufficient for identifying milder heart murmurs and it can be hard to detect some types of arrhythmias (Tavel, 1996; Blass et al., 2013; Szilvási et al., 2013; Vörös et al., 2015; Grenier et al., 1998). In case of acoustic stethoscopes, the soundwaves produced in the body of the patient vibrate the membrane of the phonendoscope, which is placed on the surface of the skin of the patient. These vibrations are conducted by the hollow, air filled tubes of the device into the ear of the clinician. Lower frequency intervals are amplified by the bell-shaped headpiece of the stethoscope, whereas higher frequencies are enhanced by the membrane itself. The conducted frequency interval however is rather narrow, and even with its amplification, the sounds are not amplified sufficiently to overcome the decrease in the hearing abilities of older clinicians. This is especially problematic, as cardiac auscultation requires practice and experience to master. It has been proven that both its sensitivity and specificity increase with experience (Tavel, 1996; Blass et al., 2013).

Digital, sensory, electronic stethoscopes register soundwaves either via electronic sensors or microphones. The low frequency interval of acoustic devices can be overcome by amplification of the sounds, occasionally even targeting specific frequencies in which heart or respiratory sounds are expected to be. This, however, can lead to increased background noise and more artifacts, as the amplification is not limited to sounds produced by the heart, respiratory organs or the abdomen and several noise producing phenomena share the same frequency intervals with the sounds the device amplifies. Thus, the rubbing sounds elicited by moving the stethoscope against the chest of the patient and the majority of background noises in the examination room are also amplified. Even though the noise caused by the movement of the stethoscope on the chest of the patient is less of an issue in human medicine, it is exacerbated by the hair coat of mammals encountered in a veterinary clinic, making it a greater problem for veterinarians. These issues can be minimized by performing the examination in a quiet room to prevent background noise (chatter of colleagues, humming of machines in the background), and by proper fixation of the stethoscope's headpiece by minimizing movement on the chest. The amplification described above further increases the importance of stethoscopes in certain hard-to-hear heart murmurs and arrhythmias. This amplification is exceptionally important for older clinicians, due to the aforementioned age-related reduction in the sensitivity of the human ears (Tavel, 1996). The quality of electronic stethoscopes has also greatly improved in the last decades, with even more selective filtration in order to eliminate auditory artifacts (Tavel, 2016; Grenier, 1998; Hoyte et al.; 2005).

Digital phonocardiograms can be created by any electronic stethoscopes that have the ability to record audio and transfer the recordings to a computer. These phonograms of the heart sounds allow the visualization of normal heart sounds, heart murmurs, and arrhythmias. The role of digital phonocardiograms will be detailed in the next section.

The diagnostic value of acoustic and electronic stethoscopes in case of heart murmurs have been extensively studied. Some publications based on research in human medicine, found that electronic stethoscopes are better suited for diagnosing heart murmurs due to the selective amplification of the frequency intervals in which heart murmurs are expected in (Tavel, 2006, Philip, 1986). Other authors preferred acoustic stethoscopes, due to the increased number of artifacts encountered when using electronic devices (Grenier et al., 1998). When examining the applicability of the two devices in the education of cardiac auscultation to medical students, no significant difference could be demonstrated between CS and ES (Hoyte et al., 2005). In veterinary medicine, our research group was the first who compared acoustic and electronic phonendoscopes in dogs with cardiac murmurs. Our studies revealed that electronic stethoscopes are better suited for the diagnosis of heart murmurs, even despite its higher background noise, provided, that the device is properly used (Szilvási et al., 2013, Vörös et al., 2012). In another study, the applicability of the two types of devices were compared regarding the diagnosis of mitral insufficiency in beagle dogs. The results of this study showed the electronic stethoscopes proved to be significantly more sensitive than the acoustic devices (Vörös et al., 2015).

At the time of writing this work, only one, human article was published, regarding the sensitivity of electronic stethoscopes in cardiac arrhythmias. However this study was mainly concerned with telemedicine and not with clinical work or education (Zenk et al., 2004). In veterinary cardiology, only one study compared the sensitivity of ES and CS, specifically focusing on the diagnosis of heart murmurs and gallop sounds in cats (Blass et al., 2013). The results of this study showed that the sensitivity of ES was lower, however, it's specifity was higher than that of CS. Based on these results, the authors recommended the electronic stethoscopes for younger, rather inexperienced users (Blass et al., 2013). Nevertheless, the authors did not evaluate the role of the two types of stethoscopes in the diagnosis of cardiac arrhythmias.

According to our knowledge, the studies making up this dissertation were the first in veterinary medicine to investigate the applicability of electronic stethoscopes and digital phonocardiograms in the diagnosis and education of canine arrhythmias.

Digital Phonocardiography

The phonogram (from Greek sound(*fono*)-image(*gram*)) is the graphical representation of soundwaves as a time and amplitude graph, where time is represented along the x axis in seconds (s) or milliseconds (ms), whereas amplitude is represented on the y axis in decibels (dB). Phonocardiography is the visualization of heart sounds as phonograms, more specifically, phonocardiograms. Heart sounds are generally represented as a sinus wave on the phonocardiogram, resulting in roughly symmetrical deflections in amplitude on both + and – y axes.

The utilization of analogue phonocardiograms traditionally recorded on paper in human and veterinary medicine has already been described in the literature decades ago. Phonocardiography was developed in the 1930s and 1940s, and its standardization began in 1950s (Sprague 1957). During the first application of the method, heart sounds were recorded by ECG devices equipped with microphones, which were then converted to analogous electronic impulses, recorded on paper, together with the ECG tracings, similarly to seismography (Häggström et al., 1995; Kvart et al., 2002). This methodology however proved to be remarkably hard to perform properly, as the limited option to filter out sounds not related to the cardiac activity of the patient resulted in a high number of acoustic artifacts. The large number of wires and the requirement of very little movement from the patient made the technique unfeasible in routine cardiological examinations both in human and veterinary medicine. Because of these challenges, traditional phonocardiography was not utilized widely in the former decades, and we only know of a few veterinary publications regarding the application of the method (Höglund et al., 2007; Pedersen et al., 1999).

The constant development and increased accessibility of digital devices have also affected phonocardiography. Certain electronic stethoscopes are capable of digitizing the otherwise analogue soundwaves by utilizing an analog/digital signal converter device (Tavel, 2006; Germanakis et al., 2009; Vörös et al., 2011). The digitized sounds can then be viewed as a digital phonocardiogram (DPCG) with the use of appropriate sound editing software. The application of the method is visible **on Figure 1** and is detailed later in this doctoral thesis.

Figure 1. *Fixature of adhesive ECG electrodes to the chest and hindlimb using an elastic net tube bandage (Ramofix).* The A/D converter (suitable for computer connection) is visible next to the animal. (Source: Szilvási and Vörös: Magy. Állatorvosok Lapja, 2014; 136, 291–299, with permission).

Heart sounds represented in this manner are suitable for demonstrating normal heart sounds, as well as differentiating heart murmurs and arrhythmias. Devices that are capable of displaying and recording synchronous ECG recordings can provide even more information, this is most commonly recorded to one stereo channel -usually the left-, whereas the heart sound is recorded to the opposite one. **Figure 2** shows a DPCG recording of a healthy dog, whereas on **Figure 3**, the DPCG of a dog suffering from aortic stenosis is visible.

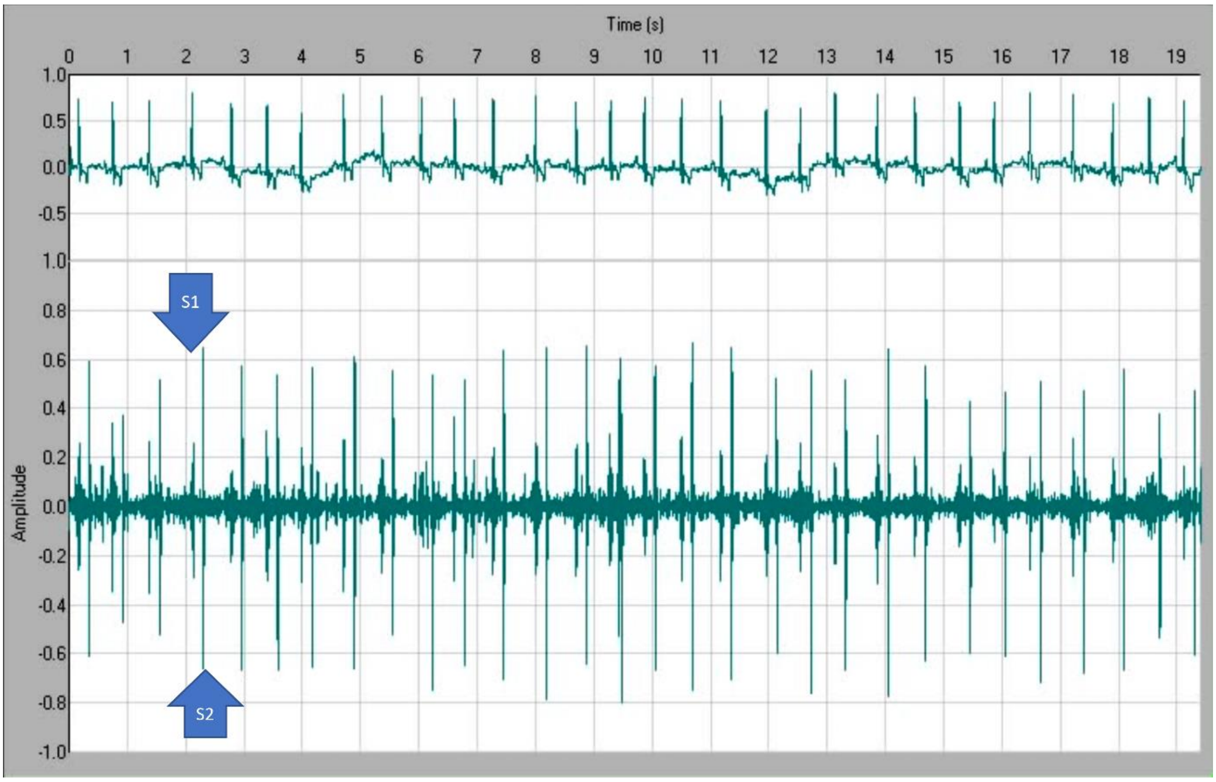

Figure 2. *Heart sounds and digital phonocardiogram (DPCG) of a healthy adult erdélyi kopó.* Sounds were recorded over the mitral valve area (left apex, 5th intercostal space).S1: sound 1, S2: Sound 2. Electrical systole starts at the Q wave and ends at the end of the T wave on the ECG followed by electrical diastole which lasts until the next QRS complex. S1 signals the start of mechanical systole and S2 signals the end of mechanical systole. Source: Heart sound Library (Vörös et al., 2010), with permission

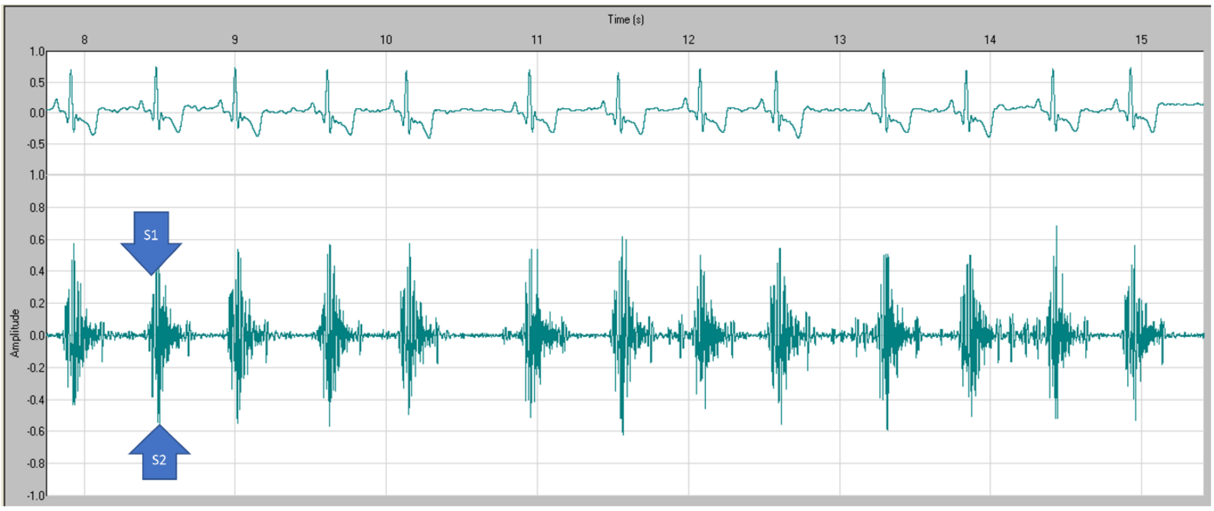

Figure 3. *Heart sounds and digital phonocardiogram (dPCG) of a 4-year old Fox Terrier with severe subvalvular aortic stenosis (SAS) producing a grade 4/6 systolic crescendo-decrescendo murmur (starting at S1 and ending before S2).*

This murmur was recorded at the point of its maximal intensity over the aortic valve area (left heart base). S1: sound 1, S2: Sound 2. Electrical systole starts at the Q wave and ends at the end of the T wave on the ECG followed by electrical diastole which lasts until the next QRS complex. S1 signals the start of mechanical systole and S2 signals the end of mechanical systole. Source: Heart sound Library (Vörös et al., 2010), with permission

The advantages of digital phonocardiography compared to traditional, paper-based phonocardiography have been detailed in many publications in the last decades. The described advantages are fewer artifacts, better filtering, options to magnify or enhance segments of the phonocardiogram, and further post processing such as the possibility to remove artifacts (Jauhar, 2006; Tavel 2006; Germanakis et al., 2008). The addition of a synchronous ECG to DPCGs is extremely useful in the examination of cardiac arrhythmias as certain auditory artifacts that may mimic heart sounds can be identified if no deflection is visible in the corresponding ECG tracings. Relating the heart sounds' timing to the ECG curve, it is possible to define the components i.e., S1, S2, S3, and S4 of the cardiac sounds. The sound phenomenon, coupled together with the deflections in other leads can confirm that the object examined on the DPCG is indeed an abnormal beat and not an acoustic artifact. The methodology of the procedure in dogs was first developed by our research group, focusing on heart murmurs and normal heart sounds (Vörös et al., 2011).

Digital phonocardiograms provide the opportunity for the clinician to visualize and analyze heart murmurs (Jauhar, 2006; Szilvási et al., 2013; Vörös et al., 2012; Germanakis et al., 2009; Vörös et al., 2011; Noponen et al., 2007; Szilvási et al., 2014). In human medicine, DPCGs have been used for this purpose for more than three decades (Jauhar, 2006; Germanakis et al., 2009). In veterinary medicine, the method of recording (traditional, analogue) phonocardiograms was published by Hassgström, in 1995. There is also a book on cardiac auscultation with phonocardiograms published by Kvart and Haggström, although they did not specify whether these are analogue or digital phonocardiograms, however, based on the images, it is suspected that they are analogue (Kvart et al., 2002). Digital phonocardiograms can also be recorded by esophageal stethoscopes, which produce better quality recordings, as there is no movement on the chest of the animal, there is limited movement artifacts due to the sedation of the animal, and any external sound or noise is greatly reduced by the body of the animal. The phonocardiograms acquired with esophageal stethoscopes were used to measure the ratio of the first (S1) and second (S2) heart sounds in healthy, sedated dogs, comparing it with the fluctuations of blood pressure (Lim et al., 2013). Digital phonocardiograms of the recorded heart sounds were presented in the cited publication. Another publication applied the same methodology of DPCG creation with the help of esophageal stethoscopes, and the created recordings were also used to analyze the amplitude differences between S1 and S2, unfortunately however, the authors did no publish the DPCGs used in their study (Park et al., 2013).

Aside from dogs, DPCGS were also published in cattle (Reisse, 2008) and horses (Fraune, 2010), along the description of the methodology of DPCG recording in these species as the gradual thesis of the authors. Our research group was the first who described the role of DPCGs in the diagnosis of canine heart murmurs (Szilvási et al., 2013; Vörös et al., 2012; Vörös et al., 2011). Other authors evaluated the applicability of digital phonocardiography to the differentiation of innocent and familiar heart diseases in dogs. This study utilized digital measurement techniques on the recorded DPCGs to predict murmur malignance. The results suggested that those murmurs that are longer than 80% of the systole (or the S1-S2 distance, measured in seconds) are likely to be pathologic, whereas shorter murmurs can either be innocent, or pathologic auditory phenomena (Marinus et al., 2017).

The parallel development of digital spectrocardiography in the last decades is also important, as it adds further details to the recordings. (Tavel, 2006). The spectrocardiogram adds another dimension to the phonocardiogram, displaying sound waves as a graphical representation of time (x axis) frequency (y axis) and amplitude (color of the point in the graph) (**Figure 4).** Due to its three-dimensional nature, spectrocardiograms can only be digital and have no analogue counterparts. The limited amount of available literature focusing on this method claim that the isolation of frequency intervals in which the amplitude changes occur can provide additional information regarding the nature of the heart sound and can be utilized in the diagnosis of mitral valve defects (Ljungvall et al., 2014).

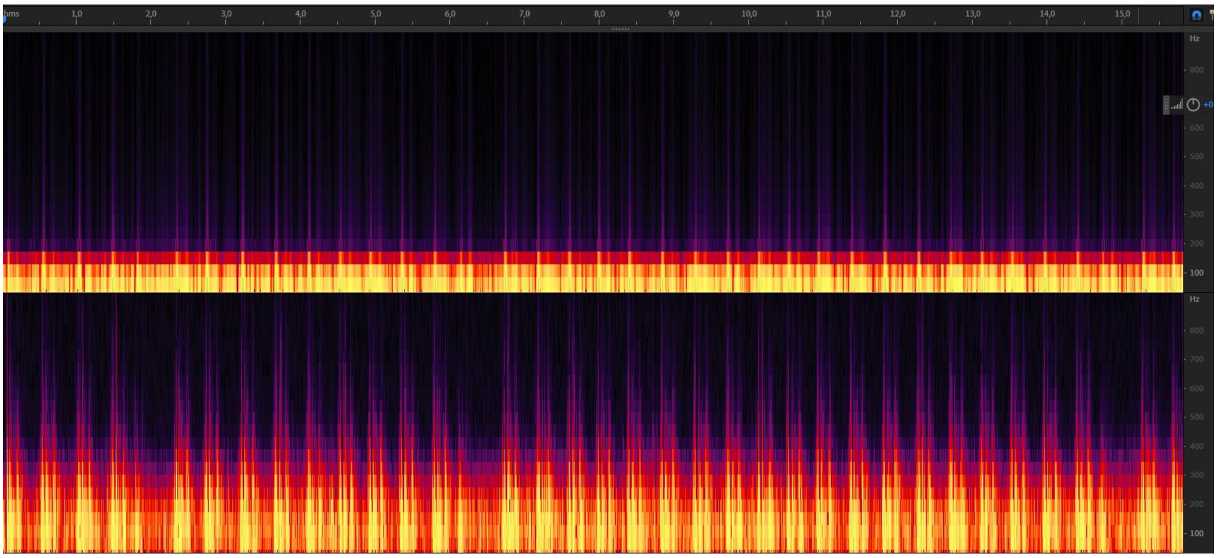

Figure 4. *Digital spectrogardiogram*.

The horizontal axis represents time (s, 1 bar is 1s) the vertical axis represents frequency (hertz , 1 bar is 100 Hz). The color of a point represents the volume of that time-frequency point (black: negative infinte dB, white: 0 dB). Figure created during our study.

The creation of DSPGs has no additional technical requirements, and can be created from any, already recorded DPCG using approriate commercially available software (for example, the DSPG in the figure was created with Adobe Audition CC).

The role of digital phonocardiography in education

Aside from their utilization in the diagnosis of cardiac disease, DPCGs have a valuable role in the education of cardiology as well. The education of auscultation faces many challenges as of the writing of this dissertation, and this affects the abilities of both veterinary and medical fresh graduates (Barrett et al., 2004; Germanakis et al., 2013). Auscultation, like many practical skills can be improved by repetition (Favrat et al., 2004). Despite this, this skill is mainly taught in the form of traditional presentations, in a theoretical manner, while opportunities for individual learning and practice remain largely unexplored. There have been multiple attempts to counteract this problem, each based on the repeated listening to heart sounds. Based on the currently available literature it is clear however, that simulated auscultation (utilizing pre-recorded, digitally manipulated, or computer generated heart sounds) does not significantly improve the student's skills when compared to traditional auscultation, especially due to the several distractions present in a clinical situation (unclear heart sounds, background noise, not identified punctum maximum, movement of the patient) making simulated auscultation 'too ideal' and the skills gained harder to translate to real life improvement (Favrat et al., 2004).

In human cardiology, the use of DPCGs has been described in the education of medical students in a collection of recordings demonstrating the alterations of the third heart sound (S3) in patients undergoing left side cardiac catheterization (Marcus et al., 2006). The participants of the study did not see the DPCGs however, instead, they were used as a standard to compare the participants' assessments of the presence and quality of S3. Their results showed that the two least experienced groups (residents and interns) had performed significantly worse in the diagnoses compared to the standard phonocardiographic evaluation. These results suggest, that DPCGs can provide additional information that can help clinicians with lower experience to diagnose alterations in the S3.

Naylor et al., 2001 referred to phonocardiography as the 'gold standard' for evaluating the educational value of recorded heart sounds in veterinary medicine. In the cited publication, they evaluated the diagnostic abilities of veterinary students and veterinary clinicians categorized into different groups, based on experience in auscultation. In order to measure this, they used analogue recordings of heart murmurs and arrhythmias of horses, however the research itself did not include the use of phonocardiograms – they only used non digital phonograms to establish the abnormalities present in the audio recordings utilized in the study and compare the participants' diagnoses to them.

Prior results of our research group

Our research group was the first in the world to utilize DPCGs as training materials in the education of veterinary cardiology (Ehlers et al., 2010). During this study, DPCGs of normal heart sounds and heart murmurs were used. The sound files were recorded by our research group from healthy dogs as well as from those with various cardiac murmurs. In that study, DPCGs with synchronous ECGs were generated by utilizing the Welch Allyn Meditron Analyzer System's Analogue/Digital converter to transfer data to a PC. The 'Meditron Analyzer' software, packaged with the device was used to display the recordings, and the freely available audio editing software, Audacity to edit, filter, and amplify the recordings.

Creating adequate quality DPCGs, especially with synchronous ECGs provides several challenges in non-sedated dogs. Dogs generally do not tolerate recumbent positions for the extended periods of time required to produce adequate quality recordings, therefore a standing position is preferred. This positioning is safer from larger motion related artifacts originating from the attempts of the patient to stand up from recumbency. However, standing positioning also has several factors that can reduce the quality of the recordings. These are the following, disturbing factors: minor movements of the animal, such as smaller steps, or shifts in bodyweight, resulting in artifacts in both the audio recording and the synchronous ECG, background noise originating from normal clinic work in the surroundings, movement of the electrodes on the patient's skin resulting in baseline deviations, as well as auditory artifacts originating from the movement of the stethoscope's head against the animal's hair. Other issues include certain heart murmurs being quieter, or harder to hear, as well as certain arrhythmias not resulting in recognizable auditory changes, or some ECG wave alterations with low amplitude sounds and ECG waves (e.g., 2nd degree atrioventricular block (AV block)). These factors must be addressed, as any recording can only be suitable to be utilized in education if it is of the best possible quality i.e., it can be, free of artifacts, and presents a proper example of the taught alteration. After experimenting with multiple configurations of electrodes, our research group found that adhesive ECG electrodes attached to the patient's skin via a Ramofix® elastic bandage resulted in the electrodes following minor movements of the patient, and not causing shifts in the ECG curve. Sound recording is facilitated by previous shaving of the area of the heart, preventing any auditory artifact formation due to movements of the stethoscope against hair. Even with all these precautions, not all dogs are suitable for recording, as some are overly active under clinical circumstances, whereas others might not tolerate the elastic bandage, or the adhesive electrodes.

Sounds that are weak can be amplified with the following technique – developed by our research group: the recorded material was filtered with built in low and high pass filters of the freely available Audacity software, to remove or at least dampen respiratory sounds or other artifacts (Vörös et al., 2011). If the amplified sounds correspond to an abnormal beat, the electronic signs are visible on the synchronous ECG as well, although neither Audacity, nor the Meditron Analyzer software provide the ability to enhance ECG curves. In order to present the special waveform (.Wav) files created by the Welch Allyn Meditron device in a video format, we used the screen capture software Camstudio and OBS studio (in later recordings) and recorded the phonocardiogram while playing the sounds relating to it. This produced an MPEG-2 format video that can be played back in most computers running Windows XP or higher Windows versions. In later parts of the study, all videos were uploaded to Youtube for education purposes, allowing it to be viewed on an even larger scale of devices, including Apple computers and handheld devices, without losing significant audiovisual detail.

In order to utilize the recordings in education of cardiology, a blended learning module was created together with the University of Veterinary Medicine Hanover (TiHo) (Ehlers et al., 2010). The results of the research regarding this course showed significant improvement in the performance of all evaluated clinical years compared to their performance on the pretest, and the acceptance and opinions toward digital phonocardiography as a learning tool was overall positive. However, an important limitation of this part of the study was that no control group was involved.

The recordings created for this study, along later recordings of our research group were used to create an on-line heart sound library (named Heartsound Library). This website, built together with TiHo is designed to help in the diagnosis of normal and abnormal heart sounds of dogs. It is freely available at https://tinyurl.com/mas26dp6 (Vörös et al., 2010). Recordings of heart murmurs collected by our research group have been available on this website for multiple years as of the writing of this doctoral thesis. Each recording is annotated and is accompanied by descriptions in English. These normal and abnormal heart sounds are presented in mp3 formatted audio, and mpg format DPCG recordings, and include, but not limited to the different intensities of heart murmurs (from normal to grade 1-6) and heart diseases resulting in the formation of heart murmurs or arrhythmias. The authors recommend listening to the recordings 'blindly' i.e., starting with the mp3 recordings, and then continue by viewing the DPCG recordings with the visual data to "see" what they were hearing. Another possible use is for clinicians – they can compare the auscultatory findings of their own cases to the recordings available in the heart sound library, further enhancing their diagnostic capabilities.

Aims of the own studies

The following goals have led to the studies and for making up this dissertation.

1. The adaptation of the methodology developed to DPCG creation from heart murmurs to arrhythmias. The reason for picking this aim is because heart murmurs and arrhythmias have a different phonocardiographic appearance, and the methodology established for the recording of adequate quality murmurs (focusing on the enhancement of specific frequency intervals) might not be the best approach to record arrythmias, where changes in rhythm are demonstrated. Another aim for this part of the study was to reevaluate the available devices for DPCG creation as the range of accessible electronic stethoscopes have changed over time.
2. Document the phonocardiographic appearance of the most common canine cardiac arrhythmias.
3. The other part of this work was designed to evaluate the use of the recorded arrhythmias in the education of veterinary students. This goal became especially important due to the COVID pandemic, which placed the emphasis of self-assisted learning.
4. The final aim was the expansion of the heart sound library with good quality DPCGs and ECGs of the most common arrhythmias of dogs.

1. Digital phonocardiography of cardiac arrhythmias in dogs

1.1 Introduction

When designing the methodology for recording DPCGs of arrhythmias in dogs, our research group was faced with several challenges.

The electro- and phonocardiographic appearance of arrhythmias greatly differ from that of heart murmurs. First, as murmurs are not visible on the ECG tracing, the role of the synchronous ECG on the DPCG is to help identify S1 and S2 sounds, and the location of the murmur in the heart cycle. As indicated on Figures 2 and 3, the electrical ventricular systole starts at the onset of the Q wave and ends at the end of the T wave. The electrical ventricular diastole starts after the end of the T wave and ends at the beginning of the consecutive Q wave. In case of the DPCG, heart murmurs are usually visualized as periodic or sometimes continuous baseline ‘noises’, superimposed on the heart sounds.

Arrhythmias however result in alteration in the ECG tracing, and, in case of additional pathological beats, like in the case of ventricular extrasystoles (VES), they can create deflections in the DPCG that sometimes can resemble artifacts morphologically (i.e., in their appearance). Therefore, a stable, simultaneous ECG tracing can greatly help in isolating abnormal beats from artifacts and is necessary for proper evaluation of the DPCGs for arrhythmias. The identification of additional heart sounds becomes a challenge without synchronous ECG recordings, and extrasystoles, even if identified, cannot be differentiated as originating from the atria or the ventricles. Based on our experience, without multiple ECG leads present, it is not possible to establish with certainty if an auditory object on a DPCG corresponds to an abnormal beat, or if it is only noise.

This requires adapting the originally established methodology for cardiac murmurs to meet the requirements listed above: to be able to provide a stable, ideally multiple channel ECG lead next to the phonocardiogram. Unfortunately, at the time of the study, and the writing of this doctoral thesis, no single device existed that was capable of recording multiple lead ECGs together with DPCGs. Another challenge we faced was that the device used in the previous investigations of our research group, the Welch Allyn Meditron Master Elite Stethoscope, is no longer available commercially, which further prompted the necessity to investigate other methods of recording DPCGs with synchronous ECG tracings.

Therefore, we sought to record canine arrhythmias using digital phonocardiography with simultaneously acquired ECGs and to compare their diagnostic value with the ECGs appearing on the phonocardiogram itself and with those recorded by a diagnostic multi-lead electrocardiograph.

We then compared the recording quality of two electronic stethoscopes for their ability to produce digital phonocardiograms that could be used for educational or diagnostic purposes.

1.2 Materials and methods

1.2.1 Dogs and study design

We examined 32 dogs in order to adapt the digital phonocardiogram recording technique established by our research group for recording heart murmurs to cardiac arrhythmias. The dogs age ranged from 4 months to 9 years old, and the population consisted of various breeds, with mixed breed dogs being predominant. Regarding their gender, 18 dogs were male, and 14 were female. Of these, 25 dogs only had a physiological respiratory arrhythmia. These 25 dogs arrived at the Department and Clinic of Internal Medicine, University of Veterinary Medicine Budapest for various endoscopic (otoscopy, gastroscopy, respiratory) examination procedures and to the SchiAb Veterinary Centre, Érd, Hungary for planned surgical interventions. Of these 25 dogs, 16 were anaesthetized before the planned endoscopy or surgery. In these cases, all animals underwent procedures requiring general anaesthesia, which were unrelated to our examination. Dogs were premedicated and induced with 0.5 mg/kg diazepam and 5 μg/kg dexmedetomidine iv. or with 0.5 mg/kg diazepam and 6 mg/kg ketamine. The inhalation anaesthesia was maintained with isoflurane. An analysis of cardiac alterations elicited by anaesthesia (e.g., bradycardia or atrioventricular blocks) did not belong to the goals of the present study. The remaining 9 dogs were examined awake.

Seven of the 32 dogs were presented for evaluation of cardiac disease. All seven dogs had tachyarrhythmias: atrial fibrillation (n=2), atrial premature complexes (n=2), ventricular premature complexes (n=2) and paroxysmal ventricular tachycardia (n=1). These dogs were examined without sedation.

In all cases, written consent was gained from each owner before starting the study. The implemented procedures were compliant with the guidance of the Animal Welfare Committee of the University of Veterinary Medicine, Budapest.

1.2.2 Physical examination

All dogs underwent a detailed physical examination with special regard to the cardiorespiratory system. One investigator (KV) performed both conventional cardiac auscultation (with a

Sprague Rappaport type conventional, acoustic stethoscope) and digital auscultation (with a 3M Littmann Electronic Stethoscope Model 3200 and a Meditron Welch Allyn electronic stethoscope).

1.2.3 Echocardiography

Echocardiography was performed as described for routine clinical echocardiography (Bonagura and Fuentes, 2015; Brown et al., 2015; Vörös et al., 2015).

1.2.4 Digital phonocardiography

Digital phonocardiograms were made and processed with the Welch Allyn Meditron Master Elite Stethoscope and Analyzer System (Welch Allyn Corp., USA) as described earlier in humans and in dogs with cardiac murmurs (Germanakis et al., 2008; Vörös et al., 2011). This sound digitalizing system includes the recording of synchronous, Einthoven lead II ECGs (**Figure 5**).

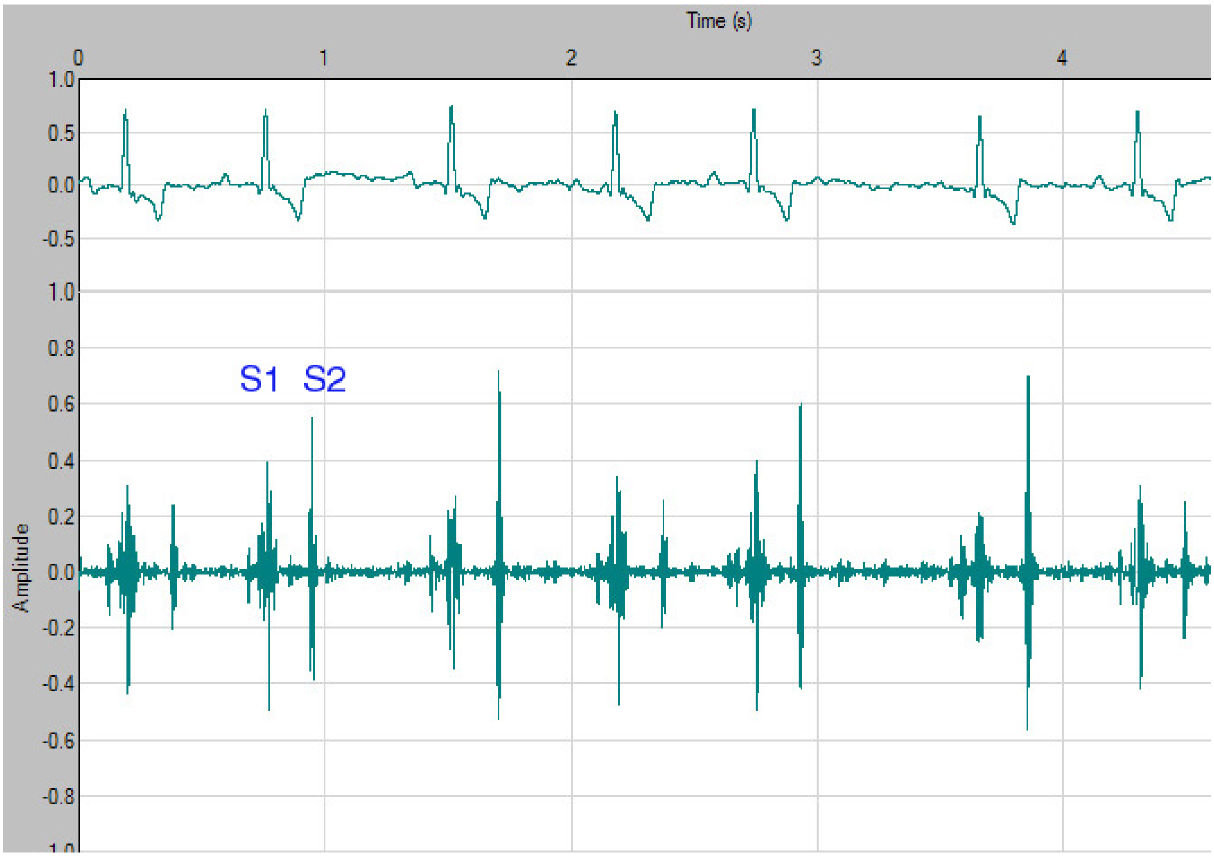

Figure 5. *Digital phonocardiogram (DPCG) of a healthy Beagle recorded with the Welch Allyn Meditron system.*

The X axis represents time, the Y axis represents the amplitudes/wave forms of the heart sounds. The upper part of the image shows the simultaneously recorded (synchronous) Einthoven lead 2 bipolar electrocardiogram (ECG). S1: Heart sound 1, S2: Heart sound 2. (From Vörös et al.: Acta Vet. Hung. 2011; 59, 23-35. with permission)

The digital files were stored and analyzed on a personal computer as .wav (16-bit waveform) files. These Meditron .wav files contain both the simultaneous ECG (left channel) and sound (right channel) data and were replayed and analyzed with the dedicated software of the Welch Allyn Meditron digitizing software. The .wav files were converted to conventional .wav and .mp3 files by using the freely available shareware program Audacity® (https://www.audacityteam.org). The original Meditron digital phonocardiogram video recordings were also converted from the original Meditron .wav files into video .mpg files with the CamStudio™ (www.camstudio.org), similarly to the digital phonocardiogram recordings of the cardiac murmurs that can be found in our heart sound library (Vörös et al., 2010).

Awake dogs were examined standing, with two adhesive flat ECG electrodes fixed with Ramofix flexible band on the thorax and one on the left gluteal region (**Figure 1**) as reported earlier by Szilvási and Vörös (2014). The three electrodes allow the recording of modified versions of the conventional Einthoven bipolar leads, with Lead II corresponding to the signal produced by the white and red electrodes. This was made to provide good-quality recordings in standing animals as shown on Fig.1. Sedated dogs were examined in right lateral recumbency with the Welch Allyn Meditron system, where clip electrodes on the limbs were used for recording the ECG signals as the traditional method (Edwards, 1987; Tilley and Burtnick, 2009). In this group, recordings were also obtained with the 3M Littmann Electronic Stethoscope Model 3200 to produce digital phonocardiograms with the relevant software, as described by Marinus et al. (2017).

1.2.5 Electrocardiography

An Innobase Pico type 7-channel Holter ECG (Innomed Medical Inc., Hungary) was used, equipped with clamp electrodes to follow cardiac function and rhythm during the study. Standard bipolar Einthoven I, II, III as well as unipolar Goldberger aVR, aVL, and aVF leads, and one Wilson thoracic (precordial) lead were recorded simultaneously with this instrument. Together with the Holter recordings, the Welch Allyn Meditron system was also used to produce synchronous ECG curves parallel with the digitalized phonocardiograms. To compare the events on the Holter ECGs with the digital phonocardiogram recordings, we created a unique artifact as a “time mark” on the Holter ECG recording at the start of the digital phonocardiogram recording by touching and moving one of the electrodes by hand for one second.

1.2.6 Comparison and analysis of the ECGs and Welch Allyn digital phonocardiograms

The ECG recordings were examined based on two parameters: (1) deviation from the baseline, and (2) the number of artifacts.

On the ECG recordings of the Holter instrument and on the digital phonocardiograms, the maximal baseline deflection was calculated, by measuring the difference between maximal and minimal points of the baseline on the Y axis, presented in mV. For the Welch Allyn Meditron electronic stethoscope, only a single, transthoracic bipolar ECG was recorded and evaluated (**Figure 6**).

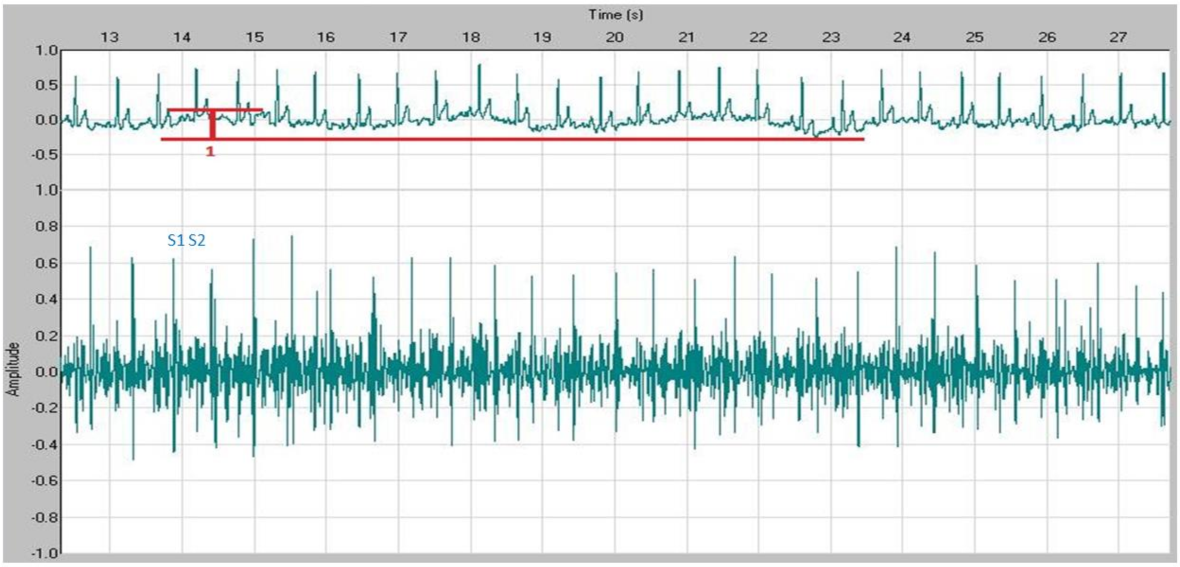

Figure 6. *Measurement of the ECG baseline deviation on a digital phonocardiogram (DPCG) recorded with the Welch Allyn Meditron system.*

The baseline deviation is the difference between the highest (upper, smaller horizontal line) and the lowest (lower horizontal line) points of the baseline, in mV. S1: first heart sound, S2: second heart sound.

For Holter-produced ECGs, all seven leads were examined (**Figure 7**).

Figure 4

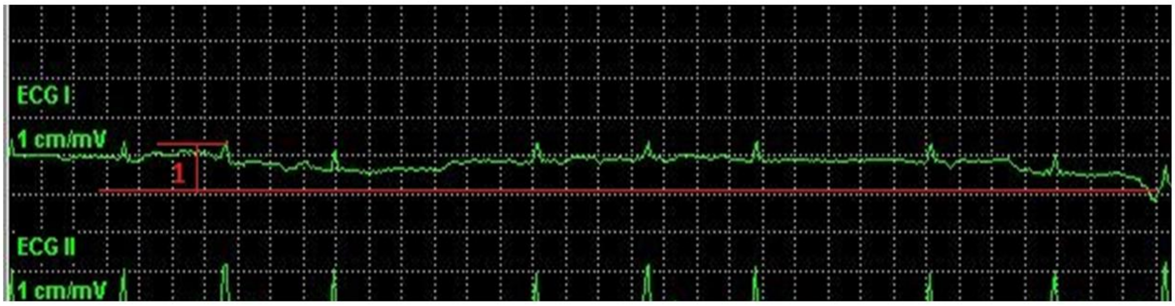

Figure 7. *Measurement of the ECG baseline deviation of Einthoven bipolar lead 1 on an ECG recording made with the Innomed Holter ECG system.*

The baseline deviation is the difference between the highest (upper, smaller horizontal line) and the lowest (lower, horizontal line) points of the baseline, in (1) mV

Artifacts were counted over a 12-sec period, in a manner consistent with the examination of baseline deviation, on the single lead in the case of Meditron recordings, and on all seven leads in the case of Holter recordings. Because artifacts tend to be absent in some leads on the 7-lead ECG, we examined all seven leads separately.

We then examined the ECGs of the seven dogs with pathological arrhythmias by comparing the presence of the extrasystole on ECG and digital phonocardiogram recorded simultaneously by the Welch Allyn Meditron system with the extrasystole present on the 7-lead Holter ECG.

1.2.7 Comparison of digital stethoscopes

We then compared digital phonocardiograms recorded by Welch Allyn Meditron and Littmann digital stethoscopes in 10 cases. First, we measured baseline noise and heart sound amplitude, using an image editing software (Adobe Photoshop CC 2018). We constructed a ratio of average S1 amplitude in pixels to average baseline noise amplitude. With this ratio, a high value means a more distinguishable heart sound. We then counted the number of artifacts over a 12-sec period.

1.2.8 Statistical analyses

We compared the counts of artifacts between the two electronic stethoscopes by Mann−Whitney U tests, corrected for small sample sizes, because only one dog had data obtained by both stethoscopes. We compared the artifacts between the Welch Allyn Meditron and the Holter ECGs using Signed Ranks tests, corrected for small sample sizes. All statistical analyses were performed using a free online statistical calculator (http://vassarstats.net/).

1.3 Results

1.3.1 Technique and applicability of ECG and digital phonocardiogram recording methods of arrhythmias

We could only obtain standardized, reproducible data from 10 out of the 16 sedated dogs. In general, we obtained good-quality ECGs in the 9 standing, awake dogs and in the 10 sedated dogs using the ECG system of the Meditron Welch Allyn electronic stethoscope (**Table 1**).

Table 1. *Baseline deviation of the ECG signals on the Innomed Holter and on the Welch Allyn Meditron DPCG recordings*

mV: millivolts; **PSA**: physiologic sinus arrhythmia; **SR**: sinus rhythm; **PVT**: paroxysmal ventricular tachycardia; **X**: baseline deviation could not be evaluated due to high noise

Case	Breed	Age (year)	ECG diagnosis	Innomed Holter (mV)	Welch Allyn Meditron (mV)
1	Doberman Pinscher	5	PSA	3.9	X
2	American Bulldog	0.3	SR	1.14	0.3
3	Mixed breed	1	PSA	2.9	0.01
4	Rottweiler	4	PVT	5.8	0.1
5	Cane Corso	3	SR	X	X
6	German Shepherd Dog	2	SR	10.5	0
7	Chihuahua	3	SR	7.4	X
8	English Bulldog	0.9	SR	19.7	0.1
9	Bichon Havanese	9	SR	1	0.2
10	Mixed breed	0.9	PSA	X	0.5

Both electronic stethoscopes produced phonocardiograms that allowed identification of the cardiac rhythm in all 10 cases included in the study. Even in cases with higher baseline noise, we could identify a physiologic heartbeat from the digital phonocardiogram or the corresponding ECG. We found that the Meditron Welch Allyn electronic stethoscope produced recordings of reasonable quality (where both baseline noise and artifact count could be evaluated) in five cases, but not in the other five. On the other hand, we found it harder to create digital phonocardiograms of adequate quality with the Littmann 3200 electronic stethoscope which produced 3 adequate and 7 inadequate quality recordings

The digital phonocardiographic appearance of common canine cardiac arrhythmias and abnormal beats are demonstrated in **Figure 6-8.**

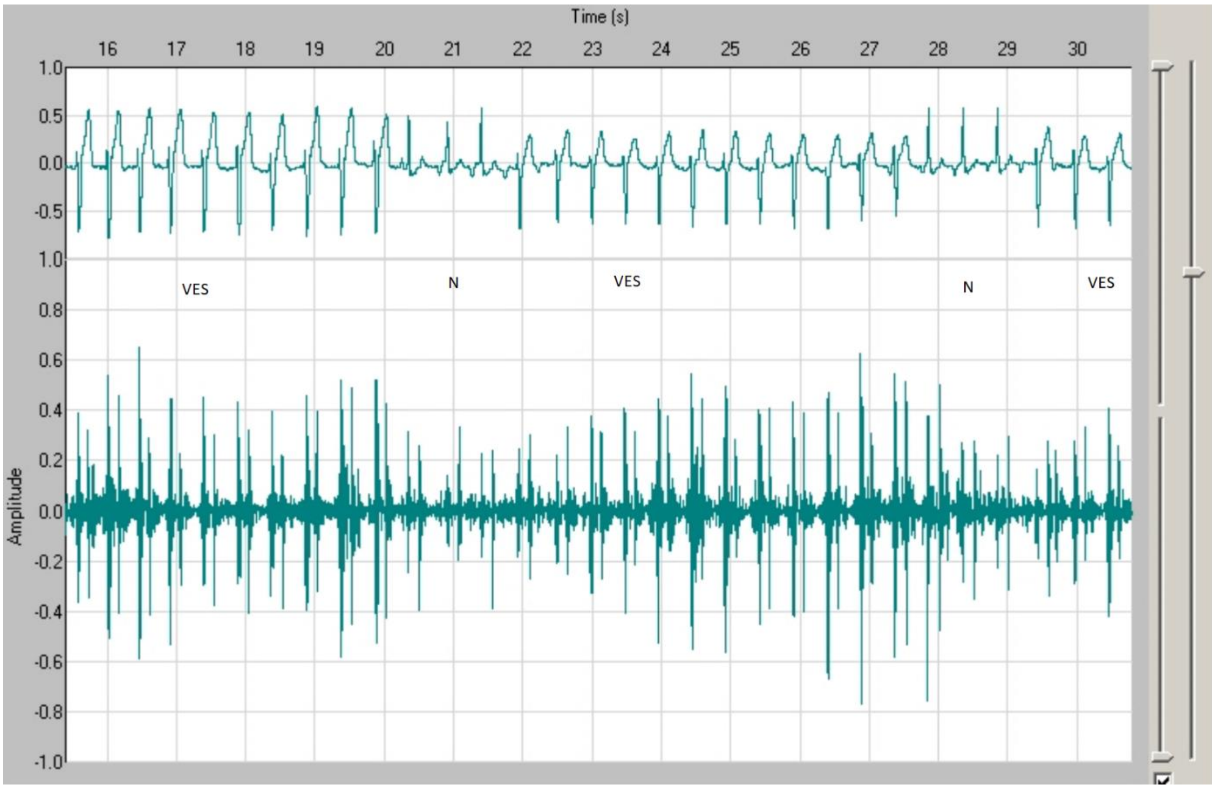

Figure 6. *DPCG and ECG recording of a dog with paroxysmal ventricular tachycardia.* The run of ventricular extrasystoles with abnormal ECG complexes is marked with the text **VES** whereas normal beats are marked with **N**. Note the seemingly random amplitude of both S1 and S2 beats on the DPCG during the VES episodes, and the relatively constant S1 and S2 amplitudes on the normal segments. The changes in phonographic appearance of the heart sounds are in accordance with the ECG tracing. Recording made by the Welch Allyn Meditron Electronic Stethoscope.

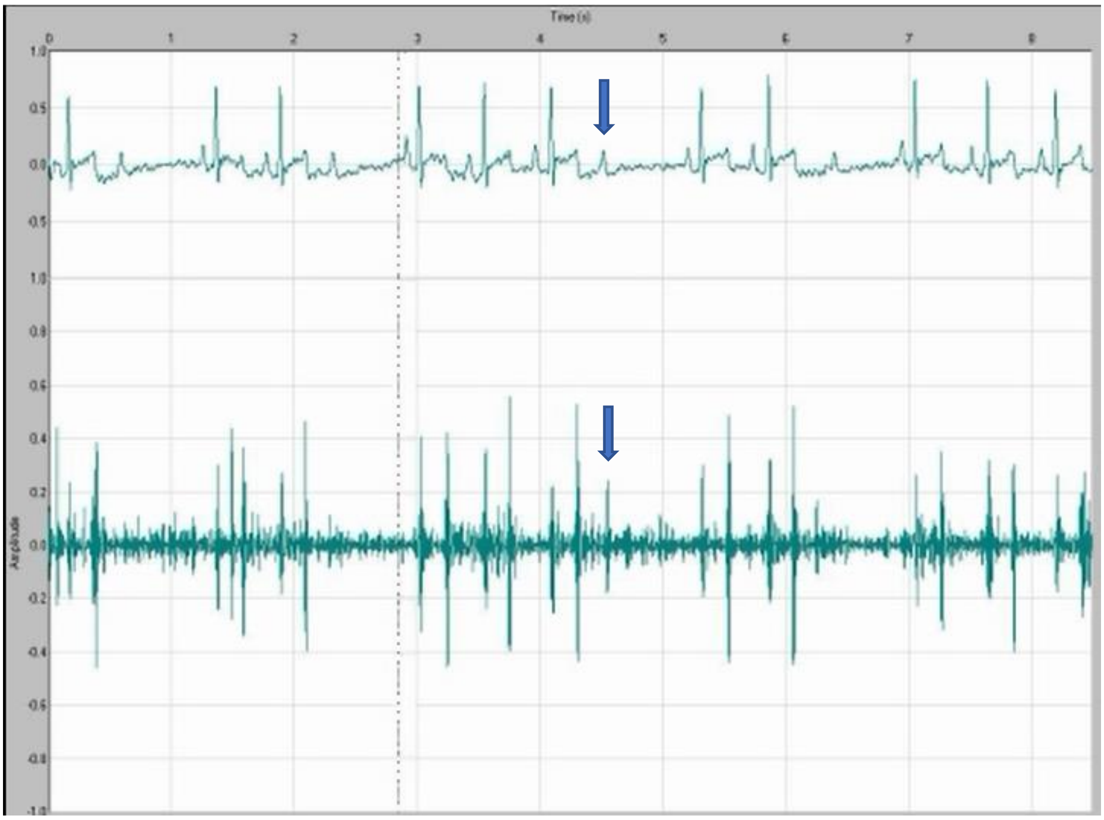

Figure 7. *DPCG and ECG recording of a dog with second-degree atrioventricular (AV) block.* The condition is characterized by isolated P waves without consecutive QRS complexes when the impulse is not conducted from the atria to the ventricles. They can be isolated like in this image or occur in runs. One isolated P wave is marked with an arrow both on the ECG and on the phonocardiogram.

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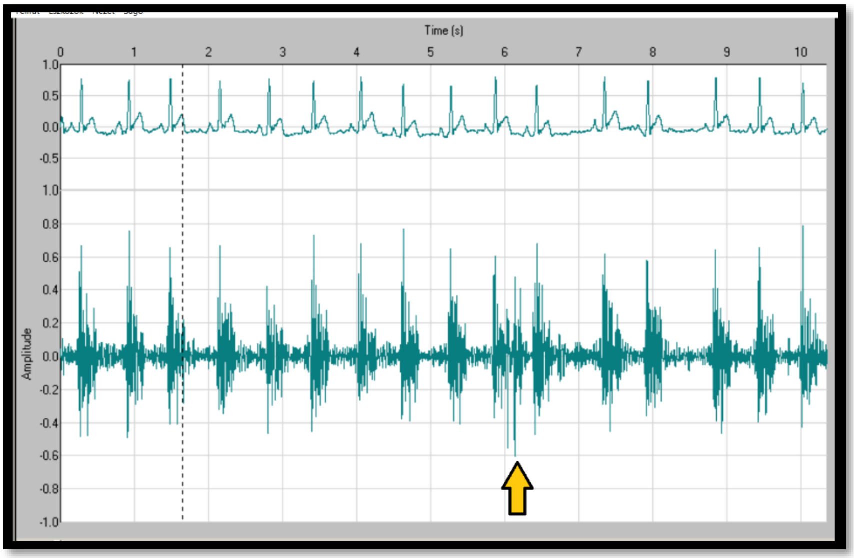

Figure 8. *DPCG and ECG recording an abnormal beat (orange arrow) not causing deflection in the ECG trace.*

A possible explanation of the phenomenon in the figure is that the vector of the abnormal beat was perpendicular to the vector of the single lead (Lead II) the ECG tracing was recorded from. This abnormal beat was most probably a premature extrasystole as to the simultaneous auscultatory finding.

1.3.2 Comparison of the Welch Allyn Meditron and the Holter system for ECG recording of arrhythmias

The ECGs obtained with the Welch Allyn Meditron electronic stethoscope and the Holter ECG demonstrated substantial baseline artifact which affected interpretation of the ECG in 20–30% of the cases. Overall – when not on a level that prevented interpretation – the Welch Allyn Meditron ECG appeared to have a smaller baseline artifact than the Holter ECG, although we did not make a statistical comparison of the amplitude of the artifact.

In five cases, the high baseline noise hindered artifact counting (marked with an X in **Table 2**). The number of artifacts on ECGs produced by the Welch Allyn Meditron and the Holter ECG where we could obtain counts did not differ (Results of the Wilcoxon Signed Ranks Test: W=17, critical W=21. Since the W value of the analyzed population is below the critical W, the result is considered non significant).

Table 2. *Comparison of the number of artifacts of the ECG signals on the Innomed Holter and on the Welch Allyn Meditron DPCG recordings. The numbers represent the count of artifacts*
PSA: physiologic sinus arrhythmia; **SR**: sinus rhythm; **PVT**: paroxysmal ventricular tachycardia; **X**: artifact number could not be evaluated due to high baseline noise

Case	Breed	Innomed Holter	Welch Allyn Meditron	ECG diagnosis
1	Doberman Pinscher	0	X	PSA
2	American Bulldog	0	1	SR
3	Mixed breed	2	1	PSA
4	Rottweiler	2	0	PVT
5	Cane Corso	X	X	SR
6	German Shepherd Dog	3	0	SR
7	Chihuahua	2	X	SR
8	English Bulldog	2	0	SR
9	Bichon Havanese	1	0	SR
10	Mixed breed	X	1	PSA

1.3.2 Comparison of the Welch Allyn Meditron and the 3M Littmann 3200 systems for digital phonocardiographic recording of arrhythmias

There was no significant difference between the noise produced by the two systems (**Table 3**). Over 50% of the cases examined with either stethoscope had such high noise (marked with X) that we were unable to count the number of artifacts. The number of artifacts produced by the Welch Allyn Meditron and the 3M Littmann 3200 electronic stethoscopes did not differ (Results of the Mann-Whitney U Test: U_A:10.5, Critical U_A: 1 to 14. Since the U_A value of the examined population is within the critical limits of the test, the results is considered non significant) (**Table 4**).

Table 3. *Comparison of the baseline noise on the digital phonocardiogram recordings with the Welch Allyn Meditron and with the 3M Littmann 3200 electronic stethoscopes.*

Values show the ratio between the highest audible heart sound to the baseline noise in pixels. Higher values mean lower noise

PSA: physiologic sinus arrhythmia; **SR**: sinus rhythm; **PVT**: paroxysmal ventricular tachycardia; **X**: Signal-to-noise could not be evaluated due to the quality of the recording

Case	Breed	Welch Allyn Meditron	3M Littmann 3200	ECG diagnosis
1	Doberman Pinscher	X	5.6	PSA
2	American Bulldog	3.5	X	SR
3	Mixed breed	19.2	6	PSA
4	Rottweiler	X	X	PVT
5	Cane Corso	X	6.5	SR
6	German Shepherd Dog	12.9	X	SR
7	Chihuahua	X	4.2	SR
8	English Bulldog	6.1	X	SR
9	Bichon Havanese	X	X	SR
10	Mixed breed	5.9	X	PSA

Table 4. *Comparison of the count of artifacts on the DPCG recordings made with the Welch Allyn Meditron and with the 3M Littmann 3200 systems*

PSA: physiologic sinus arrhythmia; **SR**: sinus rhythm; **PVT**: paroxysmal ventricular tachycardia; **X**: Could not be evaluated due to the quality of the recording

Case	Breed	Welch Allyn Meditron	3M Littmann 3200	ECG diagnosis
1	Doberman Pinscher	X	7	PSA
2	American Bulldog	12	X	SR

3	Mixed breed	2	12	PSA
4	Rottweiler	X	X	PVT
5	Cane Corso	X	11	SR
6	German Shepherd Dog	3	X	SR
7	Chihuahua	X	X	SR
8	English Bulldog	9	X	SR
9	Bichon Havanese	X	X	SR
10	Mixed breed	10	X	PSA

1.4 DISCUSSION

Our study shows that electronic stethoscopes produce considerable auditory artifacts, but we were able to discern cardiac rhythms in many cases despite these artifacts. Furthermore, the Welch Allyn Meditron, which includes an ECG that can be acquired simultaneously, provides a better means of analyzing arrhythmias than the 3M Littmann 3200 electronic stethoscope, which does not provide simultaneous ECG recording. Neither stethoscope produced more or fewer phonocardiographic artifacts than the other; however, the number of cases that we could analyze was extremely low, therefore drew our conclusions based on the perceived subjective usability of the devices

We previously showed that the Welch Allyn Meditron electronic stethoscope provided good-quality digital phonocardiograms of canine cardiac murmurs which were helpful in their diagnosis (Vörös et al., 2011). Based on our preliminary experiences with electronic stethoscopes and digital phonocardiography in the present study, these systems can help to detect and document canine arrhythmias, in the same way as cardiac murmurs (Vörös et al., 2011; Szilvási et al., 2013; Marinus et al., 2017).

We used adhesive ECG electrodes while recording the phonocardiograms with the Welch Allyn Meditron to avoid artifacts caused by movement while auscultating dogs in a standing position (Vörös et al., 2011). However, unlike the auscultation of cardiac murmurs, the auscultation of arrhythmias does not depend on specific auscultatory locations (i.e., puncta maxima) and correct positioning of the dog (standing). Therefore, auscultating and DPCG recording of arrhythmias can be performed in right lateral recumbency which would allow standard ECG recordings without movement artifacts.

When comparing the two techniques, phonocardiograms recorded by the 3M Littmann 3200 stethoscope were less reliable for analyzing arrhythmias, because, subjectively, the artifacts produced with this stethoscope made it difficult to identify true arrhythmias. In addition, this stethoscope has a shorter recording period (a maximum of 29 seconds), which could limit arrhythmia detection. As the 3M Littmann 3200 stethoscope does not have a possibility to record synchronous ECGs on the phonocardiograms, ventricular systole and diastole can only be distinguished by identifying the 1st and the 2nd sounds on the phonocardiograms (Blass et al., 2013; Marinus et al., 2017). The identification of additional heart sounds becomes a challenge without synchronous ECG recordings and extrasystoles, even if identified, cannot be differentiated as originating from the atria or the ventricles.

On the other hand, the 3M Littmann 3200 system seems to be easier to use due to its Bluetooth connection (<10 meters) to the computing device (computer and the relevant software).

For teaching and clinical research of heart murmurs and pathological arrhythmias, the Welch Allyn Meditron system is more suitable because of its capability of synchronous phonocardiographic and ECG recordings on the digital phonocardiograms as to the results of my thesis and of previous publications of our research group (Vörös et al., 2011; Szilvási and Vörös, 2014). The other advantage of this system is its reduced background noise due to noise filtering. This electronic stethoscope also provides audio recordings along with the phonocardiograms and ECGs. Consequently, the visual data accompanying the auditory data can help the listener to understand the sounds being auscultated (Ehlers et al., 2010; Vörös et al., 2010; Vörös et al., 2011). Naylor et al. (2001) used analogue (traditional) sound recordings of heart murmurs and arrhythmias of horses (but without ECGs and PCGs) for teaching purposes with good results. To the best of our knowledge, there is no other similar publication in the literature on education of cardiac arrhythmias.

Further digitalizing techniques like spectral analysis, acoustic cardiography, and spectrocardiography – which are beyond the scope of this thesis – can be used in the clinical research and teaching of cardiology (Tavel and Katz, 2005; Höglund et al., 2007; Ljungvall et al., 2009; Wen et al., 2014). A promising technique involves smartphone digital phonocardiography (Leng et al., 2015; Thoms et al., 2017).

Our study has some limitations as well, like the low number of cases analyzed in detail and presented in the tables. We did not attempt to analyze the particular arrhythmias elicited by anesthetic drugs, as this was not among the goals of the present study. As such, the different anesthetic protocols used in our study did not influence our technical results.

Further noise reduction is also challenging with phonocardiograms produced by the Welch Allyn Meditron electronic stethoscope, as neither Audacity, nor Adobe Audition FFT (Fourier Transform Filter) filters support a single channel application (the audio channel, with the ECG tracings being recorded in the second channel).

It is worth noting that the Welch Allyn Meditron system is no longer produced; therefore, some of the artifact issues we observed might have been addressed with newer electronic stethoscopes that might include better filters both for the audio signals and the ECG signals. The 3M Littmann 3200 remains available but has not been updated to include a simultaneous ECG recording.

Based on our investigations, the development of an electronic, wireless stethoscope with the ability of on device ECG recording in multiple leads would eliminate most of the difficulties of recording DPCGs of arrhythmias. The possibility to view the DPCGs during the examination and recording process (either on the display of the device, or on the screen of the connected device) would facilitate in bedside diagnostics, as well as quick revision of materials elected to be used in education. Bluetooth connection, and a proper software support would allow the connection of mobile phones and tablets, greatly increasing the versatility of the device, and making it suitable for house calls as well as telemedicine.

Since the conduction of the study, the EKO Duo ECG wireless electronic stethoscope has been made commercially available. The authors suggest the evaluation of this stethoscope based on the criteria in this publication, especially because of the wireless nature of this tool, and the ability of ECG recording, albeit it being single lead only.

Our preliminary observations suggest that electronic stethoscopes, when coupled with simultaneously obtained ECG recordings, might help educate veterinary students about cardiac arrhythmias as well as murmurs.

2. Remote teaching of canine cardiac auscultation using digital phonocardiograms

2.1 Introduction

Both the European Coordinating Committee on Veterinary Training and the American Veterinary Medical Association consider cardiac auscultation a “day one” competency requirement (Jorna et al., 2019). This skill is a practical one and, based on previous research, can be taught by repetition (Barett et al., 2004).

Various investigators have sought to improve education of auscultation, using both recorded (Vörös et al., 2011) and computer generated (Barett et al., 2004) heart sounds. Digitalized (either generated or recorded) heart sounds have the benefit of providing further information for the students, such as a simultaneous electrocardiogram (ECG), that can demonstrate the impulse changes within the heart, and how they relate to heart sounds. Digital phonograms of the heart sounds - phonocardiograms (DPCGs) - can be created using appropriate software, directly from the recorded heart sounds, providing a visual representation of the sound waves using a time-amplitude graph (Durand et al., 1995). Different heart sounds (S1-S4), cardiac murmurs and abnormal beats (e.g., arrhythmias) can be visualized on the DPCGs. When presented in the same file (a video file where the audio channel is the heart sound and the video feed is the DPCG) students can visualize amplitude differences corresponding to different cardiac events, including harder to hear murmurs, which still alter the phonocardiogram (Szilvási et al., 2014). This is further enhanced by simultaneously recorded ECGs (Vörös et al., 2011).

In 2020 and 2021, veterinary and medical education faced significant challenges due to the COVID-19 pandemic, with reliance on remote and self-guided learning methods. Universities transferring to online education and enforcing remote learning limited the teaching of many practical skills that require physical interaction between the teacher, students, and patients, affecting the academic performance of students (Mahdy, 2020). Although auscultation is a practical skill, it does not necessarily require live animals and physical contact to be effectively taught – several publications have shown successful transfer of this skill via recorded and created materials (Barett et al., 2004). A benefit of digital phonocardiograms among these learning materials is that they also present the otherwise solely auditory heart sounds in a bisensory, audiovisual manner. Previous research suggests that utilizing bisensory educational materials improves learning outcomes compared to resorting to only auditory training

(Bernstein et al., 2013). Researchers recommend including physiologic (non-pathological) examples in training materials because of the bias towards abnormal findings that less-experienced trainees display (Boutis et al., 2010).

In human medicine, a recently published review evaluated 42 research papers detailing remote teaching methods of cardiac auscultation, including online, digital resources, mobile apps, podcasts, serious gaming and social media, reporting variable effectiveness of the individual platforms (Bridgwood et al., 2021). In that review, online modules focusing on specific subjects demonstrated non-inferiority compared to lecture-based learning, but no superiority was established. Online seminars, tutorials and symposia presented as slides however, demonstrated improved learning outcomes in the evaluated articles when compared to in-person tutorials.

Ehlers et al. (2010) reported teaching veterinary students auscultatory skills by providing DPCGs of canine heart murmurs. These authors used the sound collection methodology constructed by Vörös et al. (2010), which is unique, as it allows simultaneous ECG and sound recording. However, the authors did not include a control group. Furthermore, the authors did not compare the two different training methods (self-study web-based training and a face-to-face seminar) to a training method without DPCGs or ECGs. Naylor (et al., 2001) published the sole article in veterinary medicine on using analogue sound recordings -but no ECGs or DPCGs - of equine cardiac murmurs and arrhythmias for education. To our knowledge, no similar study exists in small animal veterinary cardiology. In human cardiology, we are aware of only one study examining the sensitivity of electrical stethoscopes for recording and identifying cardiac arrhythmias in telemedicine (Zenk et al., 2004). To our knowledge, no prior research in veterinary medicine exists that on the additional educational value of ECG tracings to DPCG recordings.

The aim of the present study was to evaluate the impact of online remote teaching methods, utilizing DPCGs and synchronous ECGs, on development of veterinary students' ability to identify canine heart murmurs and arrhythmias.

2.2 Materials and methods

DPCG recording and editing

Digital phonocardiograms of canine heart sounds were recorded and processed during the prior studies by our research group (Vörös et al., 2011, Szilvási et al., 2014, Vörös et al., 2012, Balogh et al., 2021). The video files were annotated using Adobe Premiere Pro CC.

Student population

Forty-two students from the University of Veterinary Medicine, Budapest (UVMB) participated in the study. Students volunteered for the study, and were recruited from third (preclinical), fourth and fifth (clinical) years. In the frame of the curriculum of UVMB, all students completed the third-year subject “Clinical Diagnostics”, including lectures and basic practical lessons on physical examination of the cardiovascular system. Each student provided a nickname for the study to retain anonymity, while allowing us to track group-based and individual improvement.

The students were randomly divided into three groups (using the random number function in Microsoft Excel and organizing them according to value). A larger control group (n=20) was created to counter the expected drop off based on literature and our previous research.

Pre- and post-training tests

Each group underwent a pre- and post-training test within a four-week interval. Both tests consisted of the same 10 canine heart sounds, with two multiple choice questions about each sound file (**Table 5**). The first question required the student to identify the cardiac abnormality (murmur, arrhythmia) or a normal heart sound from the recording. The second question was predicated on the answer to the first question. If a student correctly answered ‘heart murmur’ for a recording, they were asked to identify the type of heart murmur from the presented options (plateau murmur/machinery murmur/crescendo/decrescendo/crescendo-decrescendo murmur). If a student answered “arrhythmia” for a recording, they were asked to identify the type of arrhythmia from the options provided (respiratory arrhythmia, bradyarrhythmia, tachyarrhythmia, isolated ventricular extrasystole). If a student answered “normal heart sound” for a recording, they were not directed to a further question. The follow-up questions for murmurs and arrhythmias allowed students to choose ‘I don’t know’ to reduce guessing, however the first question did not have this option, as students already underwent necessary training to be able to answer it.

Table 5. *Pre- and post-training test questions and answers.*

Q1: First question, **Q2:** Second question **A:** Arrhythmia, **N:** Normal heart sound, **M:** Murmur, **TA:** Tachyarrhythmia, **PM**: Plateau murmur, **BA:** Bradyarrhythmia, **MM:** Machinery murmur, **IE**: Isolated Extrasystole**, CDM**: Crescendo-decrescendo murmur. The two possible follow up questions (identify the type of murmur/identify the type of arrhythmia) question are presented in the same row due to their mutual exclusivity in this study (no recordings with simultaneous murmur and arrhythmia were included).

Question Number	1	2	3	4	5	6	7	8	9	10
Q1	A	N	A	N	M	A	M	M	A	M
Q2	TA	-	TA	-	PM	BA	MM	PM	IE	CDM

The 10 cardiac recordings included 2 normal heart sounds, 4 pathological arrhythmias, and 4 heart murmurs. They were presented in the same order to students on the pre- and post-training tests. Students did not receive feedback on their score. Although students completed both tests from home, no measures were taken to prevent cheating other than asking in the briefing session to not cheat, as it would serve no benefit, other than to distort the results. Students had a day long window to complete both tests, to fit their differing schedule. Pre- and post-training test recordings were audio only and did not include DPCGs.

Training

The investigators asked students undergoing self-study (n=12) to spend 3 hours on a website, created for the purpose of this study, that demonstrated the normal and abnormal heart sounds including, but not limited to, those of the tests via sound files (mp3) and annotated videos of the DPCGs (mpg) created from them, containing synchronous ECGs. The fact that certain recordings were created from the sound files of the tests was not mentioned on the website.

The second group of students (n=10) participated in a one-hour webinar that detailed the individual heart sounds in the heart sound library itself, examining heart sounds and DPCGs including but not limited to those appearing in the test. The presenter commented on all recordings. This presentation was recorded and shared with the group for later review. The presenter held a question-and-answer session after the lecture. Similarly to the self study website, the fact that the presentation contained sounds from the tests was not mentioned or commented on.

The third group of students (n=20) served as a control group. These students had no training between the pre- and post-training tests, i.e., they had to rely on their understanding of the material presented during the teaching of the "Clinical Diagnostics" course.

Before the post-training test, there was a two-day-long washout period for each training group, during which they could not access their respective learning materials (the self-study website and the recording of the webinar). Each student from the self-study group had to state how much time they spent on the training website. Students who had been allocated to the webinar session were asked about whether they attended the webinar, watched the recording afterwards, both or none. Dropoff was measured in all groups – students who participated only in the pre-training test or did not spend time with the provided materials for their respective group were excluded from the study. Based on these requirements, no student was excluded from the study from either training group, while 6 students were excluded from the control group, because they failed to take part in the post-training test, resulting in a final number of 14 students in that group. The two training groups had no access to their training materials during the tests.

Scoring

Students scored one point for each correct answer for both tests. Each student acquired a score for the first set of questions (out of 10) and second set of questions (out of 8). A student failing to answer a question correctly in the first set would not be provided with an opportunity to answer the relevant question in the second set. We also tallied the scores for each subset of recordings: normal heart sounds (maximum possible score = 2), murmurs (maximum possible score = 4 for each set), and arrhythmias (maximum possible score = 4 for each set).

Statistical methods

Pre-study power calculations were not performed because the voluntary nature of student enrollment prevented us from altering the sample size within the time available for the study. Post-hoc power calculations on non-significant results were performed with the software G*Power Version 3. 1.9.7 to determine if a realistically increased sample size could detect differences in these outcomes.

To ensure that the three groups of students were similarly trained prior to the trainings, we first compared the pre-training test scores for the first and second question between the three groups using a Kruskal-Wallis test, with Dunn's Post-hoc testing when appropriate.

To detect a training effect, we then compared differences in the pre- and post-training scores for the first and second question between the three groups using a Kruskal-Wallis test with Dunn's post-hoc testing where appropriate.

We also examined the pre- and post-training scores for the first question for each group separately using a Wilcoxon Signed Ranks test. Significance was established at $p<0.05$.

2.3 Results

The pre-training scores for the first question did not differ between the groups (P=0.22). We also failed to detect differences in the pre- and post-training scores for the first question between the groups (P=0.2). However, both training groups (self-study and webinar) showed improved post-training scores (P=0.024 and P=0.037, respectively) compared to their respective pretest scores while the control group did not (P=0.49).

The pre-training scores for the second question did not differ between groups (P=0.9). However, both training groups showed improvement after training, compared to the control group (P=0.00031 for the self-study group, P=0.0073 for the webinar group and P=0.98 for the control group).

When analyzing the subcategories of the first question (heart sounds, murmurs, arrhythmias), the differences in pre- and post-training scores between groups did not differ for the first murmur questions (P=0.187), normal heart sound questions (P=0.29) or arrhythmia questions (P=0.39).

When analyzing the subcategories of the second question (murmurs, arrhythmias), both training groups showed improved scores for the murmur questions (P=0.002 and P=0.0003, respectively), and arrhythmia questions (P=0.005 for both groups), compared to the control group (P=0.77 for murmur questions, P=0.61 for arrhythmia questions).

Pre- and post-training test performance of all three groups are presented in **Figure 9**.

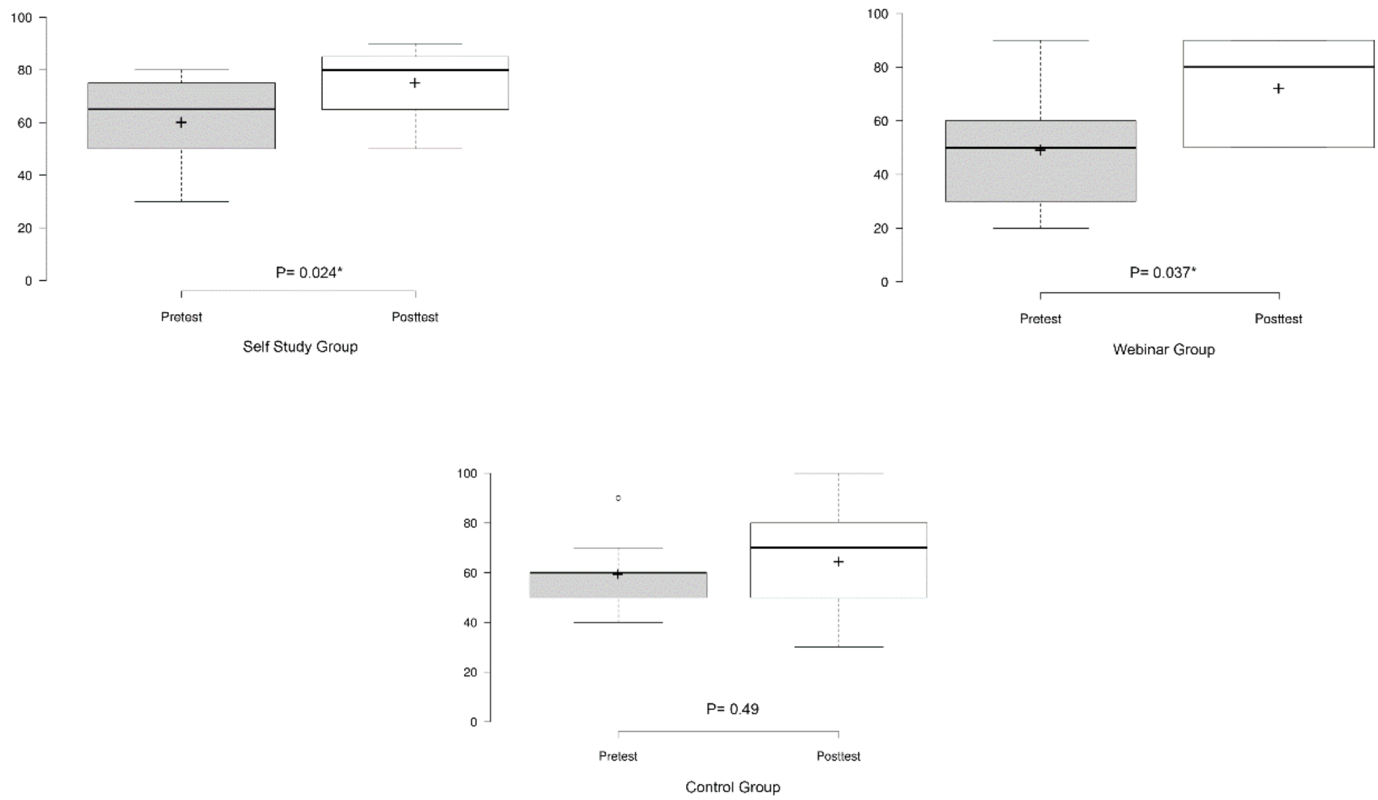

Figure 9. *Pre- and post-training test scores of all three groups.*

Top left: self-study group. Top right: webinar group Bottom: control group. The y axis represents achieved score, in percentage. * Represents statistically significant difference. Box plot bottom and top borders represent the 1st and 3rd quartile, respectively. Horizontal bold lines represent the median of values. Bottom and top whiskers represent minimum and maximum values. Icons represent outliers. Box plots were generated using http://shiny.chemgrid.org/boxplotr/.

Individual pre- and post-training test scores of the self-study, the webinar and the control groups are presented on **Figures 10** and **11** respectively.

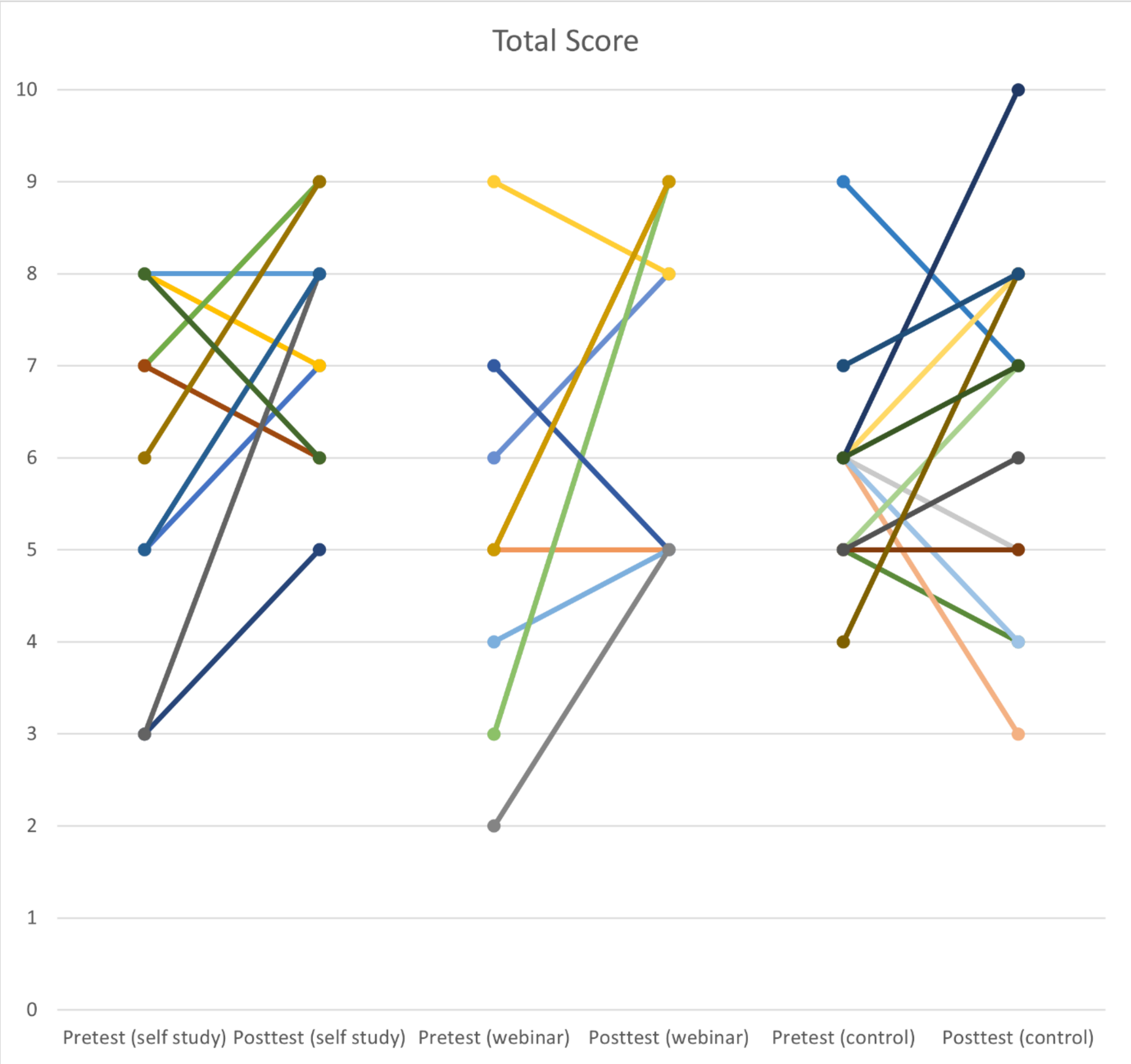

Figure 10. *Individual changes in total first question score (out of 10) for all three groups in the pre- and post-training tests.*

Each data point represents a student.

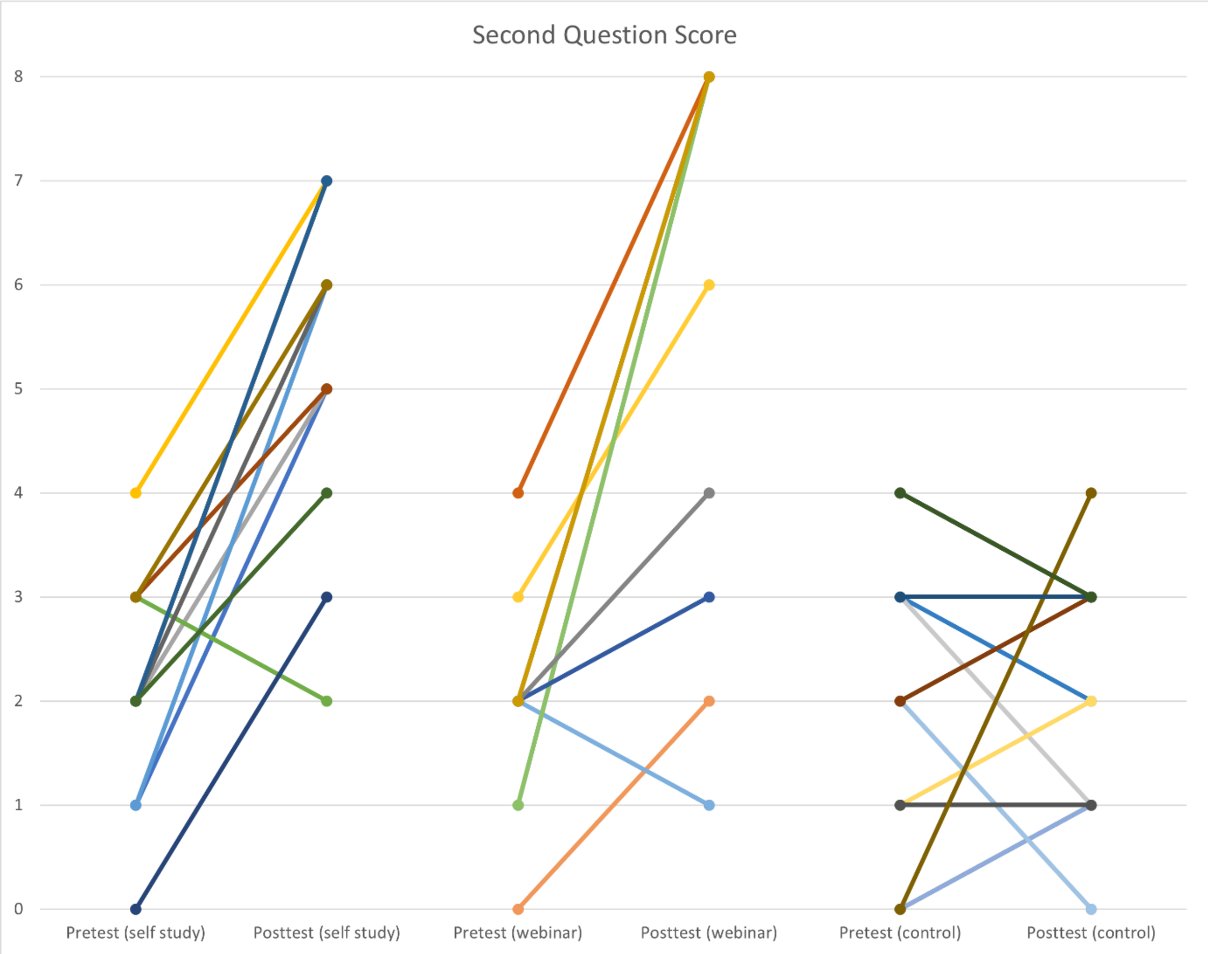

Figure 11. *Individual changes in total second question score (out of 8) for all three groups in the pre- and post-training tests*.

Each data point represents a student.

2.4 Discussion

Our study suggests that remote online training of auscultatory skills using digital phonocardiography improves the ability of veterinary students to correctly identify murmurs, arrhythmias, and normal heart sounds.

We failed to detect any difference between the three groups of students on the pre-training tests (first and second question). This might support the contention that the participating students had similar knowledge (skill) levels at the beginning of this study, despite being selected from different years in training, but can also be the result of the small sample size.

The improvements in the scores for questions one and two in the self-study and webinar groups after the training sessions, but not in the untrained group, indicate that both training methods were effective. Conversely, the failure of the control group to improve their test performance suggests that these students did not receive effective additional training during the 4 weeks between the tests. The authors did not manage to identify the reason why certain members of the control group performed worse on the posttest (even though efforts were made to prevent guessing) as individual students could not be interviewed, as their credentials and contact information were unknown to the authors to retain their anonymity.

We failed to observe a difference between the three groups in the changes of the scores for the first question. This finding seemingly contradicts the observations that both training groups had a higher post-training score than pre-training score, whereas the control group did not. Several factors could affect this. If, for example, the control group had higher pre-training scores, they would be unable to improve as much as the other two groups. However, our analysis at baseline failed to support this idea – all three groups had initial scores that did not differ. A more plausible explanation is that our sample size was too small to detect a difference between groups but could detect a within-group change (which is a more powerful analysis method). Supporting this explanation is the observation that both the self-study and webinar groups did improve their performance on the second question, compared to the control group. Also supporting this explanation is the low power of the test (0.23). Based on post-hoc power calculations, with the same pre- and post-training test differences (effect size=0.19) a sample size of 57 students would have yielded a significant difference. With the same sample size, a higher effect size of 0.25 would have been needed to show significant difference in the post tests between the groups. It is important to note however, we cannot predict whether an increased sample size would yield a significant difference.

Students failed to improve in their ability to recognize normal heart sounds. This contradicts the prior findings of Naylor et al. (2001) where even the student group managed to identify normal heart sounds in 78% of cases. Two reasons for this discrepancy exist. First, we only included two recordings of normal heart sounds. Second, the increase in the ability to detect abnormalities might also suggest that students are indeed biased towards abnormal findings (Boutis et al., 2010).

Ehlers et al. (2010) also reported improvement in students' ability to identify heart murmurs but failed to detect a difference in performance based on year of schooling of the students. Unlike these investigators, we did not evaluate students according to clinical year. Because of the lack of evidence in the study of Ehlers and colleagues, and to further retain student anonymity, we decided not to look at the clinical year of any student participants. Further, Ehlers and colleagues measured the combined effect of the two training methods. We were unable to include a fourth student group because of the small participant population. Therefore, whether providing both self-study and webinar training to students could augment improvements in heart sound recognition remains unknown.

The improvement in the question examining specific details of heart murmurs by both training groups matches previous findings of our research group constructed by our research group earlier (Vörös et al., 2011). However, our study did not include innocent murmurs. Medical students have shown improvement in differentiating innocent and pathological murmurs after training with DPCGs, however their pre- and post-training tests included phonocardiograms as well (Vörös et al. 2010). Whether similar differentiating ability would occur with veterinary students, or by testing students with audio only recordings, remains unresolved.

We failed to show improvement after training of identifying arrhythmias. However, in cases where students correctly identified an arrhythmia, they improved their ability to correctly describe the arrhythmia after training. Again, these results might be an effect of a small study sample of arrhythmias (n=4).

Improvement in the results of the first and second question of the training groups seems to support our hypothesis that both distanced learning tools utilizing DPCGs have positive learning outcomes on student's performance in identifying canine cardiac sounds, however there are several limitations to our study.

One limitation of the study is that it did not involve test sessions involving live dogs and bedside examinations. This would have been important, as it would measure if the increase in the efficiency to identify recordings translates into identifying heart sounds *in situ*. However, due to the current regulations related to the COVID-19 pandemic, we were unable to conduct such examinations.

Another limitation of the study was the lack of self-assessment included in the self-study material, as this might increase the effectiveness of this teaching method.

Further limitation of the study is that qualitative feedback from students was not collected – this would have provided valuable feedback on the students' perspective of the examined teaching methods, as well as potential challenges that could have affected learning outcomes.

Although the webinar group did not have access to the recording of the DPCGs in the washout period, the Heartsound Library (Vörös et al., 2010) was not taken offline. The students were not provided the hyperlink of this resource until the end of the posttest and it was only presented to them in a screen share during the webinar, and even though they could have located the library via internet searching during the washout period, the authors did not consider this as a factor that could potentially alter their results.

Even though recurring heart sounds (those that appeared both in the tests and the training) were not explicitly mentioned to students, their presence could alter the results, as there is evidence supporting repetition improving the ability to identify heart sounds (Barrett, et al., 2004). The authors recommend that further research should utilize different heart sounds in their training than those used in the tests.

Finally, no group underwent training without DPCGs. Even though there is documented evidence supporting positive learning outcomes of multisensory training, we can only conclude that both additional training methods were successful compared to no extracurricular training, however the role of DPCGs in this success cannot be established until further research is done that includes training without DPCGs.

In conclusion, our study shows that students can improve their ability to identify and characterize heart sounds by remote training, however the role of DPCGs in this improvement remains unclear. There is no difference in effectiveness of the two training methods (self-study or webinar), except for the ability to detect normal heart sounds, which should be reevaluated using an altered webinar structure, providing a greater emphasis on normal heart sounds. Therefore, students should be provided with both learning options and be allowed to choose the option they prefer. Our results suggest that educators should consider creating virtual veterinary patients, similar to human medicine, where there was improvement in the student’s knowledge in cardiology using virtual patients as a delivery method for similar recordings.

3. New scientific results

1. Objective, quantifiable parameters have been established as the basis of comparing phonocardiograms and electrocardiograms created by different electronic stethoscopes. These parameters are the baseline deviation and the number of artifacts and can be used when evaluating other tools in future research.
2. The methodology for recording normal heart sounds and murmurs previously developed by our research group is applicable to the recording good quality DPCGs of cardiac arrhythmias.
3. The digital phonographic appearances of common canine cardiac arrhythmias have been documented.
4. Educational materials utilizing DPCGs provide significant improvement in both the diagnosis of heart murmurs and arrhythmias, regardless of the delivery method of these material. The improvement in the ability to identify arrhythmias via auscultation after training with DPCGs has not been demonstrated in veterinary medicine before this study.
5. The Heartsound Library constructed by our research group with canine cardiac murmurs has been expanded with DPCGs enhanced with synchronous ECGs and audio recordings of canine arrhythmias in the frame of the present study. The recordings presented on the site are annotated with key markers, and they are freely accessible worldwide.

4. Prospects for further research

Based on the results presented in this doctoral thesis, further prospects for research have arisen, regarding further streamlining the creation of DPCGs, and isolating the exact impact of them in the education of auscultation. In order to answer these questions, the following studies can be suggested:

1. Evaluation of other, commercially available electronic stethoscopes, including the EKO Duo ECG electronic stethoscope according to the parameters presented in our study.
2. Development of a wireless electronic stethoscope capable of ECG recording.
3. Evaluation of the isolated impact of DPCGs in the improvement of student's performance with the inclusion of an extra student group receiving training not utilizing DPCGs.
4. Evaluation of the cumulative impact of webinar and self-study materials utilizing DPCGs, with the inclusion of a fourth student group participating in both training methods.

Alternatively, further research is suggested in the diagnostic and educational value of DSCGs, especially, as spectrocardiograms can be created from any good quality phonocardiogram, including our existing library of heart sounds. The following research is suggested:

1. Evaluating the role of spectrocardiograms in isolating auditory artifacts from abnormal beats in digital phonocardiograms.
2. The comparison of the role of DSCGs and DPCGs in the diagnosis and education of canine heart murmurs and arrhythmias.

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