CARDIOSCOPE: ECG SONIFICATION AND AUDITORY AUGMENTATION OF HEART SOUNDS TO SUPPORT CARDIAC DIAGNOSTIC AND MONITORING

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ABSTRACT

CardioScope is a sonification/auditory augmentation tool intended to support cardiac diagnosis and monitoring. It allows users to record and visualize synchronized Electrocardiogram (ECG) and Phonocardiogram (PCG) signals, to sonify the electrical activity of the heart or to augment the sound produced by its mechanical behaviour. As first step towards a realtime-interactive auditory augmentation, we here propose an auditory augmentation method using amplitude modulation that allows users to accentuate specific segments of the heart sound in order to make pathological signals from the heart sound more salient. We present a set of sound examples illustrating the proposed method, and discuss results of a preliminary qualitative test with two physicians who are doing their residency in cardiology.

1. INTRODUCTION

The idea of using our listening capabilities to support medical diagnosis has been present in humanity for a long time. In 1816 there was a giant leap in this domain when the French doctor René Laënnec rolled a piece of paper to make a tube that he could place between his ear and the chest of one of his patients in order to better listen to the internal sounds of the body. This moment marks the invention of the stethoscope. It was also Laënnec who introduced the term auscultation, which means listening to the sounds of the body for diagnostic purposes. In particular, the heart, the lungs and the bowel movements are first assessed by clinicians using auscultation.

Over the years, the stethoscope has become a primary tool for initial medical assessment. Auscultation is part of the basic physical exam that physicians carry out whenever they examine a patient. If they detect an abnormality, they can order further tests to obtain a deeper insight into the problem. Being able to detect such abnormalities through auscultation requires training, as the listening skills need to be developed with practice [1]. Besides the need to acquire expertise, noise conditions in medical environments can also increase the challenge of the task.

As medical technology advances, there are new tools that provide a deeper look to pathologies that are first noticed through auscultation. Nevertheless, the availability of such tools within a clinical setting vary greatly, as not all medical centers can afford the latest equipment, or the location and transportation conditions can also make it difficult to acquire specific equipment in remote places. Thus, even with new medical technology developments, the use of the stethoscope as a primary assessment tool maintains. First, because its portability and low cost make it easy to acquire even in remote places, but second, because auscultation makes it possible to get immediate feedback about the state of the patient, and thus to proceed accordingly in a proper time frame.

Given our listening abilities and our capabilities to discern patterns and changes in the signal [2], other forms of auditory feedback have become an integral part of medical monitoring, an example of this is sonification. The term sonification was officially introduced to the research community during the first half of the nineties by Scaletti and Craig [3] and it was later defined by Kramer et al. as transforming data into sound with the purpose of conveying information [4].

In the medical field, sonification is already used as a monitoring tool. A well-known example is the pulse oximeter, a device that measures the oxygen saturation level in the blood and produces a short duration sound in synchronization with the pulse rate. The pitch of the sound decreases if the oxygen saturation level diminishes, thus calling for immediate attention of clinicians. Current technology developments provide opportunities to integrate auditory tools such as auscultation and sonification to support medical diagnosis and monitoring.

As already mentioned, the field of auscultation focuses on several body systems (respiratory, cardiovascular and gastrointestinal). In this research project, we focus on the cardiovascular system [1], which is of particular relevance since according to the World Health Organization cardiovascular diseases are the first cause of death in the world [5].

In terms of sonification of cardiac signals, there are already research efforts to sonify features of electrocardiograms (ECG) with medical purposes[2] [6, 7, 8]. ECG sonification aims to support diagnosis and monitoring in situations where the visual sense is already focused on a primary task (e.g., performing a cardiac procedure) or in situations where the capabilities of the auditory system could help discern patterns that are not evident in the visual representation.

Besides sonification and auscultation, there is another approach that could enhance medical auditory based tools, in particular auscultation. Auditory augmentation is defined by Bovermann et al. [9] as “a paradigm to vary the objects sonic characteristics such that

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[1] Cardiovascular means that is related to the functioning of the heart, blood and blood vessels

[2] Electrocardiograms are visual representations of the electrical activity of the heart.

their original sonic response appears as augmented by an artificial sound that encodes information about external data. All this manipulation does not affect the sounds original purpose”. In digital stethoscopes, there are already approaches to enhance the characteristics of the sounds mainly through noise and interference reduction and amplification of the signal [10]. However, taking into account the nature of heart sounds, it is possible to propose other types of sound enhancement so that the features of interest in the signal are made more noticeable. Inspiration can be drawn from auditory contrast enhancement, a method to make intrinsic features of a sound (or differences between multiple sounds) more salient so that the underlying information can be better perceived [11].

In this research work, we propose the *CardioScope* system that combines ECG and heart sound signals in order to provide a broader overview about the state of the heart. First we record synchronized ECG and PCG signals and use the ECG signal as a reference point to find important segments of the heart sound signal. In the following section we explain the main characteristics of ECG signals and heart sounds. The signal acquisition process is described in Sec. 3. Furthermore, the method for the ECG-synchronized auditory augmentation of heart sounds is explained in Sec. 4. In Sec. 5 we introduce the *CardioScope* User Interface that allows users to acquire ECG and stethoscope signals simultaneously and interactively control basic features of the auditory augmentation in real-time. Finally, a discussion as well as conclusions are presented in Sec. 7 and Sec. 8.

2. ECG AND HEART SOUNDS

The stethoscope (1816) and the ECG (1903) are two of the earliest developments for cardiac assessment, they are also two of the most used methods. The sounds heard through the stethoscope give important cues about the state of the heart; however in order to give a precise diagnostic further tests need to be carried out, for example, electrocardiograms.

2.1. ECG and PCG signals

For the purposes of this research project, the ECG and the phonocardiogram and its timely connection play a major role. The cardiac cycle and the relationship between the electrical impulses displayed by the ECG and the heart sounds visualized as the phonocardiogram are shown in the Wiggers diagram, Fig. 1, alongside different pressures and ventricular volume of the heart.

In healthy persons the heart rhythmically pumps blood through the vascular system of the body to maintain oxygen supply. As part of the electromechanical coupling electrical impulses initiate the contraction of the heart muscle and therefore maintain a steady blood flow. The initiator of electrical impulses is called the sine node. From the sine node the electrical impulse is transferred via the atria to the atrioventricular node and further to the ventricles of the heart. The electrical activity can be visualized by recording an electrocardiogram (ECG).

Oxygen depleted blood is transported by the venous system to the heart during the diastole which is the relaxation phase. The blood enters the right atrium and is forwarded in the tension phase to the right ventricle. Right atrium and right ventricle are separated by the tricuspid valve. The right ventricle pumps the blood during the systole through the pulmonary valve in the pulmonary circulation. The blood enters the lungs and becomes oxygenated before returning to the left atrium. During the tension phase blood flows from the left atrium to the left ventricle passing the mitral valve before finally entering the systemic circulation through the aortic valve during the systole. The blood becomes distributed via arteries and arterioles to the organs of the body and in the periphery. In the different parts of the venous and arterial system, pressures can be measured during different phases of the heart cycle. See Fig. 1. A stethoscope can be used by medical providers to auscultate heart sounds. Heart sounds are physiologically generated by the closing of the heart valves. However, heart sounds are not generated directly by the valves itself. The sound waves are due to turbulence caused by their closing.

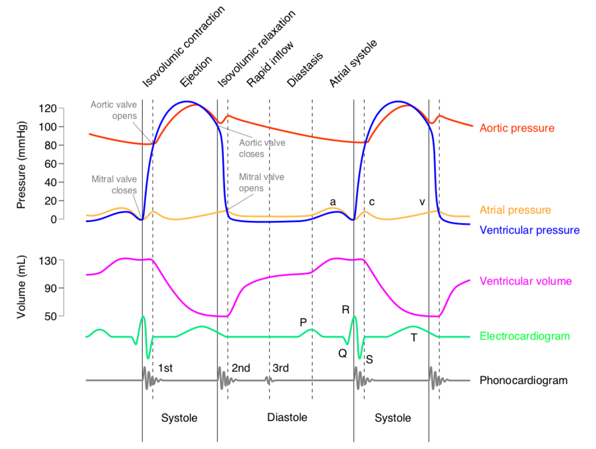

Figure 1: Wiggers Diagram. Image by adh30 revised work by DanielChangMD who revised original work of DestinyQx from Wikimedia Commons. Licensed under CC BY-SA 4.0.

The first heart sound (S1 or 1st) is produced during the time of the closing of the mitral and tricuspid valves. See Fig. 1. Since the closing of the mitral valve precedes the tricuspid valve by a fraction of a second the first heart sound is physiologically split. This splitting is hard to discriminate for a human ear when auscultating. The second heart sound (S2 or 2nd) is audible during the closing of the aortic and pulmonary valve. Normally the aortic valve closes just before the closing of the pulmonary valve which can also lead to a splitting of varying duration.

S1 and S2 can be auscultated in healthy adult humans. There might be additional sounds in adults in cases of pathological conditions or physiologically in children. For example, the third sound (S3 or 3rd) is considered normal in children or athletes but pathological in adults. S3 is a very low frequency sound produced during ventricular filling, a period also known as diastole (See Fig. 1). The cause of the sound is not yet very clear, it has been said to be related to volume-overload in the ventricles [12], but latest research has also linked it to the diameter of the mitral valve [13]. Furthermore, there might be heart murmurs which are always referred to as pathological.

2.2. The ECG signal

The ECG is a visual representation of the electrical activity of the heart. A standard ECG has twelve leads or channels that depict the activity of the heart from different angles.

In each cardiac cycle, the resulting signal depicts a set of intervals and reference points that physicians evaluate in order to detect anomalies in specific regions of the heart. Figure 2 shows the standard reference points found in every cycle. The beginning of the cycle is given by the P wave that represents atrial depolarization, then there is the QRS complex that represents ventricular depolarization. This is followed by the isoelectric ST segment, which depicts the time between depolarization and repolarization of the ventricles. Finally, there is the T wave as a result of the ventricular repolarization.

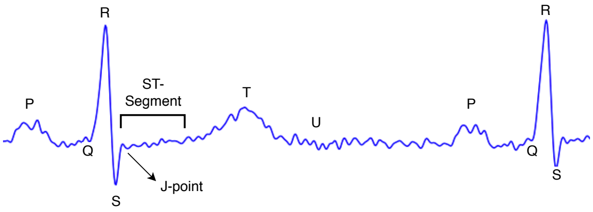

Figure 2: ECG standard reference points (P, Q, R, S, J point, and T), and ST-segment

2.3. Heart sounds

Recordings of heart sounds are known as Phonocardiograms (PCG). As explained in section 2.1 during the cardiac cycle the heart makes a set of sounds that result from the vibrations created by the closing of the valves. Figure 3 shows S1 and S2 during a cardiac cycle.

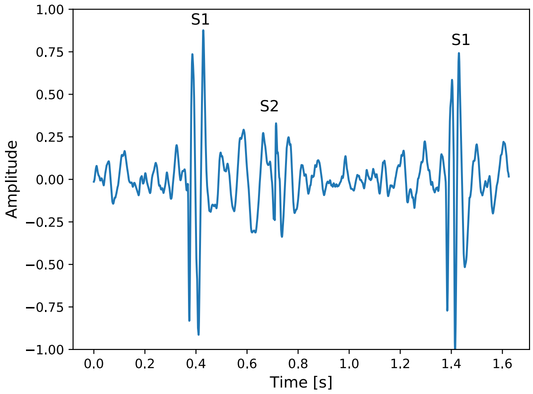

Figure 3: Heart sound depicting S1 and S2

When an abnormality in the heart sound occurs, it is called a murmur. Nonetheless some murmurs are considered harmless [12]. The most common murmurs involve turbulence due to improper closing of the valves after ejection of the blood or due to obstruction of the valves. Such murmurs cause changes in the frequency and intensity of the heart sounds. A broader overview about heart sound murmurs can be found in [14]. Figure 4 depicts changes in the envelopes of heart sounds when different types of murmurs are present. For example, case B illustrates a pathology known as aortic stenosis. This murmur is caused by an obstruction in the aortic valve (See Sec. 2.1), as a result, the second sound (S2) is not a clean short duration valve-closing sound as in case A, but instead it produces a noisy bell-shaped waveform that starts before the actual closing of the valves.

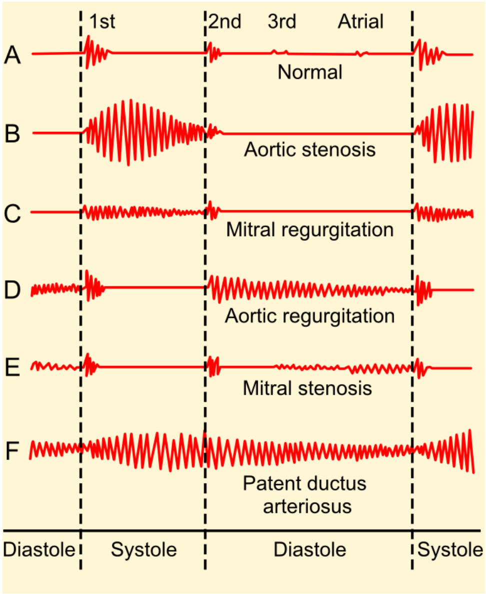

Figure 4: Heart murmurs. Image by Madhero88 from Wikimedia Commons. Licensed under CC BY-SA 3.0.

In order to better hear specific murmurs that are related to a particular heart valve, physicians place the stethoscope in specific areas of the chest. Common heart auscultation places are shown in Fig. 5 and are marked with the letters P, A, T and M, indicating each of the valves (Pulmonary, Atrial, Tricuspid and Mitral) .

3. SYNCHRONIZED SIGNAL ACQUISITION

ECG signals are usually recorded through a medical data acquisition system, while the stethoscope signal can be easily recorded by a microphone connected to an audio interface. Both are analog electrical signals which can be captured by stereo Analog-to-Digital Converters (ADC).

For the first prototype, we use the ECG Sensor from the BITalino (r)evolution plugged kit[3] [15]. It requires an input voltage V_{cc} between 2.0 and 3.5 V (see [16]) which we supply through a 3.7 V rechargeable battery. Additional $V_{cc}/2$ is provided through a simple voltage divider with two 10 k Ω resistors. The ECG sensor then outputs a value between 0 and V_{cc}. An additional voltage regulator

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[3] BITalino: `https://bitalino.com`

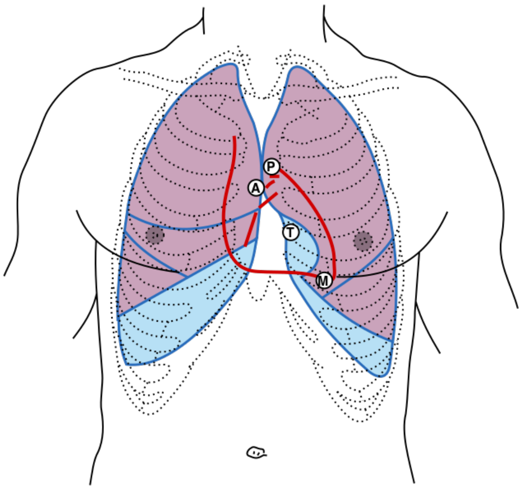

Figure 5: Common heart auscultation locations. Image by Henry Vandyke Carter via Wikimedia Commons. Derivative work by Huckfinne. Licensed under CC0 1.0

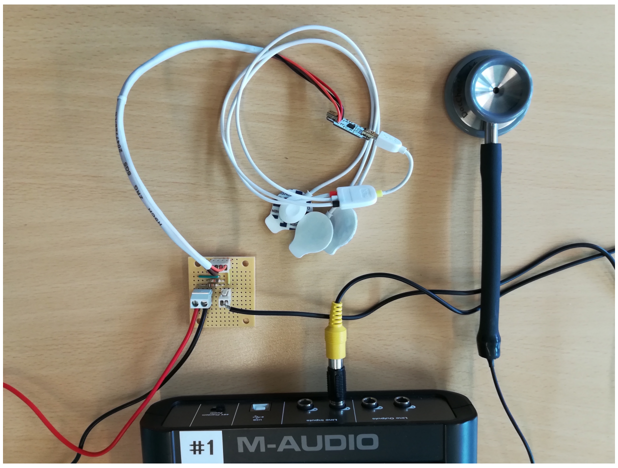

Figure 6: ECG and PCG recording system

can produce a stable reference voltage of 3.3 V and would thus theoretically allow reconstruction of the absolute voltage values from the digital signal. However, we omitted this step for the first prototype. To create a centered/bipolar audio signal, we rely on the analog DC-removal high-pass filter that is already built into the audio interface. The centered signal between $-V_{cc}/2$ and $+V_{cc}/2$ then sufficiently matches the specification of a +4 dBu line level audio signal which goes from $-V_{peak}$ to $+V_{peak}$, with $V_{peak} = 1.736$ V. A photo of the ECG and stethoscope hardware is shown in Fig. 6.

For stethoscope recording, we use a DocCheck Advance II dual head stethoscope chest piece attached to a short rubber tubing. An AKG C417 PP miniature microphone is inserted into the open end of the tubing and connected to the microphone preamplifier of the audio interface.

Both ECG and stethoscope signal are recorded by an M-Audio Mobile Pre USB audio interface. The downside of this procedure is that the ECG sensor and thus electrodes are electrically connected to the audio interface and thus computer which could introduce additional noise. The electrical connection between the human body and the audio interface through the ECG electrodes is no greater risk than a microphone held in the hand.

In the case of medical equipment products, there is a safety standard that needs to be met when devices are in direct contact with the patients. If there is an electrical connection to the heart of the patient the CF type standard needs to be taken into consideration.

4. ECG-SYNCHRONIZED AUDITORY AUGMENTATION OF HEART SOUNDS

Considering the nature of heart murmurs explained in section 2.3, we propose *ECG-synchronized auditory augmentation* as a method to accentuate segments of interest in the heart sound cycle. The augmentation is achieved using amplitude modulation. The idea is to accentuate sound segments that correspond to heart murmurs while attenuating the amplitude of segments that are outside of the region of interest.

4.1. R-peak detection and heart sounds segmentation

Signals recorded through a stethoscope can be quite noisy. For example, moving the stethoscope around the skin or ambient noises in the medical environment can mask the signal of interest, which on the one hand can make the auscultation labor more difficult and on the other hand can make the segments detection in the heart signal more challenging when using automatic systems.

There are several approaches to perform segment detection in heart sounds [17]. One of them is to use the ECG signal as a reference for the segmentation [18, 19] and, since we already have synchronized recordings of the two signals (ECG and PCG), we opt to use the ECG signal for the segmentation process.

Taking into consideration the temporal relation between the electrical and mechanical signals shown in Fig. 1, first, we detect the R-peaks in each cardiac cycle. In order to perform the R-peak detection, initially we apply a low-pass filter with a cutoff frequency of 70 Hz to eliminate frequencies that are outside of the range for ECG diagnostics [20]. Then we implement the method proposed by Worrall et al. [21] in a time window of 200 ms.[4].

Figure 7 depicts the R-peaks detected in one cardiac cycle and their temporal relation to S1 and S2.

4.2. The amplitude modulation signal

The amplitude modulation signal is calculated for each cardiac cycle. The reference to determine the duration of each cycle are the R-peaks found in the ECG signal. Once a cardiac cycle in the ECG signal is detected, we create the amplitude modulation signal for the current heartbeat with period T_i. In the off-line implementation the period is calculated based on the time difference between consecutive R-peaks Δt_{RR}. In the real-time implementation, the interval between subsequent heartbeats can be predicted by applying a linear regression to a series of past *M* inter-beat intervals.

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[4] The typical QRS duration for a healthy adult with a heart rate of 60 beats per minute (bpm) is 100 ms

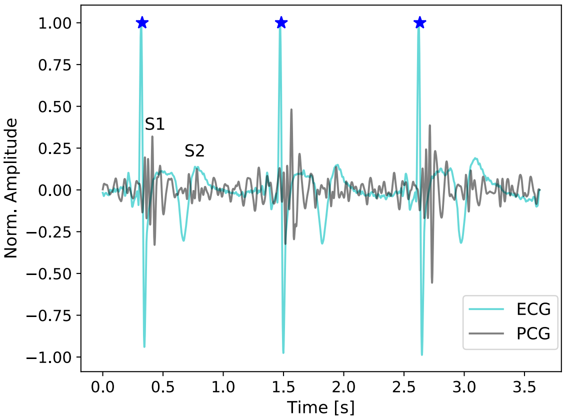

Figure 7: R-peak detection

We define the amplitude modulation signal in the ith heartbeat as

$$\text{mod}_i(t) = (1 - g_a) + g_a \cdot w \left(\frac{t - \beta \cdot T_i}{\alpha \cdot T_i} \right) \qquad (1)$$

for $0 \leqslant t \leqslant T_i$, where g_a is the accentuation parameter, β is the relative time lag before the window starts and α is the relative window length.

The window w is defined as

$$w(t) = 0.5 \cdot (1 - \cos(2\pi t)) \qquad (2)$$

for $0 \leqslant t \leqslant 1$, otherwise 0.

Sound H1 [5] corresponds to a heart sound of a healthy subject recorded using the method described in Sec. 3. The healthy heart sound is presented in order to provide an auditory reference of a healthy signal. Next, we present the auditory augmentation method using pathological data.

In order to test how the *ECG-synchronized auditory augmentation* method performs in pathological heart sound signals, we use a selection of heart sounds obtained from the *Classifying Heart Sounds Challenge* database [22]. This database contains a series of recordings including normal sounds, murmurs, extra heart sounds or artifacts. We selected a group from the murmur category to create the sound examples.

Sound P1.1 corresponds to a pathological heart sound from the previously described database. *Sound P1.2* is the auditory augmentation of *Sound P1.1* using parameters $g_a = 0.9, \beta = 0.4$ and $\alpha = 0.3$ (See equation 1). Figure 8 depicts the *Sound P1.2* heart sound modulation. This auditory augmentation focuses on S2, thus making more noticeable the murmur related to these heart valves (aortic and pulmonary).

A different pathology can be heard in *Sound P2.1*. In this case, the murmur is longer than in the previous example, it starts around S2 and it prolongs until S1. An auditory augmentation of *Sound P2.1*, is presented in *Sound P2.2*. The parameters used for the augmentation are: $g_a = 0.9, \beta = 0.5$ and $\alpha = 0.4$. Figure 9 illustrates the previously described augmentation.

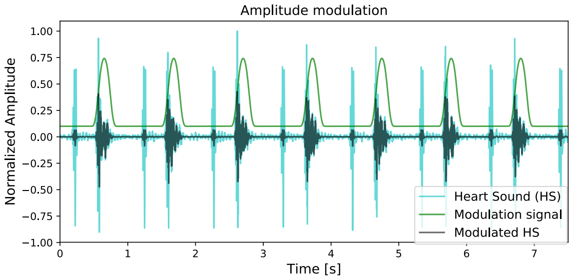

Figure 8: Amplitude modulation of *Sound P1.1*. The original waveform is shown in cyan color, the modulation signal is presented in green and the modulated heart sound is shown in black color.

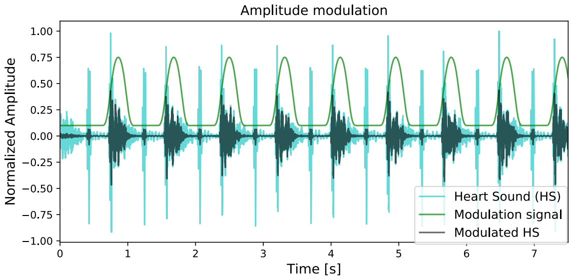

Figure 9: Amplitude modulation of *Sound P2.1*. The heart sound is shown in cyan color, the modulation signal is presented in green and the modulated heart sound is shown in black color.

5. THE CARDIOSCOPE INTERACTIVE GUI

Auscultation itself is a highly interactive process. Physicians place the stethoscope at different locations to better hear specific sounds (See Fig. 5). Furthermore, they can choose between the two sides of the stethoscope (diaphragm/bell) to accentuate a given frequency range.

The *CardioScope* interactive GUI (See Fig. 10) allows users to acquire and visualize synchronized ECG and PCG signals in real time. Moreover it provides basic controls to enhance the signal using filtering and gain controls.

At present, the amplitude modulation method is not yet implemented in real time, however, it is planned to be included in the next development of the *CardioScope* application.

5.1. Listening modes and ECG sonification methods

CardioScope has a listening mode module that allows users to select between three listening options (1) ECG sonification: to listen to the sonified ECG signal, (2) Stethoscope: to listen to heart sounds and (3) ECG and stethoscope: which plays the ECG sonification on the left channel and the heart sound on the right channel.

The implemented ECG sonification methods are the result of our previous work, in which we proposed a set of sonification designs focused on arrhythmias[6] [8, 23] and the elevation of the ST-

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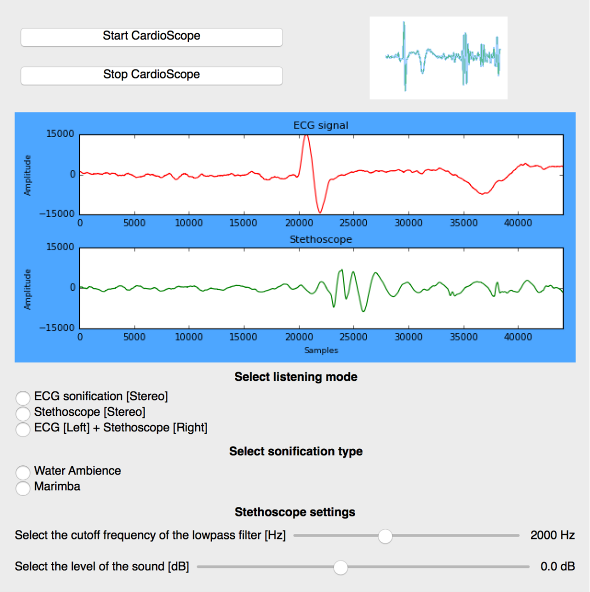
[5] See section 9 for supplementary material.

[6] Rhythm disturbances in the heart



Select listening mode

○ ECG sonification [Stereo]
○ Stethoscope [Stereo]
○ ECG [Left] + Stethoscope [Right]

Select sonification type

○ Water Ambience
○ Marimba

Stethoscope settings

Select the cutoff frequency of the lowpass filter [Hz] 2000 Hz

Select the level of the sound [dB] 0.0 dB

Figure 10: CardioScope GUI

segment [24] (see Fig. 2), which can be an indicator of myocardial infarction (MI)[7].

6. PRELIMINARY QUALITATIVE TEST

We consulted two physicians who are doing their residency in cardiology in order to have their opinion about the use of the *ECG-synchronized auditory augmentation* method in cardiac auscultation tasks. The physicians were asked to listen to a set of auditory augmented heart murmurs and to provide their feedback. Considering that this is a preliminary step towards the design of a qualitative user study, they were not asked to evaluate the interactive tool. One of the physicians regarded the proposed augmentation method as helpful, as it was possible to focus more on the pathological heart murmur by attenuating/filtering unwanted sounds in the heart signal. However, the physician also stated that it is important to not fully attenuate other sounds within the heart cycle as then it would be harder to identify which part of the cycle is being listened to. The other consulted physician had a more doubtful opinion about the benefit of the proposed method. First, because there is a traditional way of doing auscultation that hasn't been changed in a long time, and adjusting to the new method would require time from doctors and students. The second argument was that if a physician listens to what might be a heart murmur, then there would be a follow-up check using ultrasound or other methods. However, the proposed augmentation method could then be helpful in remote areas or countries where they don't have such possibilities about the availability of several medical devices.

7. DISCUSSION

The *CardioScope* system is a tool to support cardiac diagnostic and monitoring based on auditory displays. *CardioScope* aims to provide a broader overview about the state of the heart by combining ECG and PCG signals.

Current medical technology developments have made it possible to create multiple tools for cardiac diagnosis. Most of them rely on visual feedback, technologies such as echocardiography, Heart CT scan and Cardiac Magnetic Resonance Imaging (MRI) are among the most common ones. At present, there is an ongoing discussion about how these new tools could replace the role of the stethoscope [25, 1]. Nevertheless, it is important to keep into account that the availability of such tools depend on how well equipped medical centers are. For example, in remote places access to modern medical equipment is rather limited, which raises the question on how to improve health care conditions in these communities [26]. In addition, there is a part of the medical community that believes the stethoscope shouldn't be replaced but instead used in conjunction with tools of increasing demand such as portable ultrasound devices for echocardiography [25].

It is known that the human auditory system is a very powerful tool to detect patterns and changes in the signals, and auscultation has proved that these abilities can be used in cardiac assessment. Moreover, the use of ECG sonification as a medical supporting tool had also shown promising results [7, 24, 23]. Thus *CardioScope* serves as a tool that focuses on the powerful abilities of our listening system and uses different auditory display techniques to enhance cardiac features. The idea is that physicians can overcome current challenges in the interpretation of ECG signals that are a limitation of visual displays and limitations in the auscultation process due to internal and external noises and poor audio quality. State of the art digital stethoscopes already implement noise reduction to provide better signal quality, nevertheless there is still room to improve the quality and salience of signal features acquired through a stethoscope.

The proposed method of *ECG-synchronized auditory augmentation* provides new possibilities to the auscultation process, not only from the diagnostics perspective, but also for educational purposes, since it makes features of interest in the heart sound that are the cues to the detection of cardiac pathologies more salient. For example, the proposed augmentation method allows physicians to emphasize murmurs that derive from specific regions, such as the mitral and tricuspid valves (S1) or the aortic and pulmonary valves (S2), thus making such murmurs more noticeable during the auscultation process.

The feedback that we received from the consulted physicians falls in line with the current medical discussion previously described, about the role of the stethoscope and its use in conjunction with other cardiac medical technologies. On the one hand, the proposed auditory augmentation is regarded as useful as it can attenuate unwanted sounds and thus make pathological patterns more salient, however on the other hand, there are physicians that would rather rely on the traditional auscultation method or use other technologies such as echocardiography in order to make a diagnostic. A reason for that, however, could lie in the fact that the cardiologists listened to the sonifications outside a closed-interaction loop: if they would have controlled parameters such as α interactively, e.g. by adjusting a slider, then it would have been directly clear when in time the heard sound occurs relative to S1 and the R-peak. We believe that establishing a closed-loop interaction is crucial for

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[7] Lack of oxygen supply in the heart due to a blocking of the coronaries

acceptance and profitable use of CardioScope.

If the *ECG-synchronized auditory augmentation* method is introduced as an auscultation tool, a training phase would have to be made so that medical doctors learn to recognise the patterns using the augmented method, however, such training is already the base to learn how to do traditional auscultation. In order to have a better idea about the scope and limitations of the proposed method, it is necessary to carry out a user study. We plan to conduct a qualitative user study involving experts from the medical field in order to determine the significance of the auditory augmentation of heart sounds in the auscultation task.

In the current system development version the auditory augmentation is not yet implemented in real-time mode. However, this is plan to be included in the next development. Moreover, gathering a database of pathological ECG and PCG recordings it is also one of the future tasks of this project.

8. CONCLUSIONS

We introduced the CardioScope system that allows users to acquire synchronized ECG and PCG signals and listen to the signals in three different modes: (1) ECG sonification, (2) auditory augmentation of PCG (3) ECG and PCG. Additionally it offers a set of controls to filter and amplify/attenuate the heart sound signal in real-time. Furthermore, we presented and auditory augmentation method for heart sounds based on amplitude modulation to accentuate specific segments of the signal in order to better detect pathological sounds.

We regard the combined use of ECG and PCG in CardioScope as offering a versatile tool, of relative low cost, which could be applied for cardiac diagnostic in remote areas, and could support physicians in situations when a visual display is not an ideal option or when the noise conditions difficult the auscultation task.

A further quantitative user study still needs to be conducted in order to determine how *CardioScope* can support physicians in their everyday activities involving interpretation of ECG signals and auscultation of heart sounds.

9. RESOURCES

Examples of the segmented amplitude modulation are provided in: http://dx.doi.org/10.4119/unibi/2938001

10. ACKNOWLEDGMENT

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11. REFERENCES

[1] Tom Rice, "Learning to listen: auscultation and the transmission of auditory knowledge," *The Journal of the Royal Anthropological Institute*, vol. 16, pp. S41–S61, 2010.

[2] Brian Moore, *Psychoacoustics*, pp. 459–501, Springer New York, New York, NY, 2007.

[3] Carla Scaletti and Alan B. Craig, "Using sound to extract meaning from complex data," 1991, vol. 1459.

[4] G. Kramer, B. Walker, T. Bonebright, P. Cook, J. Flowers, N. Miner, and J. Neuhoff, Eds., *Sonification Report: Status of the field and research agenda*, Palo Alto, 1997.

[5] "Cardiovascular diseases (cvds)," `https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)`, Accessed: 05.08.2019.

[6] Hiroko Terasawa, Yota Morimoto, Masaki Matsubara, Akira Sato, Makoto Ohara, and Masatoshi Kawarasaki, "Guiding auditory attention toward the subtle components in electrocardiography sonification," Georgia Institute of Technology, 2015.

[7] Jakob Nikolas Kather, Thomas Hermann, Yannick Bukschat, Tilmann Kramer, Lothar R. Schad, and Frank Gerrit Zllner, "Polyphonic sonification of electrocardiography signals for diagnosis of cardiac pathologies," *Scientific Reports*, vol. 7, pp. 44549, 2017.

[8] Andrea Lorena Aldana Blanco, Steffen Grautoff, and Thomas Hermann, "Cardiosounds: Real-time auditory assistance for supporting cardiac diagnostic and monitoring," in *Proceedings of the 12th International Audio Mostly Conference on Augmented and Participatory Sound and Music Experiences*, New York, NY, USA, 2017, AM '17, pp. 45:1–45:4, ACM.

[9] Till Bovermann, René Tünnermann, and Thomas Hermann, "Auditory augmentation," *IJACI*, vol. 2, pp. 27–41, 2010.

[10] Shuang Leng, Ru San Tan, Kevin Tshun Chuan Chai, Chao Wang, Dhanjoo Ghista, and Liang Zhong, "The electronic stethoscope," *BioMedical Engineering OnLine*, vol. 14, no. 1, pp. 66, Jul 2015.

[11] Marian Weger, Thomas Hermann, and Robert Höldrich, "Real-time auditory contrast enhancement," in *ICAD*, 2019.

[12] Turnquest AE Dornbush S, "Physiology, heart sounds," `https://www.ncbi.nlm.nih.gov/books/NBK541010`, Accessed: 20.08.2019.

[13] Hesham R Omar and Maya E Guglin, "Mitral annulus diameter is the main echocardiographic correlate of s3 gallop in acute heart failure.," *International journal of cardiology*, vol. 228, pp. 834–836, 2017.

[14] Bernard M. Karnath and William Norman Thornton, "Auscultation of the heart," 2002.

[15] Hugo Plácido Da Silva, José Guerreiro, André Lourenço, Ana LN Fred, and Raúl Martins, "Bitalino: A novel hardware framework for physiological computing.," in *PhyCS*, 2014, pp. 246–253.

[16] PLUX – Wireless Biosignals, S.A., *Electrocardiography (ECG) Sensor Data Sheet*, 2016, Rev. A.

[17] Babatunde Emmanuel, "A review of signal processing techniques for heart sound analysis in clinical diagnosis," *Journal of medical engineering & technology*, vol. 36, pp. 303–7, 07 2012.

[18] M. B. Malarvili, I. Kamarulafizam, S. Hussain, and D. Helmi, "Heart sound segmentation algorithm based on instantaneous energy of electrocardiogram," in *Computers in Cardiology, 2003*, Sep. 2003, pp. 327–330.

[19] Noemi Giordano and Marco Knaflitz, "A novel method for measuring the timing of heart sound components through digital phonocardiography," *Sensors*, vol. 19, pp. 1868, 04 2019.

[20] Gari D Clifford, Francisco Azuaje, and Patrick Mcsharry, "Ecg statistics, noise, artifacts, and missing data," *Advanced Methods and Tools for ECG Data Analysis*, vol. 6, pp. 18, 2006.

[21] David Worrall, Balaji Thoshkahna, and Norberto Degara, "Detecting components of an ecg signal for sonification," Georgia Institute of Technology, 2014.

[22] P. Bentley, G. Nordehn, M. Coimbra, and S. Mannor, "The PASCAL Classifying Heart Sounds Challenge 2011 (CHSC2011) Results," http://www.peterjbentley.com/heartchallenge/index.html.

[23] Andrea Lorena Aldana Blanco, Steffen Grautoff, and Thomas Hermann, "Cardiosounds: A portable system to sonify ECG rhythm disturbances in real-time," in *Proceedings of the 24th International Conference on Auditory Display (ICAD)*, Houghton, MI, USA, 2018.

[24] Andrea Lorena Aldana Blanco, Steffen Grautoff, and Thomas Hermann, "Heart Alert: ECG Sonification for supporting the detection and diagnosis of ST segment deviations," 2016.

[25] Francis Fakoya, Maira du Plessis, and Ikechi B Gbenimacho, "Ultrasound and stethoscope as tools in medical education and practice: considerations for the archives," *Advances in Medical Education and Practice*, vol. Volume 7, pp. 381–387, 07 2016.

[26] Donna Goodridge and Darcy Marciniuk, "Rural and remote care: Overcoming the challenges of distance," *Chronic Respiratory Disease*, vol. 13, 02 2016.