University of Hradec Králové
Faculty of Science

Bachelor Thesis

2024 **Farah Badreddine**

University of Hradec Králové
Faculty of Science
Department of Physics

Ballistocardiography of animals

Bachelor Thesis

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Study program: Physical-Technical Measurement and Computer Technology.
Field of study: Physical-Technical Measurement and Computer Technology.

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Hradec Králové 2024

Univerzita Hradec Králové
Přírodovědecká fakulta

Zadání bakalářské práce

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Studijní obor:	Physical-Technical Measurement and Computer Technology
Název bakalářské práce:	**Balistokardiografie zvířat**
Název bakalářské práce AJ:	Ballistocardiography of animals

Anotace:

Primárním cílem této bakalářské práce je prozkoumat koncept balistokardiografie u zvířat. Práce je strukturována do tří hlavních částí. První část obsahuje teoretický rámec, poskytující rozsáhlý pohled na balistokardiografii, především se zaměřením na její aplikaci u lidí. Po teoretickém přehledu se práce podrobně zabývá specifiky balistokardiografie u zvířat, diskutuje různé používané techniky a problémy, se kterými se v této oblasti setkáváme. Závěrečná část zahrnuje experimentální praktický experimentální aspekt, kde jsou analyzovány balistokardiogramy zvířat. To zahrnuje posouzení jejich přítomnosti na měřicí podložce, hodnocení úrovně jejich aktivity, určení jejich srdeční frekvence a měření dechové frekvence.

Zadávající pracoviště:	Katedra fyziky, Přírodovědecká fakulta
Vedoucí práce:	RNDr. Damián Bušovský
Oponent:	doc. RNDr. Filip Studnička, Ph.D.

Datum zadání závěrečné práce: 11.8.2021

Statement:

I declare that I have prepared my Bachelor thesis independently using AI to rephrase some sentences and to change some words and that I have listed all the sources I have used in the list of literature.

Signature

In Hradec Králové on

2-6-2024

Farah Badreddine

Acknowledgement:

Firstly, I would like to express my sincere gratitude to my supervisor RNDr. Damián Bušovský, for the continuous support, endless patience and very kind approach. His immense knowledge and guidance helped me in every aspect of this Thesis.

Additionally, I would like to thank to the institutional support of the Faculty of Science, University of Hradec Králové.

Lastly, I would like to express my gratitude to my family and friends for their unwavering encouragement and emotional support during the writing process of this bachelor's Thesis.

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Annotation:

The primary objective of this Bachelor Thesis is to explore the concept of ballistocardiography in animals. The thesis is structured into three main parts.

The first section comprises the theoretical framework, providing extensive insights into ballistocardiography, primarily focusing on its application in humans. Following the theoretical overview, the thesis delves into the specifics of ballistocardiography in animals, discussing various techniques utilized and the challenges encountered in this field.

The final segment involves the experimental or practical aspect, where animals' ballistocardiograms are analysed. This includes assessing their presence on the measuring pad, evaluating their activity levels, determining their heart rate, and measuring their breath rate.

Keywords:

Ballistocardiography, heart rate, breath rate, sensors, cardiovascular function

List of abbreviations:

SDB: sleep-disordered breathing

OSA: obstructive sleep apnea

PSG: polysomnography2

BCG: ballistocardiography

PVDF: piezoelectric polyvinylidene fluoride

SCG: seismocardiography

ECG: electrocardiography

BR: breath rate

HR: heart rate

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1.THEORETICAL PART

1.1 INTRODUCTION

Globally, healthcare expenses are expected to rise continuously, placing increasing pressure on the healthcare infrastructure, especially with the growing elderly population in the coming years. For instance, as individuals age, they may develop conditions like sleep-disordered breathing (SDB), also known as obstructive sleep apnea (OSA), along with related cardiovascular issues, which are prevalent clinical disorders. The standard method for accurately diagnosing OSA is polysomnography (PSG), conducted in specialized sleep clinics, involving an overnight stay. While PSG offers precise real-time data, it poses challenges such as complexity, invasiveness, high costs, and privacy concerns. Advancements in technology now allow for non-invasive and discreet monitoring of vital signs through innovative hardware and software. An alternative diagnostic approach for OSA and cardiovascular diseases is "BALLISTOCARDIOGRAPHY".

1.2 BALLISTOCARDIOGRAPHY

Ballistocardiography (BCG) is a non-invasive method used to produce a visual representation of the rhythmic movements induced by the heartbeat within the human's or the animal's body. These repetitive movements occur because of the swift acceleration of blood during relaxation (diastole) and contraction (systole) phases, as it is propelled through the major vessels of the body. For example, BCG offers insights into the efficiency of the circulatory system by measuring mass movements, which encompass both the circulating blood mass and the movements of the heart throughout the cardiac cycle. BCG is a technique that captures the body's movements caused by the forces generated during heart contractions, as well as the acceleration and deceleration of blood. It's worth noting that the BCG offers a wealth of valuable information in a straightforward and readily applicable manner, which is otherwise not accessible. Therefore, it serves as a valuable supplement in heart examinations.

In other words, the BCG signal records the momentum of the heart resulting from the forceful expulsion of blood into the major vessels during each heartbeat, breathing, and body movement. In recent times, various types of sensors are available for BCG signal acquisition, such as piezoelectric polyvinylidene fluoride (PVDF) sensor, electromechanical film-based sensor, pneumatic sensor, optical fiber sensor, including polyvinylidene fluoride film-based sensors, electromechanical films, strain gauges, hydraulic sensors, microbend fiber-optic sensors, and fiber Bragg grating sensors and so on. These sensors can be embedded in the patient's surrounding environment, such as bedposts, mattresses, cushions, backrests, pillows, chairs, and weighing scales, and they can be used in standing, sitting, and lying positions to monitor cardiac function

while resting, working, or sleeping, without causing psychological stress or attentional responses. Despite offering a more convenient and comfortable means of monitoring vital signs, analysing BCG sleep tracking, but factors such as mattress thickness, body movements, motion artifacts, and bed partners can degrade the signal quality. [1][2]

1.3 PHYSICAL PRINCIPLES AND TECHNICS OF RECORDINGS

The underlying principle of BCG is rooted in Newton's third law of motion, which states that every action has an equal and opposite reaction. Previously, the term "force of the heart" was more figurative, but through BCG, it has gained tangible meaning and measurability. While clinical interest in this field traces back to Starr's significant contributions, BCG has a long and storied history. A regular sequence of waves is captured in the ballistocardiogram, with major components labeled as the H, I, J, K, and L waves by Starr. Although these waves correspond to specific events in the cardiac cycle, their precise qualitative and quantitative interpretation remains challenging for several reasons.

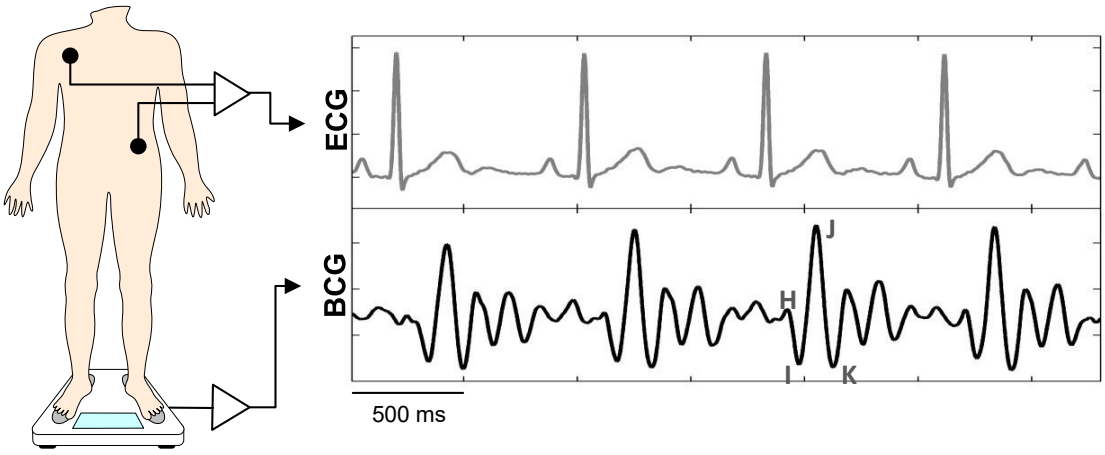

Fig. 1. Example of BCG waveforms acquired by a modified weighing scale. [3]

Both the right and left sides of the heart contribute to the ballistocardiogram, with their effects constantly fluctuating, making it difficult to distinguish their individual contributions. The recorded waves represent resultant vectors of various forces, some of which may oppose each other. In cases of rapid heart rates, waves associated with events during diastole can overlap with early systolic waves of the subsequent cycle, complicating interpretation, particularly during tachycardia. Most current ballistocardiographic techniques focus on recording forces along the body's longitudinal axis, as these best reflect the primary forces linked with cardiac contraction. However, the primary vectors related to specific blood flow aspects during

the cardiac cycle might be directed in alternative directions. To address this, ballistocardiograms can be recorded in other planes, such as the lateral direction or through multispatial vector registration. The forces produced by the expulsion of blood from the heart and its propulsion through the major vessels must traverse through various tissues, the skeletal structure, and the panniculus to reach the recording system. Consequently, the compliance of body structures, combined with the natural motion frequency of the body, imposes certain modifications on the waves recorded. It's essential to minimize body motion, including muscular activity, during the recording process. However, achieving complete relaxation, necessary for accurate BCG, can be challenging in the upright position, particularly for elderly or unwell subjects who struggle to maintain a recumbent position on a firm surface.

Most ballistocardiographs with extensive experience utilize a suspended table where the subject lies down, and body movements translate into longitudinal movements of the table, which are then recorded. However, this method introduces several distortions in the ballistocardiographic waves due to the natural frequency characteristics of the recording table. The high-frequency undamped tables, like the one developed by Starr, have a natural frequency of about 9 cycles per second. While this eliminates very low-frequency respiratory waves, it also dampens lower frequency waves of the cardiac cycle, leading to distortion in magnitude that varies with the cycle frequency. Another form of distortion, termed differentiation, occurs due to the introduction of the time constant, resulting in spurious negative waves following steeply sloped positive waves. To address the distortion inherent in the Starr table, Nickerson introduced a low frequency (1.5 cycles per second) critically damped table, although this method introduces its own set of challenges. The introduction of more direct and simpler methods for recording ballistocardiograms has garnered considerable interest due to the limitations of the Starr and Nickerson tables. These methods range from basic electromagnetic and photoelectric instruments, which, when properly constructed, exhibit minimal inherent distortion characteristics, to more complex recording devices such as bathroom scales and seismographs.[4]

1.4 HISTORY OF BALLISTOCARDIOGRAPHY

BCG, which was first discovered in the late 19th century [5], underwent extensive research from the 1940s to the early 1980s, after which its popularity declined (refer to Figure 2).

Several factors contributed to this decline:

1) the absence of standardized measurement techniques, resulting in variations in signals [6].

2) a lack of understanding regarding the precise physiological origin of the BCG waveform and clear guidelines for interpreting results, leading to skepticism from the medical community.

3) a predominant focus on clinical diagnoses (such as myocardial infarction, angina pectoris, and coronary heart disease [7,8]), which typically demand a high level of specificity and reliability that BCG had not yet achieved [9].

4) the emergence of ultrasound and echocardiography techniques, which quickly supplanted BCG and related methods for non-invasive cardiac and hemodynamic diagnostics.[10]

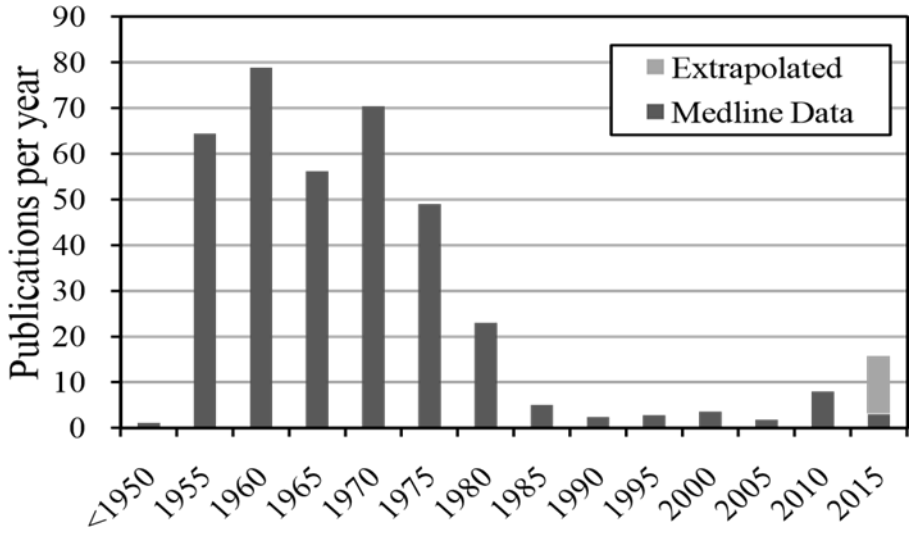

Fig. 2. Publication rate of BCG-related research from 1950until 2015. [11]

However, over the past decade or so, there has been a surprising resurgence in interest in BCG (see Figure 2). Given the numerous limitations of the method outlined above, it is reasonable to question the basis for this resurgence. [12]

In 1877, researchers delved into the study of ballistic displacements of the human body, documenting their findings for the first time (Gordon, 1877). Their experimental setup involved placing a subject on a bed suspended from the ceiling by ropes, known as a pendulum bed, while recording the subject's movements synchronously with their heartbeat. However, this method proved impractical and yielded inaccurate measurements. The movement of the bed caused by respiration overshadowed that caused by circulatory events (Alametsa et al., 2009).The 20th century witnessed the rediscovery of BCG, with Starr recognizing BCG signals as indicative of myocardial contraction strength (Starr, 1955, 1965). Early BCG devices primarily utilized special beds to track movement, but in 1939, Starr developed a modified version of the pendulum bed called the ballistocardiograph. This device, suspended from the ceiling by cables, restricted lateral movements and recorded bed displacement. Adjustments were made to minimize the influence of respiration. Another device, the Dock direct

body ballistocardiograph, involved attaching a transducer to a concrete block and a wooden bar clamped across the subject's shins (Dock & Taubman, 1949). However, flaws were identified in both Starr's and Dock's designs, particularly related to how the body was supported, leading to interference with recording and the need for frequent maintenance (Dock & Taubman, 1949).Between 1952 and 1965, significant advancements occurred in BCG instrumentation and theory, including the application of Newton's laws of mechanics to assess cardiac performance (Starr, 1965).BCG primarily focuses on observing ballistic effects such as force, impact, velocity, and momentum patterns of the body and blood, along with respiratory displacement (Talbot, 1958). Contraction of the myocardial wall generates powerful acceleration and deceleration forces (Phibbs et al., 1967). The main objective in developing the ballistocardiograph was to apply Newton's laws of mechanics to cardiovascular function (Starr, 1965), with acceleration of ejected blood being the most critical aspect to study. It is impossible to differentiate the effects of activity in the right and left ventricles, as both contribute to the ballistocardiogram, which represents the resultant of vectors rather than a pure force (Gubner et al., 1953). BCG involves studying the body's motion with each heartbeat, arising from both heart contraction and blood ejection toward the periphery (McKay et al., 1999; Pinheiro et al., 2010). The shifting center of mass of the body during the cardiac cycle creates a ballistocardiograph waveform, reflecting various events and phases resulting from cardiovascular action (McKay et al., 1999; Alametsa et al., 2008; Pinheiro et al., 2010).Ensuring proper BCG recordings requires subjects to be completely relaxed, lying supine with arms relaxed for at least five minutes before assessment to minimize unrelated forces like coughing (Talbot & Harrison, 1955; Gubner et al., 1953). However, extra movement, especially in the elderly, can interfere with accurate recordings (Gubner et al., 1953). Frequency filtering can eliminate non-myocardial vibrations such as body and respiratory movement (Bombardini et al., 2008a,b).Normal BCG typically exhibit consistency in waveforms, with strong contractility in healthy individuals producing large waveforms and weak contractility resulting in small ones (Alametsa et al., 2008; Scarborough et al., 1952). However, abnormal waveforms related to cardiac disease, diabetes, and obesity pose challenges in identification and annotation, often requiring simultaneous recording of an ECG for reference (Gubner et al., 1953).[13]

1.5 MEASUREMENT METHODS

During the predominant phase of BCG research activity, three primary types of systems were prevalent: the Starr BCG (high-frequency BCG), the Nickerson BCG (ultra-low frequency BCG), and the Dock BCG (direct-body BCG). Despite their standardization, each of these systems produced distinct BCG waveforms, leading to a lack of consistency in signals. This inconsistency likely hindered BCG's widespread adoption in clinical settings, as interpretation varied slightly. Additionally, signal processing techniques were rudimentary, with computer-based methods only coming into play in the 1970s.

Thus, it is reasonable to assert that the significant advancements in BCG over the past decades have primarily stemmed from technological innovations.[12]

One of the main technologies used in this field was the Digital BCG .Digital BCG is an innovative technology built upon the foundation of traditional BCG developed in the 20th century, combined with advancements in seismocardiography (SCG). This modern approach to BCG incorporates a sensor, a digitizing transceiver unit, and specialized software designed to capture and analyze the ballistocardiogram.The technology utilizes a highly sensitive accelerometer capable of detecting vibrations within a frequency range of 0.1 Hz to 4 kHz. This accelerometer boasts a linear dynamic range of ±2%, allowing it to accurately measure low-frequency vibrations generated by the heart's contractions, ranging from 0.05 mm/s^2 to 20 km/s^2 (McKay et al., 1999). The accelerometer is affixed to the sternum on the chest using electrode patches typically used for electrocardiography (ECG). Before data collection, the attachment area must be meticulously cleaned and prepared to ensure optimal sensor adherence. Any excess body hair or perspiration that could compromise sensor attachment and signal quality should be removed.

The ballistocardiograph accelerometer captures cardiac forces along three anatomical axes: the x-axis (from head to foot), the y-axis (from right to left), and the z-axis (from back to front). Specifically, it records seismic forces at the sternum induced by myocardial contraction. These vibrations are digitally processed by the transceiver unit, which digitizes and transmits the recorded data using Bluetooth® technology to interface with proprietary software installed on a laptop computer. All recorded data are subsequently analysed offline using the proprietary software, facilitating annotation and detailed analysis of the recorded cardiac cycle waveforms. To annotate each cardiac cycle accurately, an identification system adapted from previously described nomenclature is utilized. This system enables the annotation of systolic and diastolic timing and amplitude events, ensuring comprehensive analysis of the BCG (Scarborough, 1955; Crow et al., 1994).[13]

1.6 BCG CURRENTLY

In the recent years, there has been a notable shift in the technology side of BCG research. New sensing modalities, such as static charge-sensitive beds, piezoelectric films on furniture, and force plates, have greatly simplified the process of measuring BCG signals. Also weighing scales and developing various methods for acquiring high-quality standing or sitting BCGs. These technological advancements have made BCG more accessible and enabled its use in applications that were previously impractical, such as home monitoring. However, it is important to recognize that many of these approaches result in non-standard BCG signals (according to Scarborough's definition) due to factors such as sensing modality, direction and location of sensors, or coupling to the subject. For example, bed-based systems measuring dorso-ventral BCG s may also detect components associated with local heart motion (as observed in

seismocardiograms or apexcardiograms). Cross-axis coupling through the mattress or sensor could further complicate the signal. While this may not affect all applications, it is essential to acknowledge these complexities as they could lead to misinterpretation of the signals. [12]

Currently, there is considerable attention directed towards BCG, largely due to advancements in information technology encompassing hardware, software, and services. With the ability to integrate BCG sensors into ambient surroundings independently of medical staff presence, it has significantly influenced contemporary e-health systems. Ultimately, BCG contributes to alleviating stress during checkups and mitigating emotional and attention responses in patients. The BCG waveforms can be categorized into three primary groups: pre-systolic (often overlooked), systolic, and diastolic.

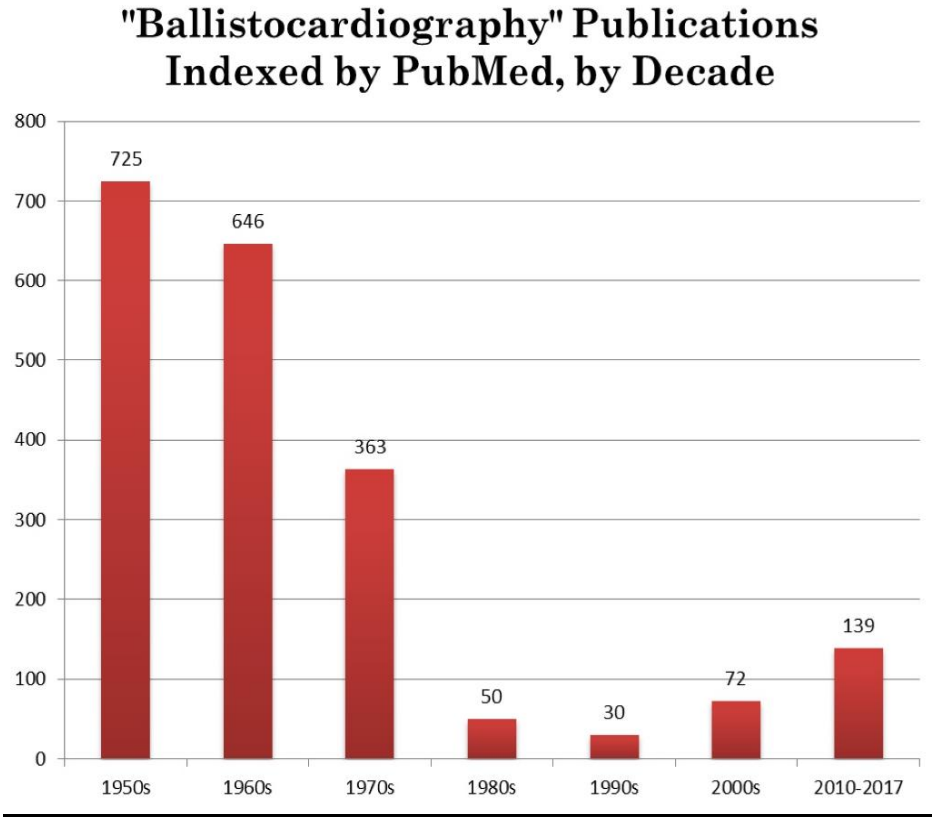

Fig.3 Ballistocardiography publications indexed by PubMed. [12]

What's old may be new again—with the technologies of a new century. No need to hold your breath.

2. BALLISTOCARDIOGRAPHY ON ANIMALS

BCG in animals entails measuring and analysing the bodily movements triggered by the heartbeat. Although commonly associated with human studies, BCG has been adapted for animal research and clinical purposes. Unlike the traditional ECG-based approach, BCG offers several advantages for cardiac monitoring in animals. It requires less preparation, as it doesn't necessitate shaving or applying gel to the animal's skin. Additionally, while ECG typically requires multiple electrodes placed on different parts of the animal's body, BCG can be obtained using a single sensor, making it a simpler and more convenient option. When integrated into a saddle or belt, this method provides a straightforward and durable means of attaching to the animal, making it ideal for cardiac monitoring. The underlying principle of BCG in animals, mirrors that in humans, where the rhythmic movements of the body correspond to blood acceleration during heart contractions and relaxation. Specialized sensors are employed to detect and quantify these movements.

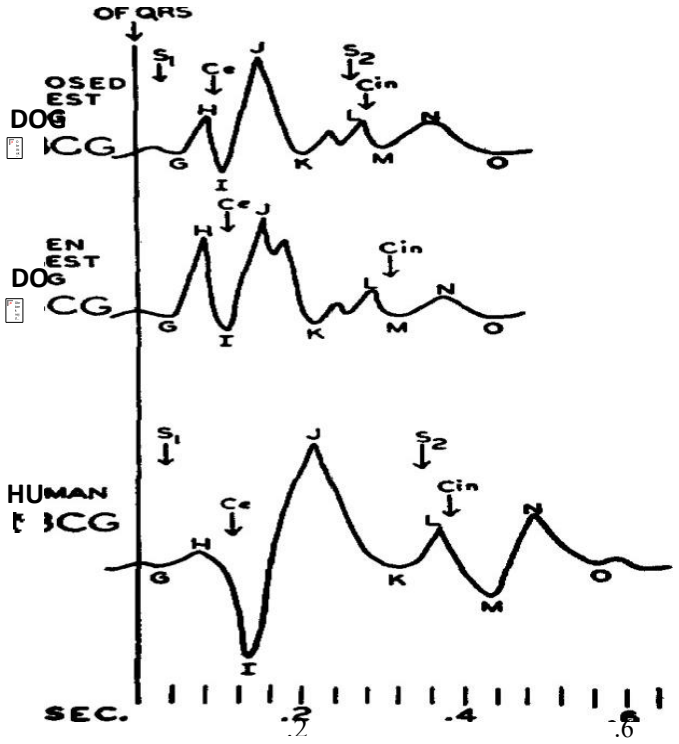

Fig.4 This is a composite drawing of a representative ballistocardiogram from the dog before and after opening the thoracic cage. A typical human tracing obtained by similar technique is presented for comparison. [14]

According to “Fig.4”, Ce indicates the onset of the carotid upstroke and Cin the carotid or aortic incisural notch. S 1 and S 2 refer to the first and second heart sounds. Note that the major differences between the dog and human ballistocardiogram are probably

the result of the short systolic period with the compression of the G-H-I-J-K sequence into a shorter period. The basic pattern and time relationships of the dog ballistocardiogram before and after opening of the chest appear comparable in most way to the human ballistocardiogram.

Applications:

- In cardiovascular research, BCG helps study various aspects of cardiovascular function, including cardiac output and heart rate variability.

- BCG aids in assessing the effects of drugs or interventions on heart health in animal models, facilitating the evaluation of pharmaceutical compounds' efficacy and safety.

- In veterinary medicine, BCG serves to monitor cardiac health, diagnose cardiovascular diseases, and evaluate the response to treatment in animals.

Techniques:

- Sensors for BCG measurements in animals are typically positioned beneath the animal, such as on a platform or weighing scale, ensuring accurate detection of bodily movements without causing discomfort.

- Specialized equipment is used to capture BCG signals, including force plates, piezoelectric sensors, or other motion detection devices.

- Signal processing and analysis techniques are applied to extracted BCG signals to derive relevant parameters related to cardiac function.

Research Areas:

- BCG studies in animals encompass various species, ranging from rodents to larger mammals like horses, contributing to our understanding of cardiac physiology and diseases, as well as the effects of environmental factors and interventions on heart function.

Challenges:

- Performing BCG in animals poses challenges such as ensuring proper sensor placement, minimizing stress during measurements, and accurately interpreting BCG signals due to anatomical and physiological differences across species.

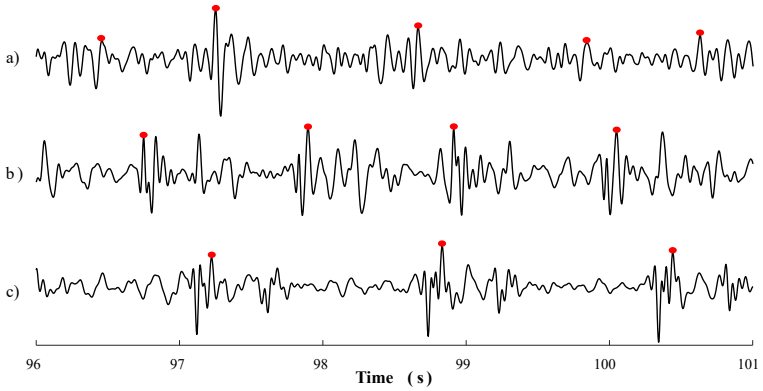

Fig.5 Examples of filtered different BCG signals with highlighted peaks in three tested animals:

a goat, **b** cow, **c** horse [15]

Overall, BCG in animals offers valuable insights into cardiovascular health and function, serving as a crucial tool for both research and clinical applications in veterinary medicine.

3. PRACTICAL PART

3.1 INTRODUCTION

BCG is a non-invasive method used in veterinary medicine to measure the mechanical movements of the body caused by the heartbeat. It provides valuable insights into cardiac function and hemodynamics in animals. In recent years, advancements in sensor technology have enabled the development of BCG pads equipped with multiple sensors, allowing for more comprehensive monitoring of cardiovascular parameters in veterinary patients. In this practical thesis, we explore the application of BCG pad measuring with four sensors of the same type in veterinary medicine. In this research we are using the pad in a currently running research in the university so we may not specify their kind. Our study focuses on the assessment of cardiovascular parameters in four distinct breeds of dogs, each tested individually. The data collected from these measurements form the basis of our investigation into the physiological responses of these canine patients. The primary objectives of this thesis are twofold. Firstly, we aim to accurately determine when each dog was present on the BCG pad and analyse their activity patterns during the monitoring period. Secondly, we seek to investigate and compare the heart rate and breath rate of the dogs.

3.2 THE AIM OF THIS MEASURMENT

Dogs, our beloved companions, come in various breeds and sizes, each with its unique characteristics and behaviours. By comparing the results obtained from the four different dog breeds, we hope to gain insights into their unique physiological characteristics and behaviours. Additionally, we aim to identify which dog presented the greatest challenge in terms of data collection and analysis and explore the reasons behind any observed differences. Ultimately, this research aims to contribute to our understanding of canine physiology and provide valuable insights into the health and behaviour of our dogs using BCG.

3.3 THE ANIMALS' PRESENCE ON THE PAD AND THEIR ACTIVITY

First, we are processing raw data from four sensors that are stored in a matrix d of four columns and a timestamp in vector t during each measurement of every animal. For demonstration purposes, we'll outline the steps specifically for "Animal 1". The same procedure will be replicated for the other three animals, with the results presented accordingly. (Some coefficients of smoothing, filtering and minimum heights and distances between peaks may vary).

```
n=5; %coefficient of sampling frequency reduction

Fs=1000/n; %the sampling frequency will be 200hz

%the following commands downsample the data in order to process and investigate the
data quickly, without losing important data.

t=downsample(t,n); %time downsampling

d=downsample(d,n); %signals downsampling

%the following commands smooth the 50Hz noise from the data because it is crucial
for improving the accuracy and quality of data analysis. The 50 Hz noise appears
as a periodic disturbance in the time domain and as a sharp peak in the frequency
domain.

for i=1:size(d,2)

d(:,i)=smooth(smooth(d(:,i),Fs/50),Fs/50);

plot(t,d) %here we plot the graph of d with respect to t.

legend('signal1','signal2','signal3','signal4') %it adds a legend box to the plot.

title('Signals') ) %it adds a title.
```

Figures 6, 7, 8 and 9 are the plots of the out zoomed raw data with respect to the timestamp:

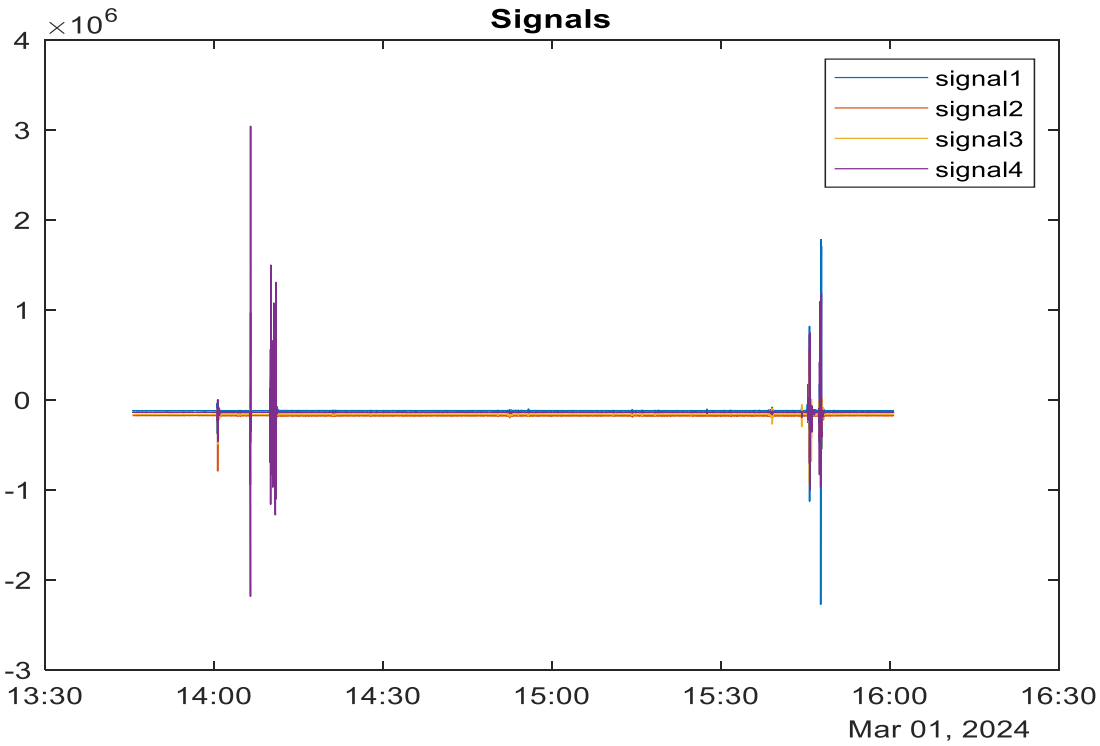

Fig.6 Signals of the sensors for "Animal 1".

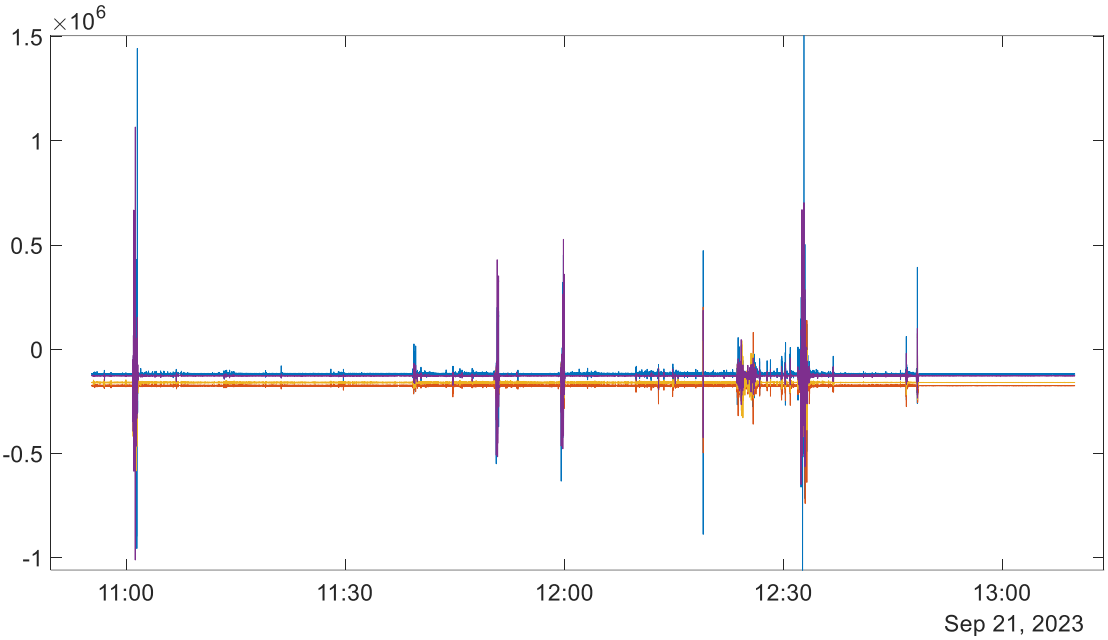

Fig.7 Signals of the sensors for "Animal 2".

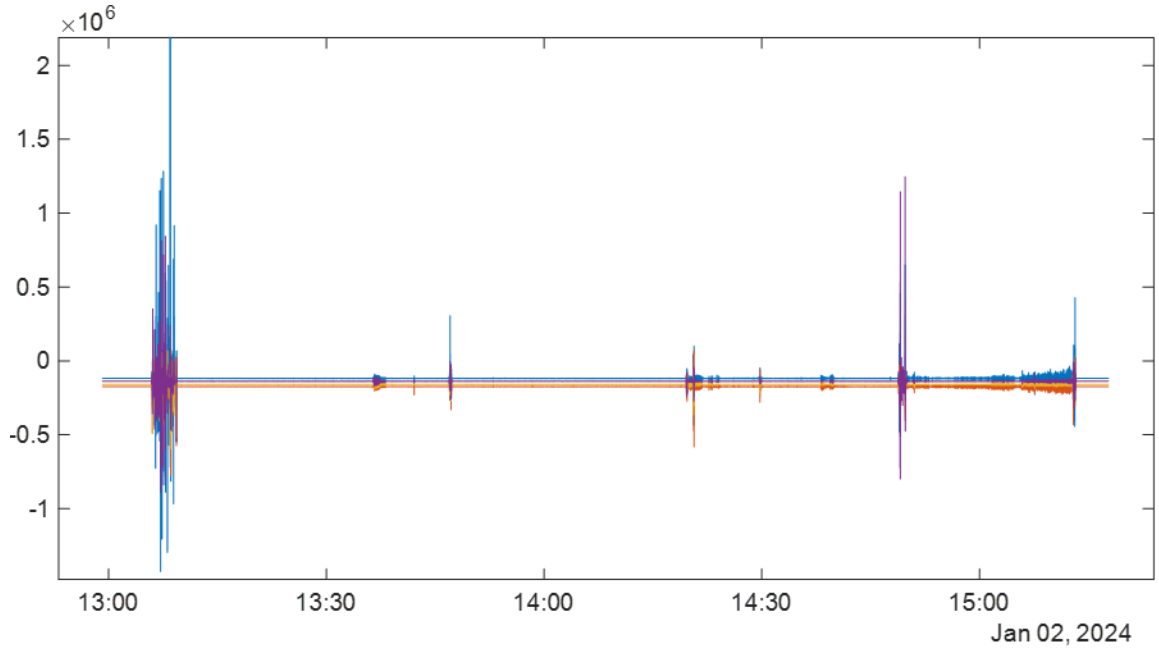

Fig.8 Signals of the sensors for "Animal 3".

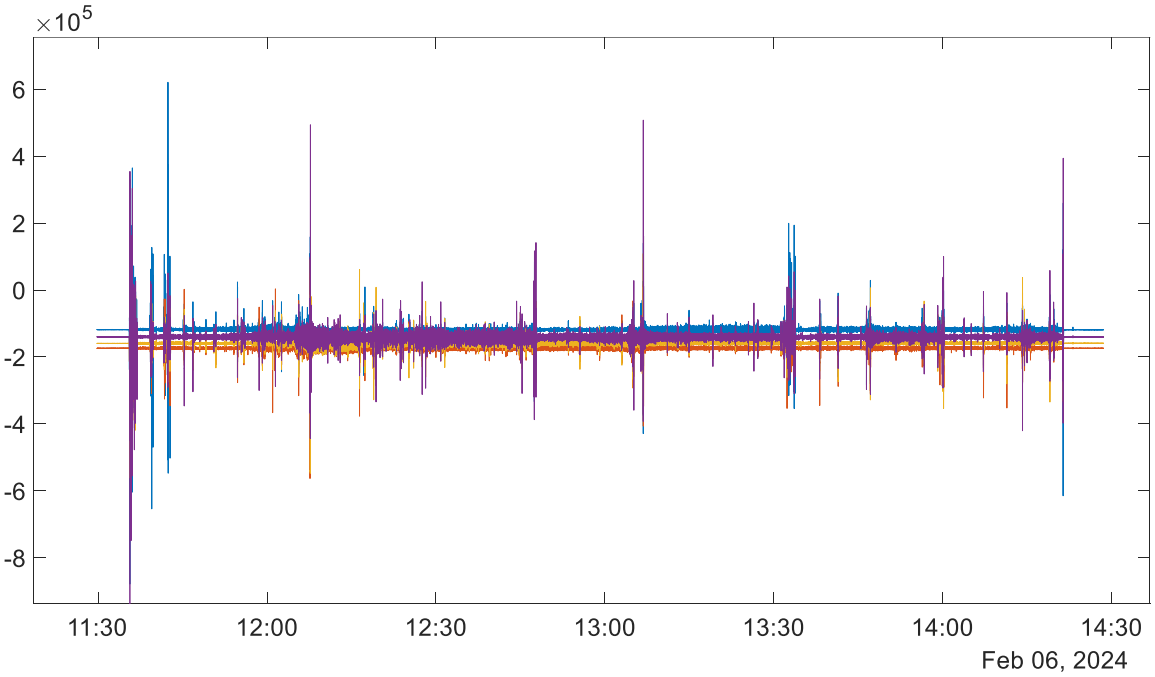

Fig.9 Signals of the sensors for "Animal 4".

To assess an animal's presence on the pad and its level of activity, we can check it by looking to the graphs for each point but it's easier to know this more analytically, so we evaluate the following parameters:

a) Moving Sum:

Before utilizing this parameter, we need to take certain steps for the signal. Initially, we'll need to execute the following codes:

```
ad=abs(d);  % first we convert all negative numbers in (d) to their positive equivalents (absolute values of (d)).

sad=sum(ad,2); %then we sum all the numbers in each row of ad (2 stands for summing in each row).

msad=movsum(sad,Fs*25); %this calculates the movsum of sad where the window length of movsum is 25 seconds.

plot(t,msad) %here we plot the graph of msad with respect to t.

>> hold on

>> plot(t,smooth(msad,120*Fs),'LineWidth',2) %here we plot the graph of smoothed msad with respect to t.
```

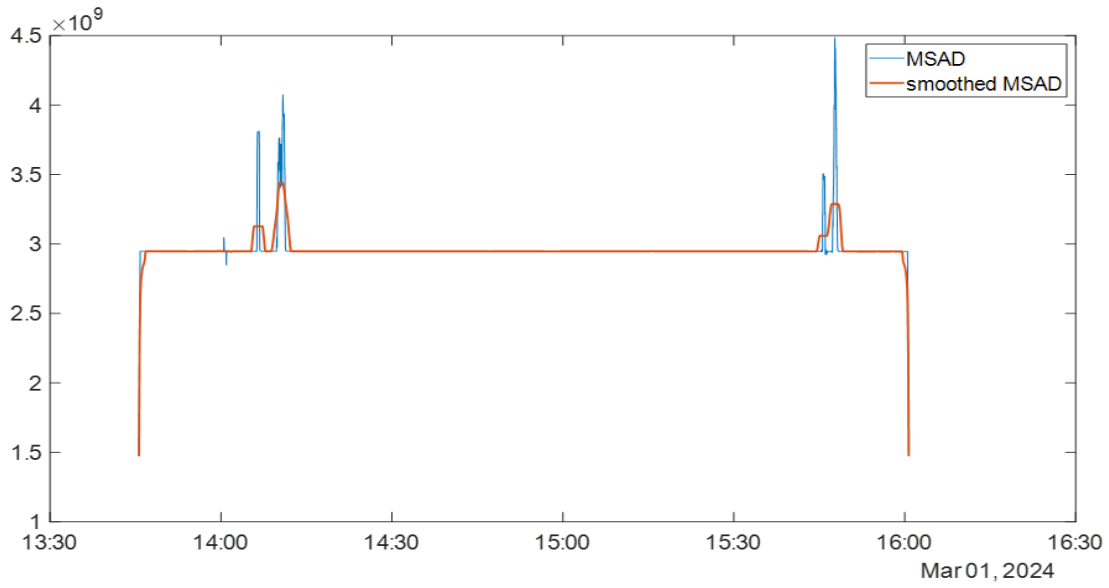

Fig 10 Moving sum graph of "Animal 1".

If we zoom in, we can see that the graph has the same size of peaks on time 13:50 (where the animal wasn't on the pad) and on the time 14:20 (where the animal was on the pad). (Fig.11)

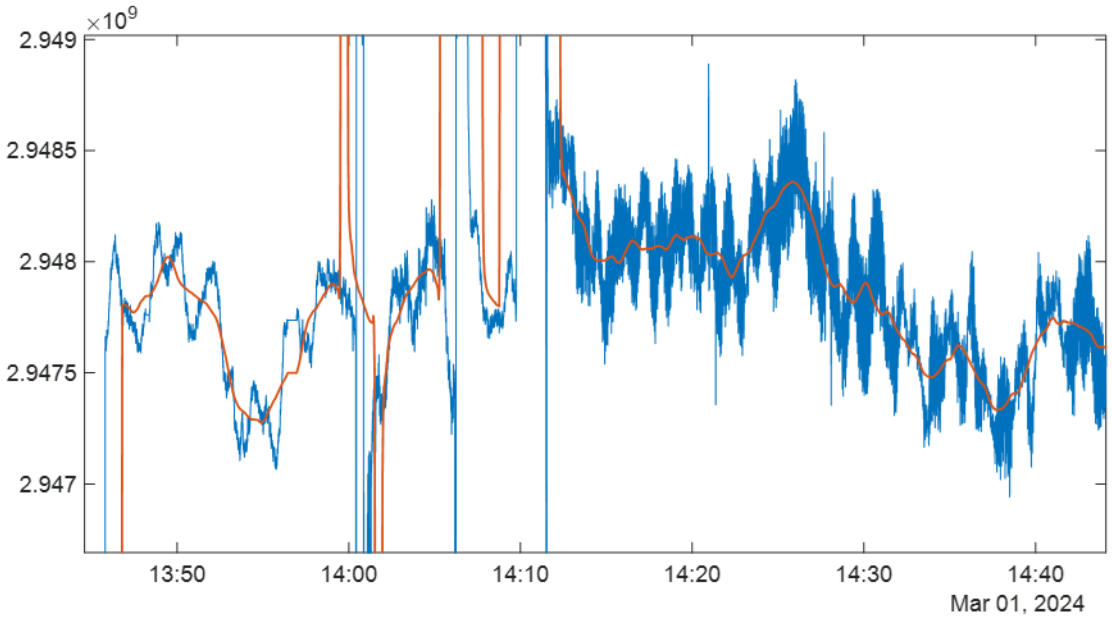

Fig.11 Close-up of moving sum graph of "Animal 1".

This means that the parameter MOVSUM is not working to know whether the animal is on the pad or not, so we will use another parameter.

b) MOVING VARIANCE:

Before using Moving variance, we also sum all the numbers in each row in d to merge the information from each sensor into one parameter. (Fig.12)

These are the codes we write:

```
sd=sum(d,2); %this calculates the sums of each row of d

mvsd=movvar(sd,25*Fs); %the moving variance of the sum of d with a window length
25 seconds.

plot(t,mvsd) %here we plot the graph of mvsd with respect to t.

hold on

smvsd=smooth(mvsd,180*Fs); %here we smooth the graph to have less peaks.

plot(t,smvsd,'LineWidth',2) %here we plot the graph of smvsd with respect to t.

legend('MVSD','SMVSD') %it adds a legend box to the plot.
```

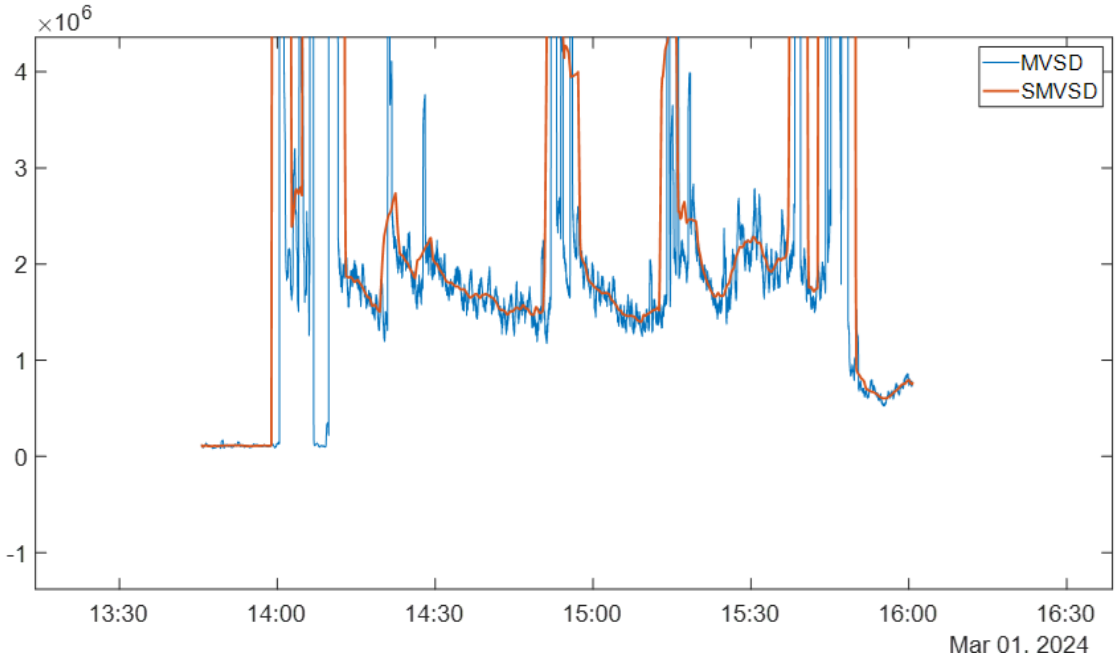

Fig.12 Close-up of the moving variance and the smoothed moving variance of d for "Animal1".

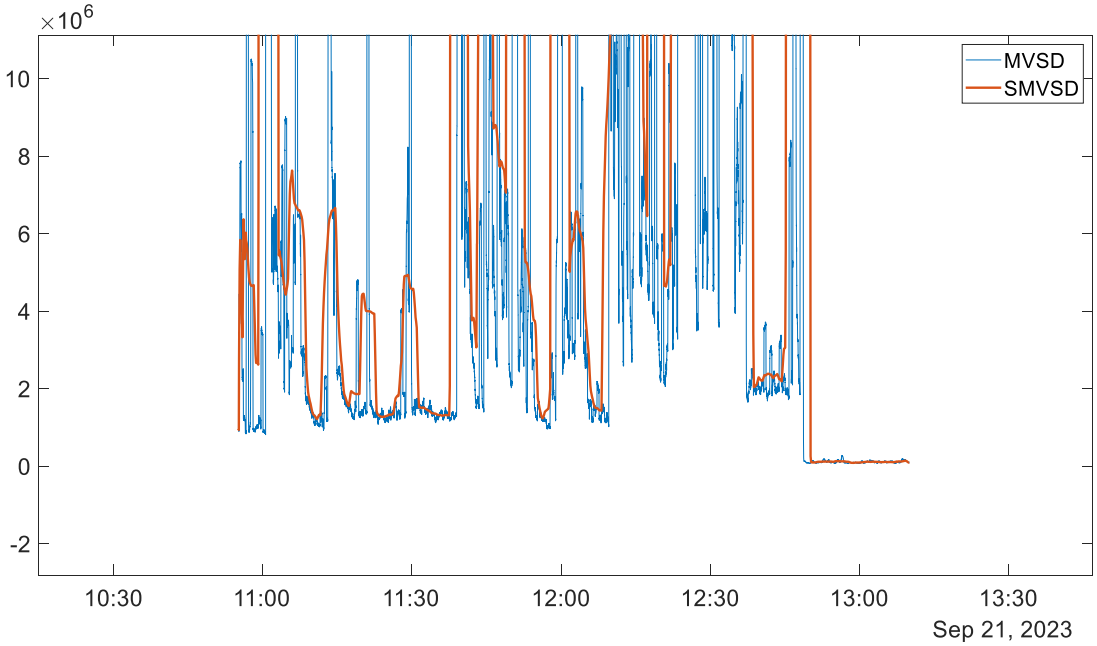

Fig.13 Close-up of the moving variance and smoothed moving variance of d for "Animal 2".

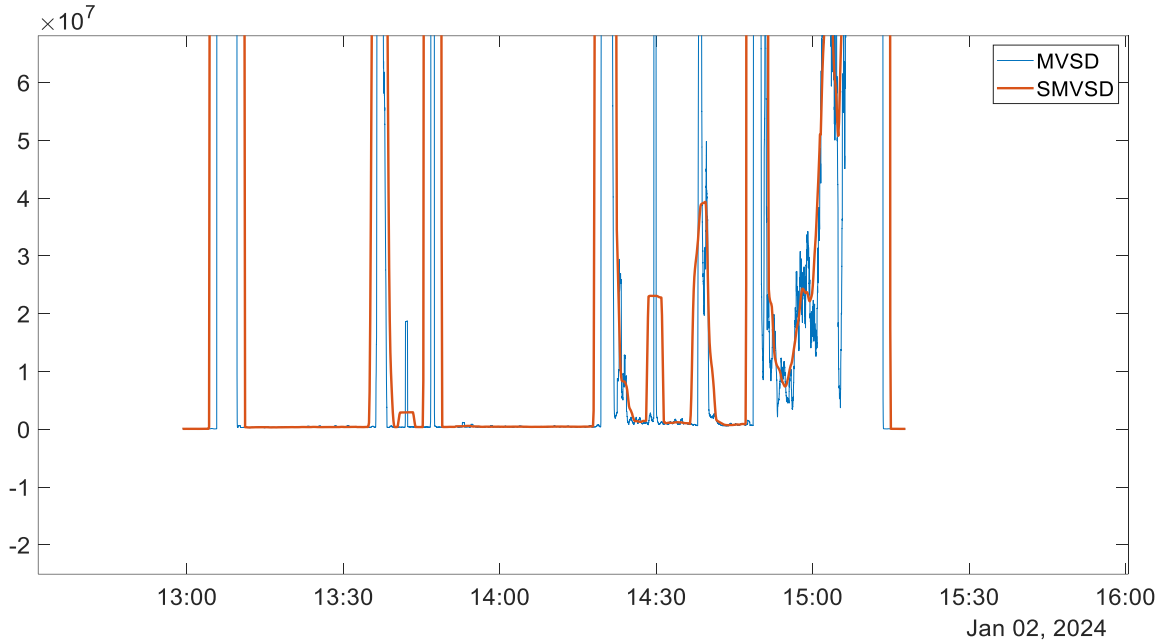

Fig.14 Close-up of the moving variance and the smoothed moving variance of d for "Animal 3".

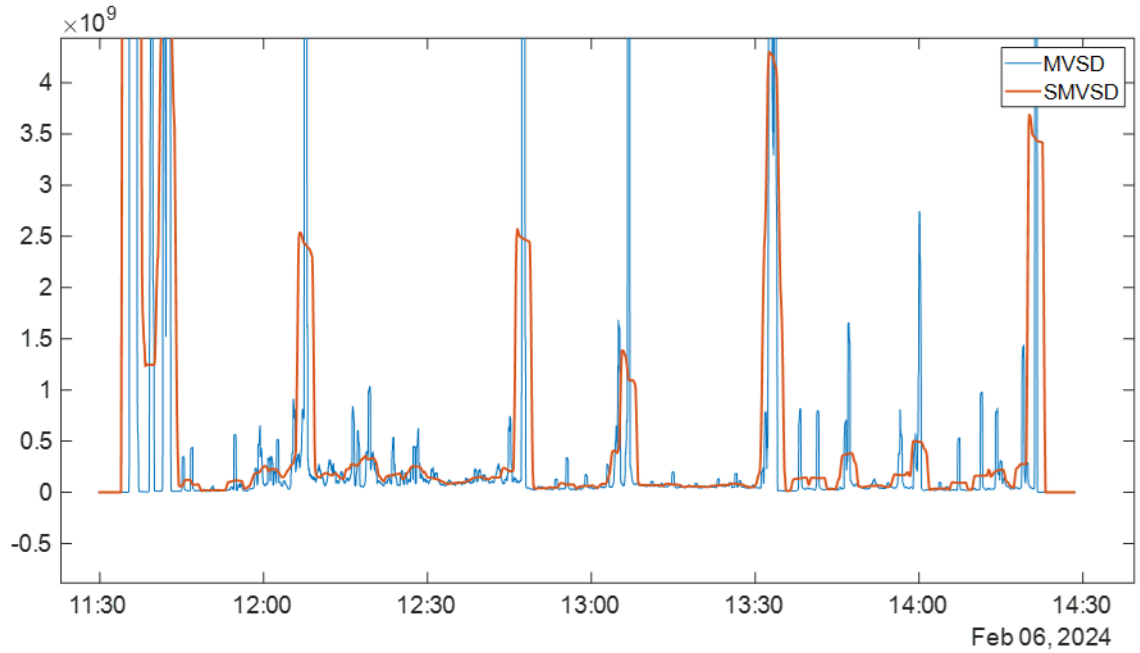

Fig.15 Close-up of the moving variance and the smoothed moving variance of d for "Animal 4".

From "Fig.12" if we zoom in, we can indicate the point H1 (a value of moving variance) where for every Y bellow this value the animal was not on the pad and for every Y larger than H1 the animal is on the pad. In this measurement it is equal to the mean of the lowest two peaks.

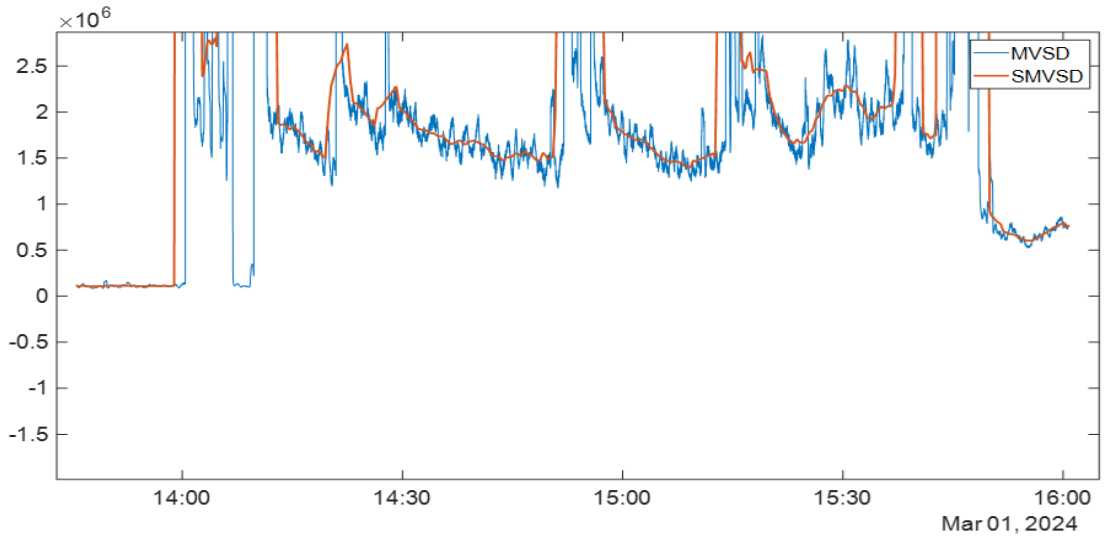

Fig.16 Close-up to the bottom of the moving variance and the smoothed moving variance of d for "Animal 1".

H1 "Animal 1" = (604026 – 108134)/2 = 247 946. (fig.16)

H1 "Animal 2" = 1 192 790.

H1 "Animal 3" = 221 505.

H1 "Animal 4" =4 605 850.

On the other hand, there is H2 (another value of Y). The animal is active in every Y greater than H2.

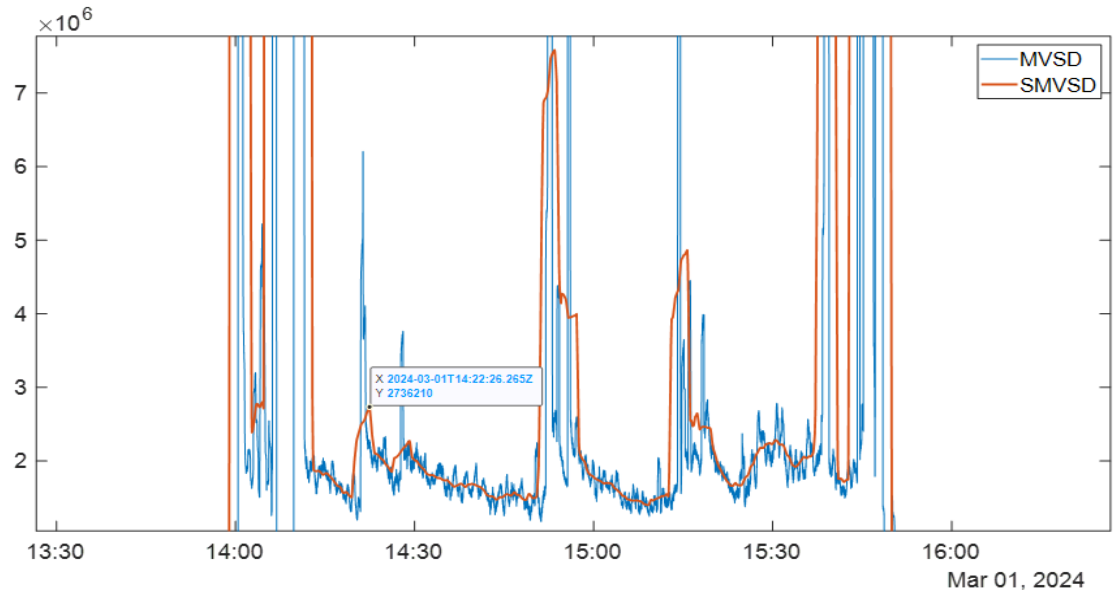

Fig.17 Close-up to the top of the moving variance and the smoothed moving variance of d for "Animal 1".

H2 “Animal1” =2 736 210. (fig.17)

H2 “Animal2” = 342 980 000.

H2 “Animal 3” = 30 550 400.

H2 “Animal 4” =228 743 000.

As observed, the moving variance effectively indicates the animals' presence and activity. It shows that all animals spent most of their time on the pad:

```
Percentage_out = (length (low) / length (smvsd))*100 %here we calculate the percentage of time, where animal was not on the pad.

Percentage_on = 100 - percentage_out %this command calculates the percentage of time, where the animal was on the pad.
```

“Animal 1” was 90,6 % of the time on the pad.

“Animal 2” was 85,2 % of the time on the pad.

“Animal 3” was 94,4 % of the time on the pad.

“Animal 4” was 94.6% of the time on the pad.

with the second and fourth animals being the most active.

3.4 BREATH RATE

To study more information about these animals such as breath rate and heart rate we should use the data where the animal was on the pad but with normal activity. So, we will study the data d that is between the two value H1 and H2 of each animal.

```
H1=247946;

H2=2736210;

low=find(smvsd<H1); %low finds the indices of smvsd that correspond to values lower than H1.

high=find(smvsd>H2); %high finds indices of smvsd that correspond to values higher than H2.

outvar=vertcat(low,high); %outvar combines the indices where the smoothed moving variance is larger than H2 or lower than H1.
```

```
outvar=sort(outvar); %then we sort the previous indices where the smoothed moving
variance is larger than H2 or lower than H1.

vft=t; %vft is the timestamp

vfd=d(:,1); %the raw data for vital functions calculating.

vfd(outvar)=[]; %it deletes the parts of d, where the smoothed moving variance is
larger than H2 or lower than H1.

vft(outvar)=[]; %here we need to do the same with the time.

plot(t,d(:,1)) %here we plot the graph of d(:,1) with respect to t.



hold on

plot(vft,vfd(:,1)) %here we plot the graph of vfd(:,1) with respect to vft.

legend('Complete RAW data','Cut Raw data') %it adds a legend box to the plot.

percentage = (length (vfd) / length (sd))*100 %here we calculates the percentage
of the raw data.
```

The cut raw data of:

“Animal 1” is 65.6 % of the raw data. (Fig.18)

“Animal 2” is 67.6 % of the raw data. (Fig.19)

“Animal 3” is 66.3 % of the raw data. (Fig.20)

“Animal 4” is 67.4% of the raw data. (Fig.21)

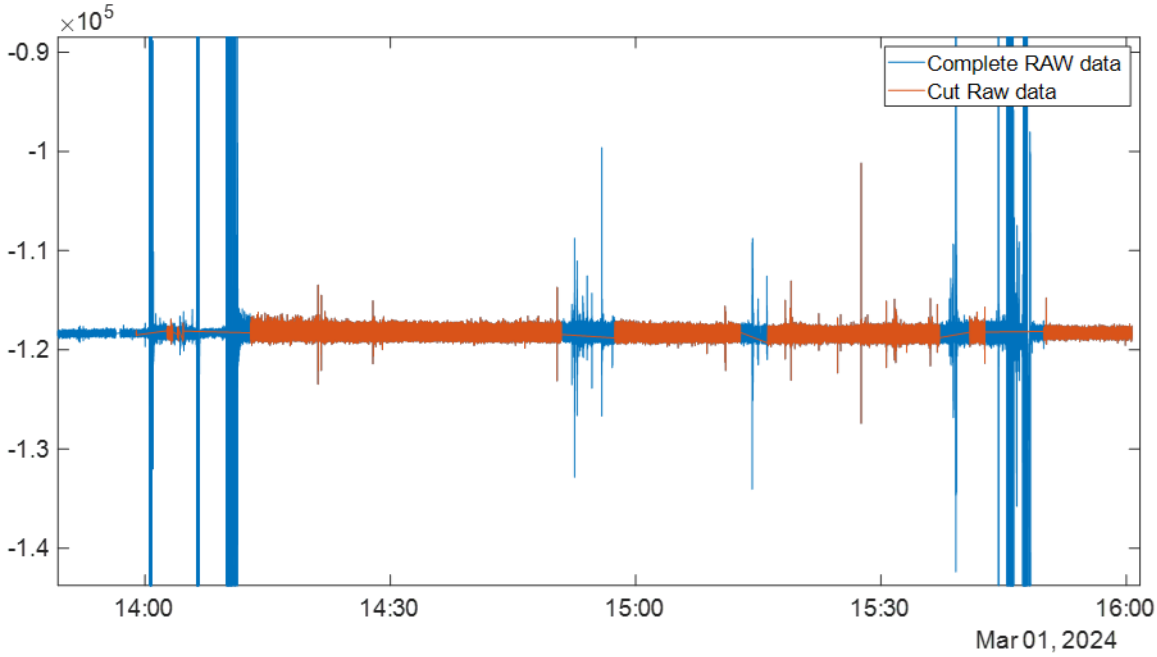

Fig.18 The raw data and the cut raw data of "Animal 1".

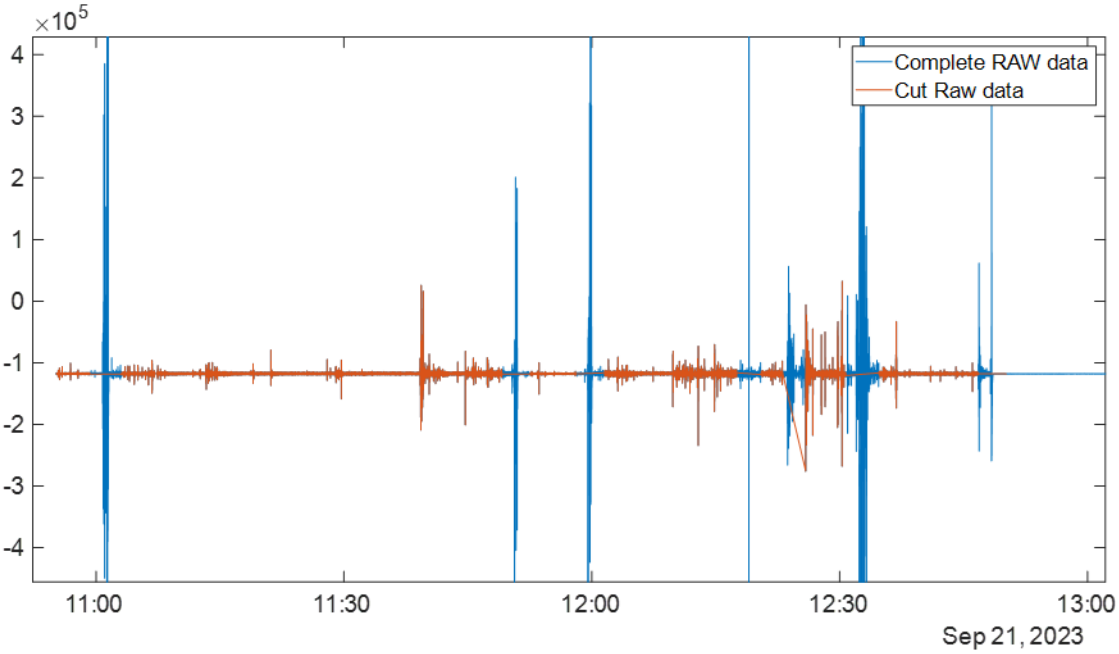

Fig.19 The raw data and the cut raw data of "Animal 2".

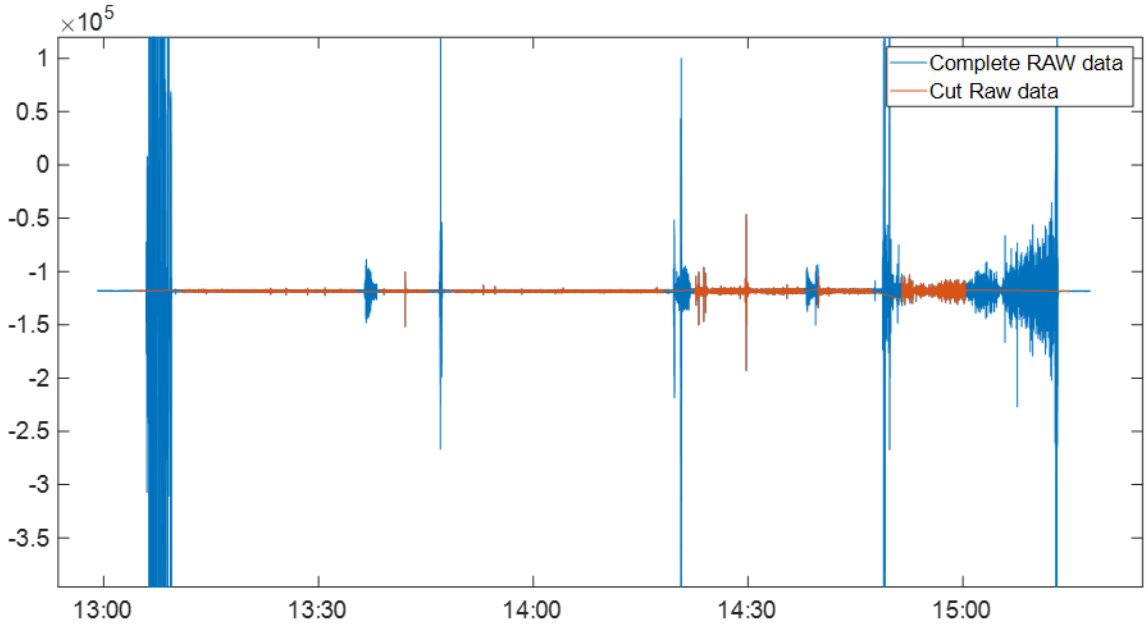

Fig.20 The raw data and the cut raw data of "Animal 3"

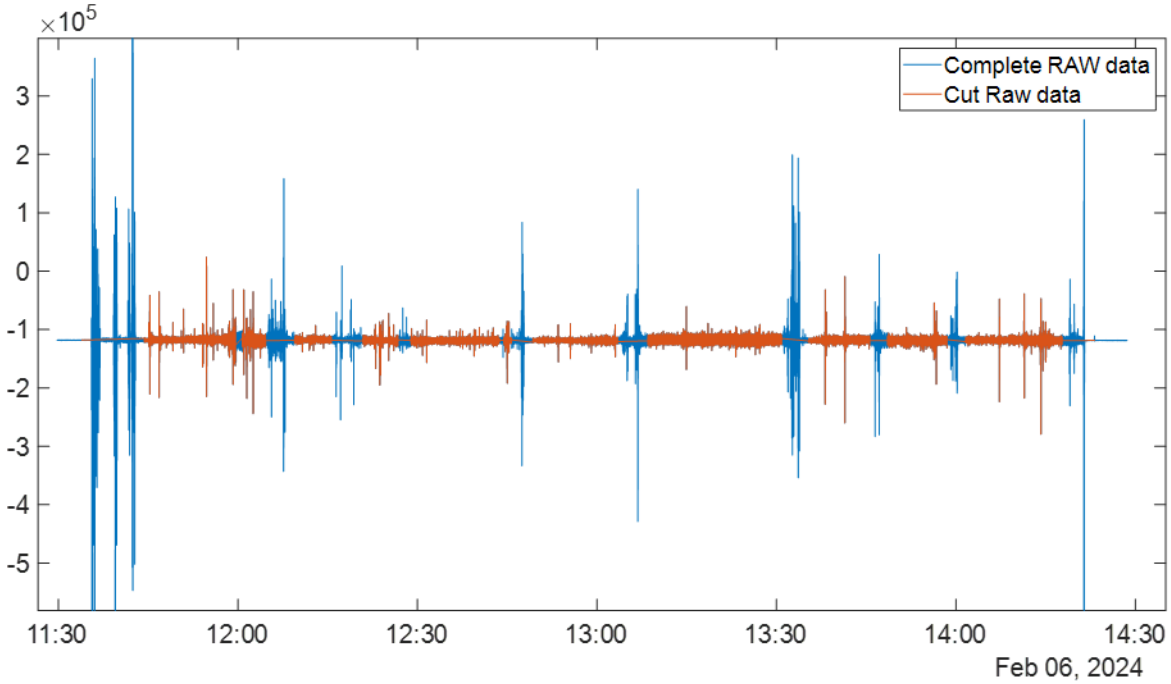

Fig.21 The raw data and the cut raw data of "Animal 4".

The breath rate is better shown in the first sensor's signal of data d, so we will use vital signal d (CUT RAW DATA). Now we zoom in to the CUT RAW DATA (fig.22). As we can see the breath rate is hard to be seen because of the huge number of hairs on the peaks that enable us to see the main peaks of the breath rate as well as in the cut raw data of the three other animals.

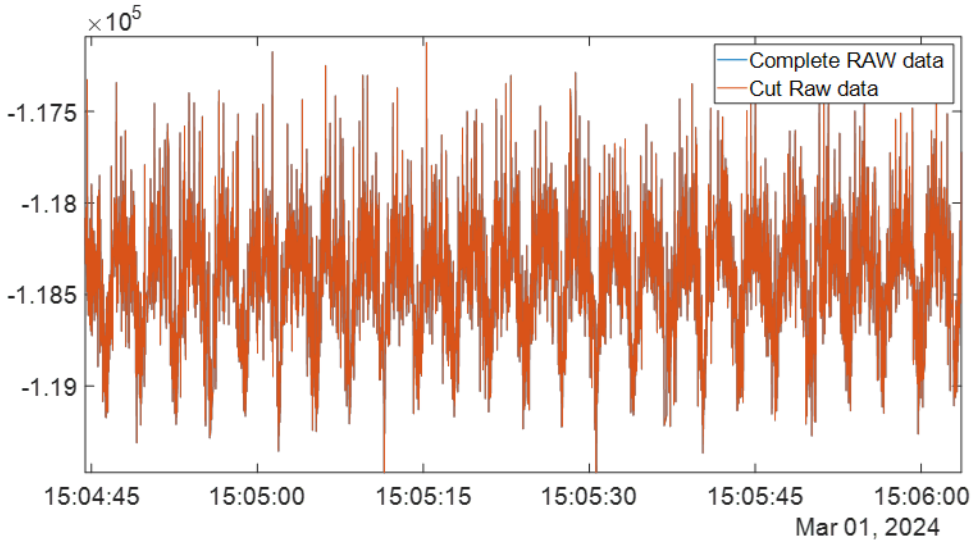

Fig.22 Close-up of the cut raw data for "Animal 1".

In this situation we need to smooth this data two times more to get clear peaks. Then we will use "findpeaks" function to see the peak of each breath (Fig.24).On the other hand according to "Animal 2" there was no need for two times smoothing because the peaks where so clear for breath rate.

```
bvfd=smooth(smooth(vfd(:,1),2*Fs),0.5*Fs); % smoothing the vital function data two times with the coefficient of Fs in the window length parameter. Here it is 2*Fs and the second is 0.5*Fs.

[yb  xb]=findpeaks(bvfd,'MinPeakHeight',-118326,'MinPeakDistance',1.8  *Fs);  %this finds the coordinates of breath peaks - minimum peak height is detected after zooming in to the raw data to check the lowest height of peaks- minimum distance is the distance between the closest two peaks in raw data.

plot(vft,bvfd) %here we plot the graph of bvfd with respect to vft.

hold on

scatter(vft(xb),bvfd(xb)) %this plot will help us to check if we have found the peaks correctly.
```

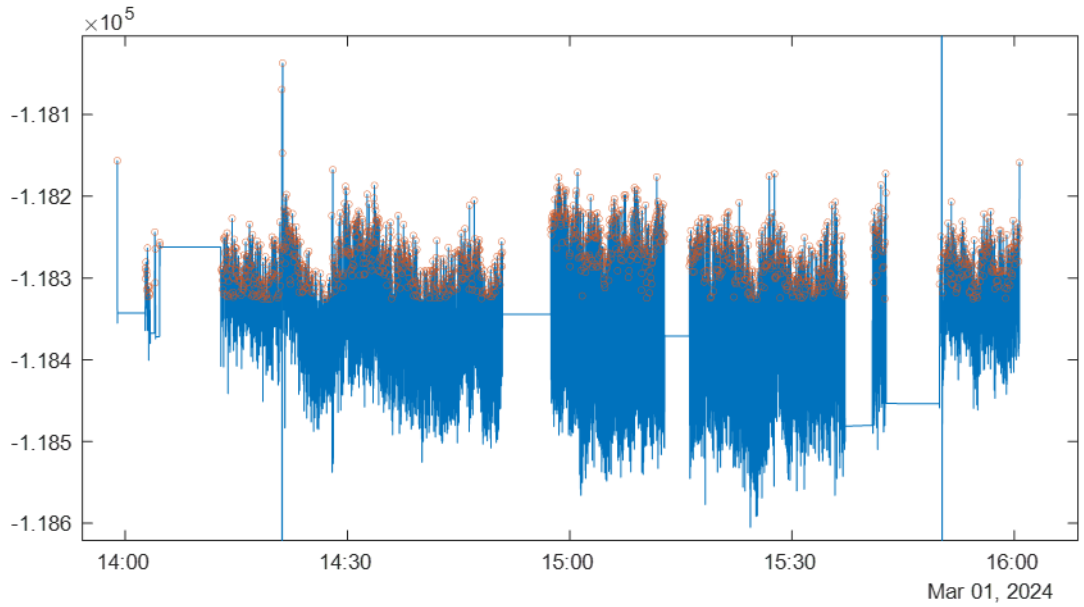

Fig.23 Breath rate peaks of "Animal 1".

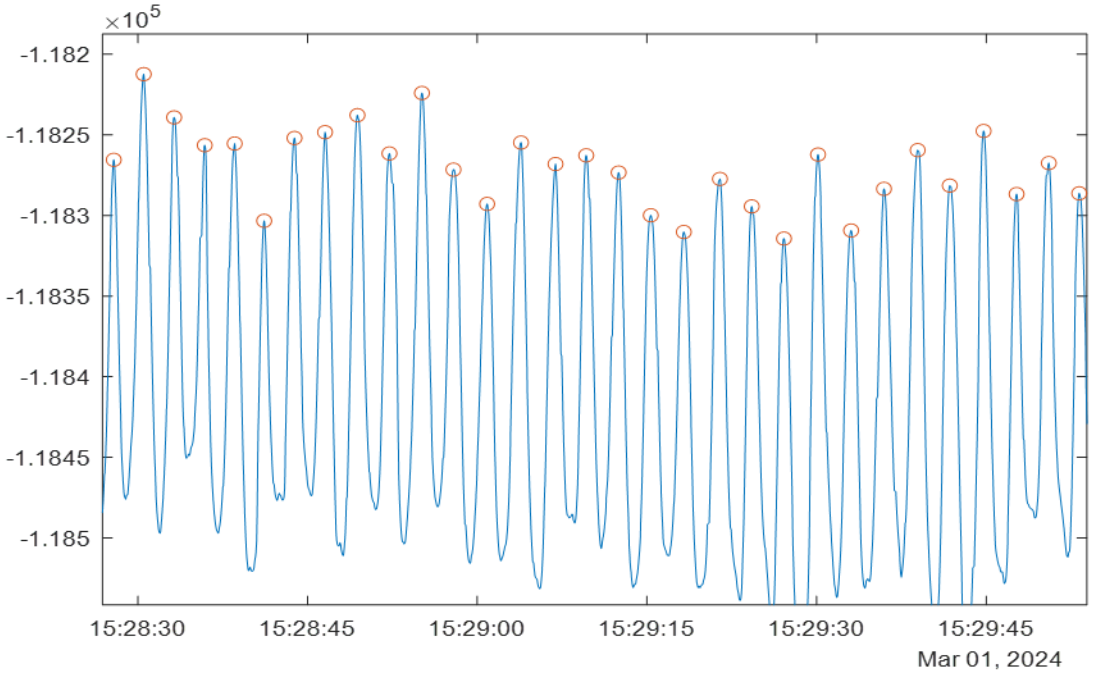

Fig.24 Close-up of the breath rate peaks "Animal 1".

The breath rate is the number of breath cycles per 60 seconds. Between each two consecutive peaks there is a breath cycle of time equals to one period. This time is equal to the time difference between the two peaks.

```
br=60./seconds(diff(vft(xb))); %calculates the breath rate
```

```
tbr=vft(xb(1:end-1)); %tbr is now time vector used for plotting breath rate.
```

In the next step we will delete the outliners. This means that we will remove all the peaks that they are too high or too low from the median peak.

```
outu=find(br>1.75*median(br)); %outu finds indices of BR values, that are higher than 1.75*median(BR).

outl=find(br<0.5*median(br)); %outl finds indices of BR values, that are lower than 0.5*median(BR).

out=vertcat(outu,outl); %it merges the indices saved in outu and outl into one vector out.

out=sort(out); %then it sort the elements of vector out just to arrange them.

br(out)=[]; %deleting the values of BR with indices saved in variable out.

tbr(out)=[]; %doing the same for time as for BR.
```

We use moving mean of breath rate to see it clearly. (Fig.25)

```
fbr=movmean(movmean(br,12),27); %applying moving mean in the BR values.

%plotting the results

scatter(tbr,br,'.') ) %create a scatter plot of br with respect to tbr with the data points represented as dots.

hold on

scatter(tbr,fbr,'.') ) %create a scatter plot of fbr with respect to tbr with the data points represented as dots.

legend('BR','filtered BR') %it adds a legend box to the plot.
```

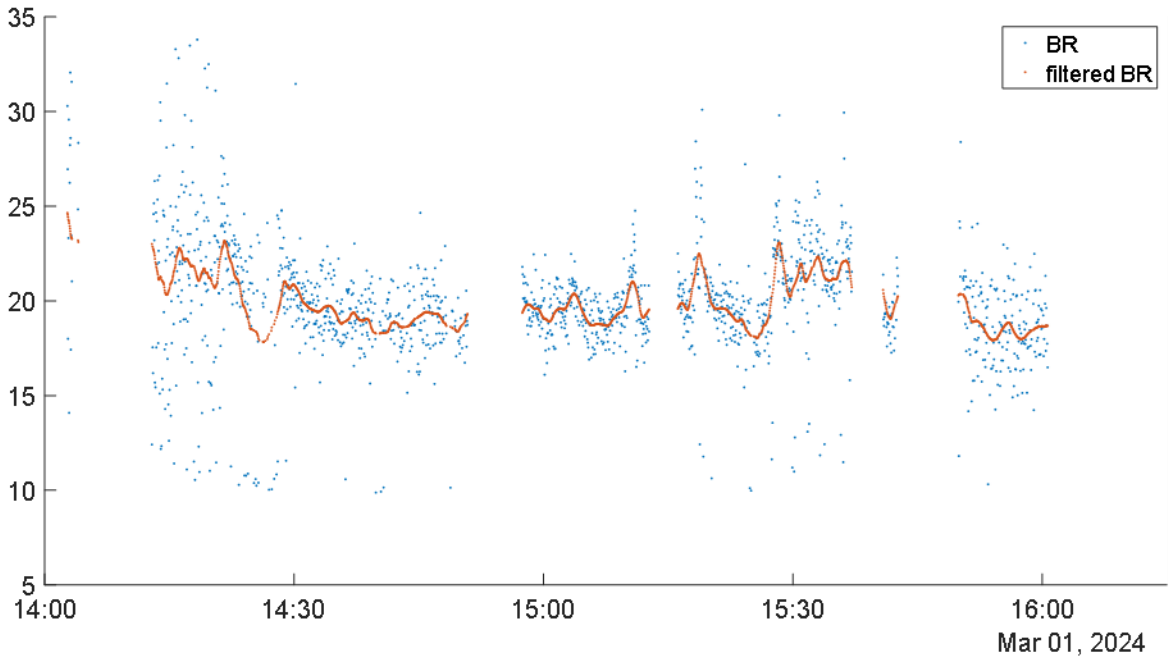

Fig.25 The breath rate of “Animal 1”.

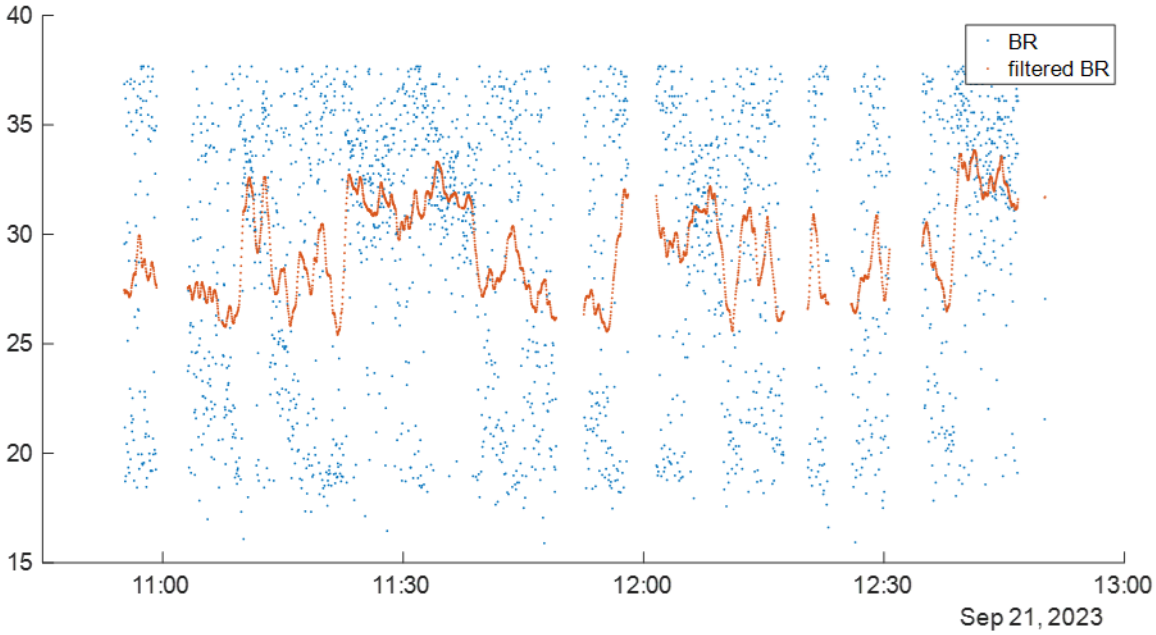

Fig. 26 The breath rate of “Animal 2”.

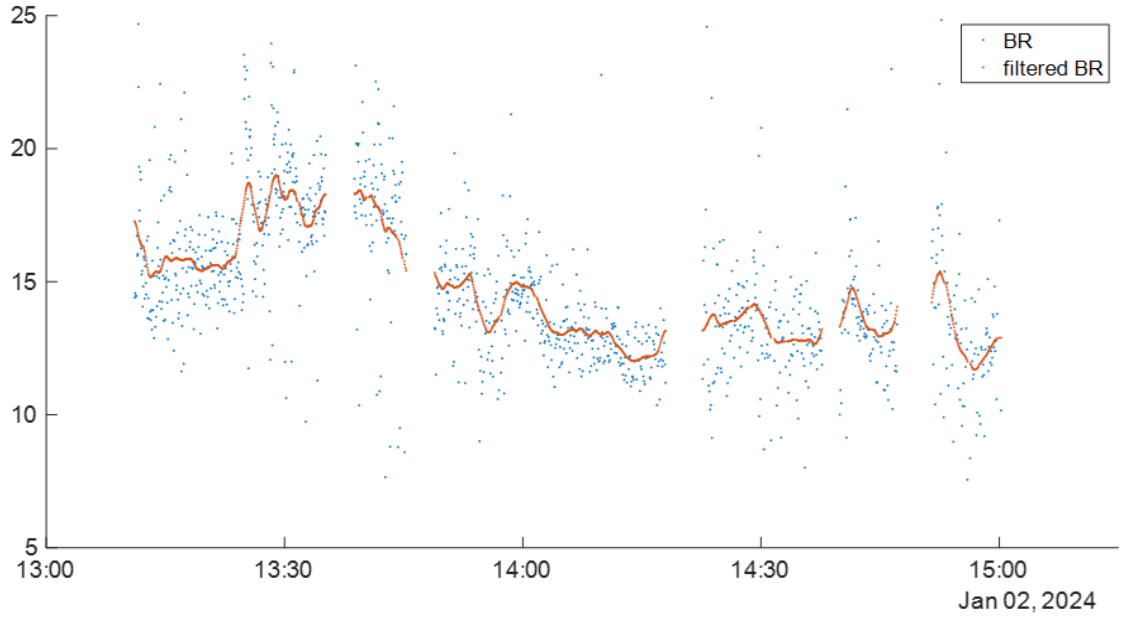

Fig.27 The breath rate of “Animal 3”.

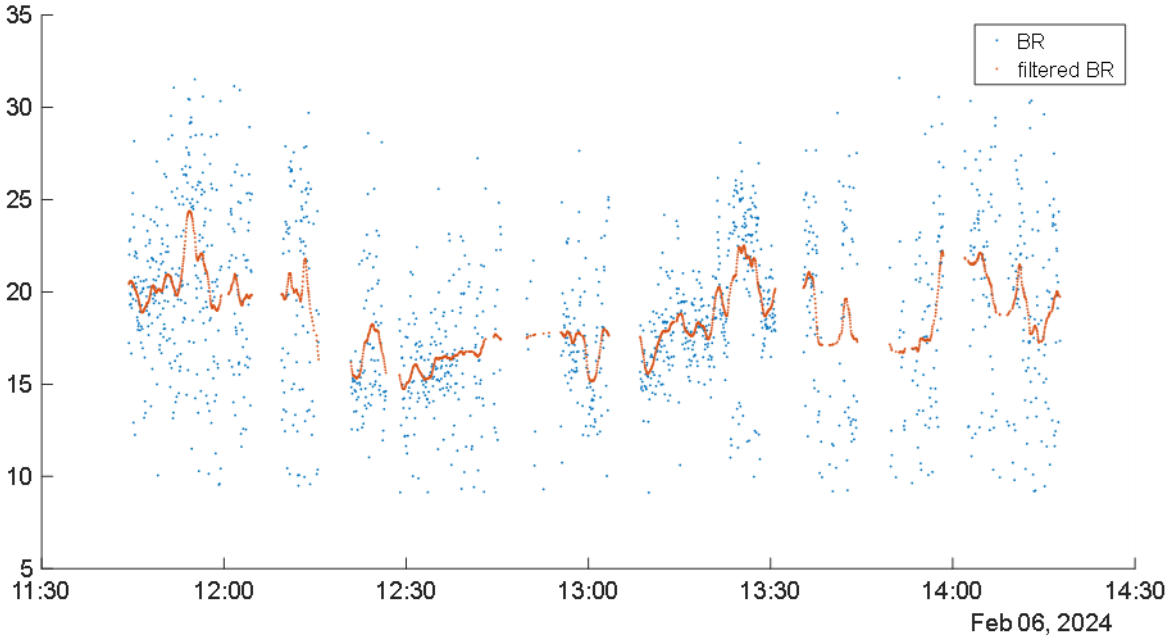

Fig. 28 The breath rate of “Animal 4”.

3.5 HEART RATE

To determine the heart rate of each animal we must also choose the best signal of the four sensors. For this measurement we also choose signal one too. The heart rate graph will be processed from the subtraction of the smoothed vfd that represent the breath trace from vfd data (CUT RAW DATA).

```
hvfd=vfd(:,1)-smooth(vfd(:,1),0.3*Fs); % to obtain just the heart trace

plot(vft,hvfd)
```

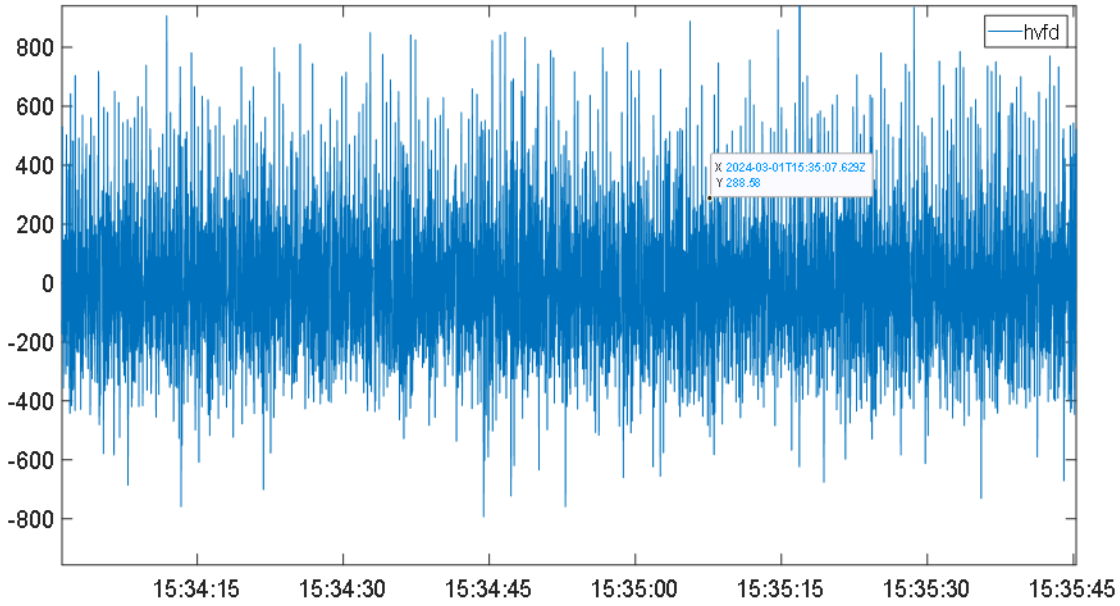

Fig.29 Graph of the heart vital function data for "Animal1"

We determined from fig.17 the value of the minimum height and width we need peaks above. Then we will find the peaks that have a minimum height equals to 288 and minimum distance peak equals to 0.3*Fs. (Fig.30)

```
[yh    xh]=findpeaks(hvfd,'MinPeakHeight',288,'MinPeakDistance',0.3*Fs);    %peaks finding - the same as by breath, don't forget to choose optimal values of the findpeaks function parameters

plot(vft,hvfd) %here we plot the graph of hvfd with respect to vft.
```

```
hold on

scatter(vft(xh),hvfd(xh)) ) %create a scatter plot with the data points represented
as dots.
```

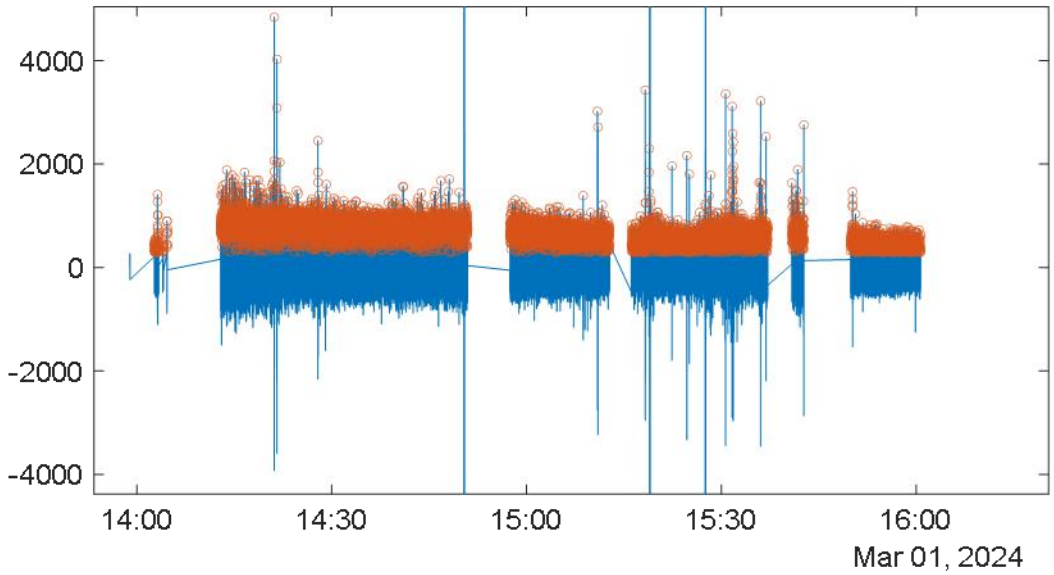

Fig.30 Graph of the hvfd with spotted peaks for "Animal1"

The heart rate is the number of pulses per 60 seconds. Between each two consecutive large peaks there is a one heartbeat of time equals to one period. This period is equal to the time difference between the two large peaks. As we did before in the breath rate studying, we will delete the outlines that they are too much higher or lower than the median heart rate. Finally, we will use moving mean then plot the heart rate. (Fig.31)

```
hr=60./seconds(diff(vft(xh))); %calculates the heart rate; the following procedure
is the same as by BR calculation

thr=vft(xh(1:end-1)); %thr is now time vector used for plotting heart rate.

outu=find(hr>1.75*median(hr)); %detecting indices of HR values, that are higher
than 1.75*median (HR).
```

```
outl=find(hr<0.5*median(hr)); %detecting indices of HR values, that are lower than
0.5*median (HR).

out=vertcat(outu,outl); %merging the indices saved in outu and outl into one vector
out.

out=sort(out); %sorting the elements of vector out just to arrange them.

hr(out)=[]; %deleting the values of HR with indices saved in variable out.

thr(out)=[]; %doing the same for time as for HR.

fhr=movmean(movmean(hr,8),20); %the moving mean of the HR

figure(31)

scatter(thr,hr,'.') %creates a scatter plot of hr with respect to thr with the data
points represented as dots.

hold on

scatter(thr,fhr,'.') ) %creates a scatter plot of fhr with respect to thr with the
data points represented as dots.

legend('HR','filtered HR') %it adds a legend box to the plot.
```

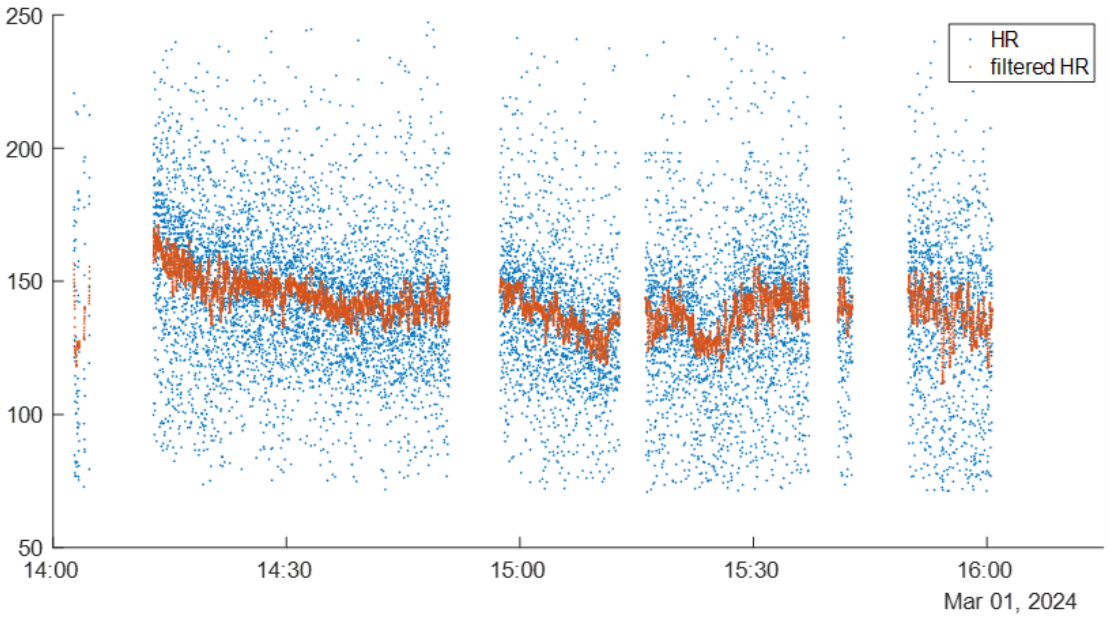

Fig.31 The filtered heart rate of "Animal 1".

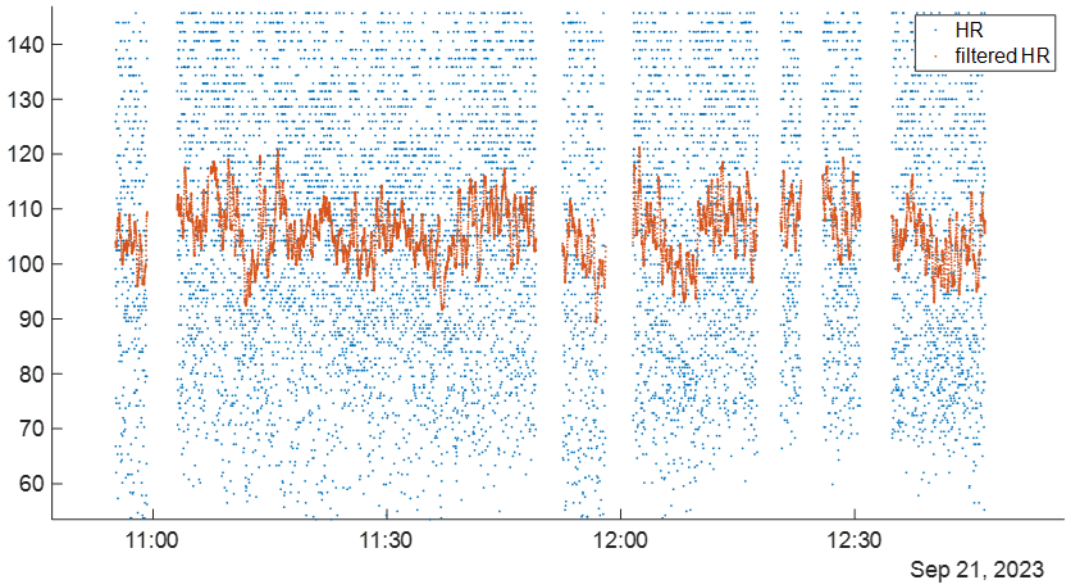

Fig.32 The filtered heart rate of "Animal 2".

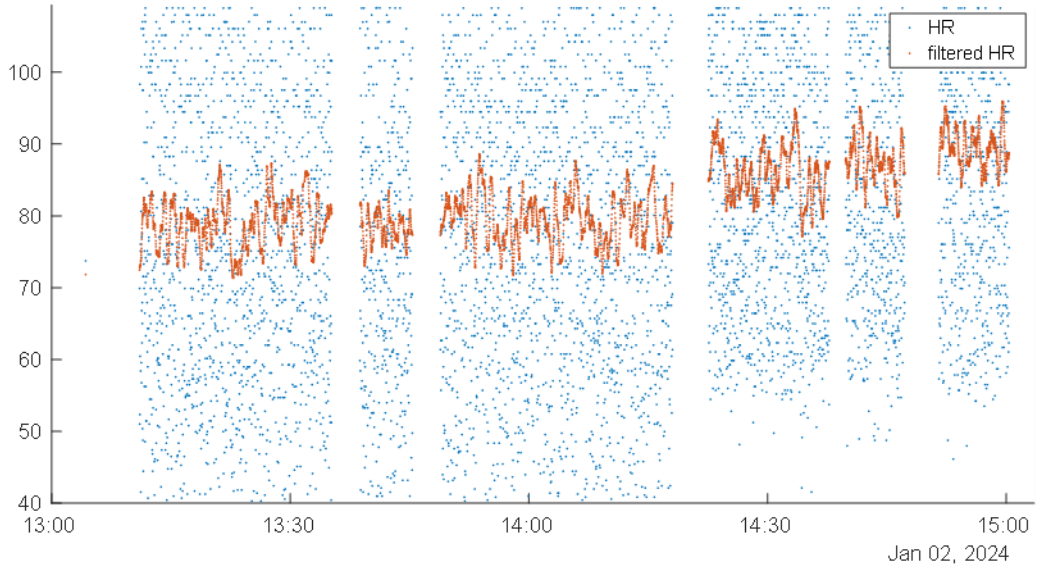

Fig.33 The filtered heart rate of "Animal 3".

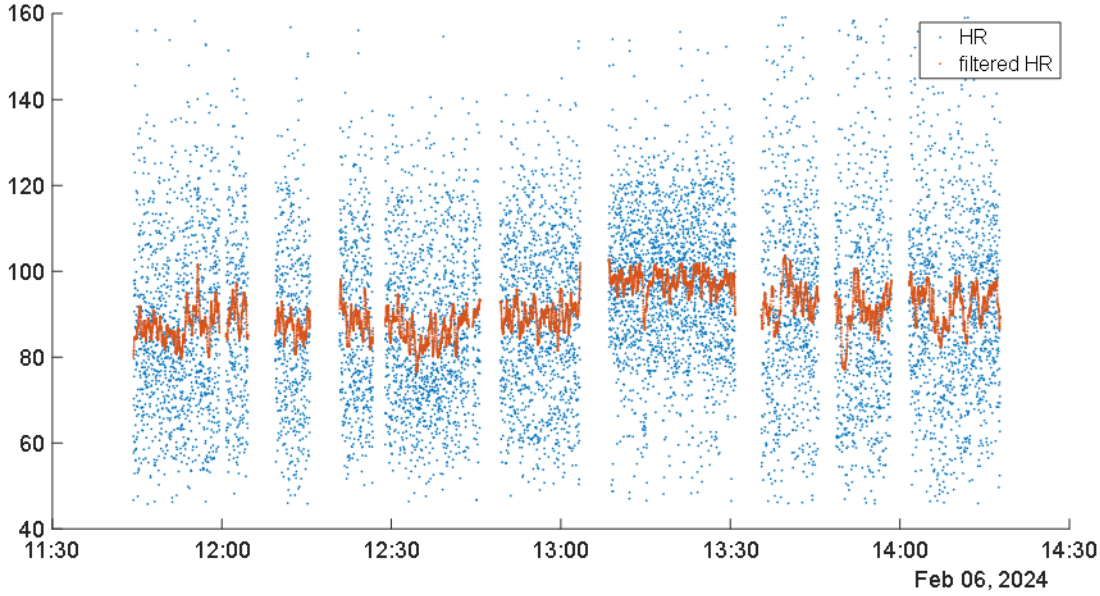

Fig. 34 The filtered heart rate of "Animal 4"

4. Discussion

One of the key vital signs for a dog is its respiration rate, typically ranging from 15 to 30 breaths per minute (bpm). If your dog is breathing faster than this, it might be excited or have just done some vigorous activity, like playing fetch or running around. However, the dog's breathing rate is consistently higher than normal, it could indicate a chronic illness, a traumatic injury, or a serious condition like heat stroke. Additionally, smaller dog breeds generally have faster breathing rates compared to larger breeds. This difference is due to smaller dogs having higher metabolisms, requiring them to breathe more rapidly to meet their oxygen needs, whereas larger dogs have slower breathing rates because of their lower metabolism.

Based on the information about normal respiration rates here's the classification of the four dogs:

- **Animal 1: 19 to 25 breaths per minute**
    - **Normal Breath Rate:** Yes, within the normal range of 15-30 bpm.
- **Animal 2: 26 to 35 breaths per minute**
    - **Normal Breath Rate:** No, exceeds the normal range of 15-30 bpm, it was hard to detect the exact breath rate because Animal's 2 activity varies a lot, sometimes so calm and other times more active. This leads to the failure of MATLAB to detect the exact filtered breath rate due to the huge difference between the values of the breath rate.
- **Animal 3: 13 to 20 breaths per minute**
    - **Normal Breath Rate:** No, as the lower end (13 bpm) is below the normal range.
- **Animal 4: 15 to 25 breaths per minute**
    - **Normal Breath Rate:** Yes, within the normal range of 15-30 bpm.

Considering heart rate, a small breed dog typically has a normal heart rate between 100-140 beats per minute (bpm). In contrast, a medium or large breed dog generally has a heart rate ranging from 60-100 bpm.

Based on the heart rate information provided, here's the classification of the four dogs regarding their breed size:

- **Animal 1: 120 to 160 beats per minute**
- **Animal 2: 100 to 120 beats per minute**
- **Animal 3: 70 to 90 beats per minute**

- **Animal 4: 70 to 100 beats per minute**

All the animals' heart rates where within the normal range other than "Animal 1", its heart rate exceeds the range. Based on Figures 31, 32, 33, and 34, the heart rates of Animal 1 and Animal 2 were high quality and easily determined because their heartbeats were consistently close in value and their peaks corresponding to heart beats were more visible.

When measuring the BR and HR of the four dogs, we noted that we used data from when the dogs were on the pad and not very active. However, since some dogs were mostly active, we had to take measurements when they were calm to slightly active. This situation makes accurately determining the dogs' BR and HR more challenging. The indication of the animals' presence and activity shows that all animals spent most of their time on the pad, with the second and fourth animals being the most active.

5. CONCLUSION

This thesis has demonstrated the effectiveness of using BCG to detect the presence, activity, breath rate, and heart rate of animals on a BCG pad. Through detailed analysis and experimentation, we have shown that BCG provides a non-invasive and reliable method for monitoring vital signs in animals. The ability to accurately detect the animals' presence and activity levels enhances the precision of heart rate and breath rate measurements, leading to better overall health monitoring. Looking towards the future, the integration of advanced data analysis techniques and machine learning with BCG data could significantly improve the accuracy and robustness of these measurements. MATLAB has proven to be an excellent platform for analysing BCG data due to its powerful computational and visualization capabilities. MATLAB's extensive library of functions and toolboxes allows for efficient processing and analysis of complex BCG signals, enabling detailed examination of heart and respiratory patterns. However, future improvements could include the development of specialized algorithms tailored specifically for BCG data, enhancing noise reduction and signal extraction processes. Additionally, real-time data analysis and the integration of MATLAB with other software and hardware systems could further expand its applicability, making BCG a more versatile and widely used tool in both research and clinical settings.

In conclusion, this study on the BCG of animals highlights the potential of this non-invasive technique to revolutionize veterinary medicine. For veterinarians, the adoption of BCG could lead to earlier detection of heart conditions, more precise monitoring of chronic cardiovascular diseases, and overall better health management for animals. The ability to obtain reliable HR, BR and rhythm data with minimal stress to the animals can significantly improve diagnostic accuracy and treatment outcomes. Looking ahead, the future of BCG in veterinary practice appears promising. Advances in technology will likely enhance the sensitivity and specificity of BCG devices, making them more accessible and easier to use in clinical settings. Further research and development could expand the range of applications, from routine health check-ups to complex cardiac assessments. The continued exploration and refinement of this technique will be crucial in realizing its full potential and securing its place in the future of veterinary diagnostics.

6. REFERENCES

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