CardioSounds: Real-time Auditory Assistance for Supporting Cardiac Diagnostic and Monitoring

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ABSTRACT

This paper presents a real-time sonification system for Electrocardiography (ECG) monitoring and diagnostic. We introduce two novel sonification designs: (a) *Auditory magnification loupe*, a method to sonify important beat-to-beat variations when doing sports activities, and (b) *ST-segment water ambience sonification*, which aims to assist clinicians in the diagnostic process by building a soundscape that exhibits ECG signal abnormalities as the analysed signal deviates from a healthy ECG. The proposed methods were designed to assist users to unobtrusively monitor their own (or their patients') heart signal in situations when a visual-only representation is not convenient for the proper fulfilment of a given task.

Using CardioSounds users receive auditory feedback in order to monitor important heart rhythm disturbances (e.g. Arrhythmia) or pathologies due to a blocking of the heart's vessels.

CCS CONCEPTS

•**Applied computing → Sound and music computing;** *Health informatics;*

KEYWORDS

Electrocardiogram, Sonification, Real-time System, Biofeedback, Process Monitoring

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1 INTRODUCTION

Sonifications have been used for monitoring real-time data streams in diverse application scenarios. Ranging from industrial processes to the weather forecast, researchers had proposed tools and methods to monitor distinct types of data [9]. One of the reasons why sonification is a good approach for monitoring, is that it allows users to focus on a main task and at the same time indirectly remain aware of peripheral or secondary processes. This property makes sonification a good candidate for monitoring biosignals either in a medical scenario or when performing everyday activities (e.g. doing sports).

As the field of smart sensors grows [2], the number of options for acquiring and sonifying biosignals such as ECG, EEG, EMG, in real-time increases as well. Nevertheless, the use of sonification for monitoring signals such as the ECG in a medical context is still in an early stage. First, because state-of-the-art methods for diagnostic and monitoring depend mainly on visual data representations and second, because real-time ECG sonification systems are often focused on representing rather low level features (i.e. heart rate) [7] or they have a more artistic approach [5] which not necessarily translates into utility for practitioners or clinicians. Additionally, current developments regarding ECG sonification for cardiac diagnostic rely primarily on offline data [1, 4, 8]. In this context, we consider that the applications of ECG sonification can be expanded towards creating supporting tools for cardiac diagnostics and monitoring, specifically, when there are limitations for continuous visual monitoring, or when more complex features than just the heart rate need to be monitored by clinicians or patients.

In this perspective, we have identified two use cases in which real-time ECG sonification could be applied to overcome the limitations previously explained: *(i) ECG auditory biofeedback when doing sports activities* and *(ii) auditory ECG monitoring to assist cardiac procedures*. In the first case, sonifying the ECG signal could support clinicians when performing procedures such as the balloon angioplasty operation [1], in which they have to constantly change the focus of attention from the patient to the medical devices used to visually monitor signals. In the second case, sonification allows users to receive feedback on their heart's current operation without having to interrupt the activity they are performing, which means they can focus their attention on their primary task, e.g. jogging, and nonetheless stay aware and informed about changes – and even warned of alarming situations – without risking possible injuries that might happen due to frequent distractions when attending to a visual monitor.

In this paper we first explain how the data is recorded. We then present the data preprocessing steps and the features extraction. Subsequently we introduce our sonification designs for the two proposed cases and present sonifications examples. Discussion and conclusions summarize the paper.

2 ECG REFERENCE POINTS AND INTERVALS

An electrocardiogram is a visual representation of the electrical activity of the heart. During a cardiac cycle, a number of intervals and reference points can be spotted in the ECG, cf. Fig. 1 . First, the P wave that represents atrial depolarization, followed by the QRS complex that represents ventricular activation. This is followed by the 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.

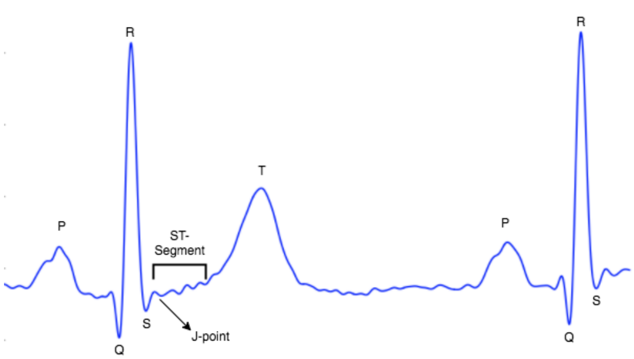

Figure 1: ECG standard reference points (P wave, Q, R, S, J point and T wave) and ST-segment.

[1]Medical procedure to restore an obstructed artery or vein.

The reference points are important as certain pathological states correspond to specific changes of the signal in segments, e.g. ST-segment elevation in myocardial infarction. In the following we refer to these points in our definition of features for sonification.

3 ECG DATA ACQUISITION, ECG SIGNAL PROCESSING AND FEATURES EXTRACTION

We record ECG data using the BITalino[2] hardware platform using an additional ECG module for each lead. This device allows real-time data acquisition and wireless transmission of the recorded signals. We currently use a single ECG lead, however, we plan multivariate extensions of our sonification designs for the near future. The recorded ECG signal is sampled at 1000 Hz. Once we have established the parameters for acquiring the ECG data, we process the signal to remove unwanted information and perform the features extraction.

Removing noise and artefacts

In order to remove artefacts and unwanted noise from the digitized signal, we remove the DC component and then apply a low-pass filter with a *cutoff* frequency of 70 Hz. We do this in order to eliminate frequencies outside the accepted range for ECG diagnostics [3]. Also, we apply a band-stop filter to remove signal noise at 50 Hz.

R peaks detection and heart rate estimation

As shown in Figure 1, the R peak is often the wave with the largest amplitude. Detecting the R peaks allows to determine the heart rate and subsequently other signal attributes. We search for R peaks implementing the method proposed by Worrall et al. [10] within a time window of 200 ms. We chose this window size because the typical QRS duration of a healthy adult with a heart rate of 60 beats per minute *(bpm)* is 100 ms. Once an R peak is found, we calculate the heart rate as $HR = \frac{60}{\Delta t_{RR}}$, where Δt_{RR} is the time between two consecutive R peaks. In order to avoid possible strong heart rate variations from phantom or missed peaks, the heart rate is calculated based on the the arithmetic mean of the last three Δt_{RR} values.

Rhythm disturbance measurements: Heart Rate variability

The heart rate variability (HRV) is a measure of the beat-to-beat time variation and it has been presented as a strong predictor of mortality after myocardial infarction (MI) [3] [6]. It can be calculated in the time or frequency domain. A simple

[2]http://www.bitalino.com.

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

metric to estimate HRV is to determine the standard deviation of the NN[4] interval (SDNN) [6]. Other common methods estimate the HRV according to a given *RRinterval* threshold that discerns healthy from pathological rhythm variations. The threshold varies depending on the used metric, some methods account for a 50 ms difference to be pathological while others give the same category for a variation as low as 20 ms [3]. Time-domain methods are used for short-time (e.g. 5 minutes) or long-time recordings (24 hours). Taking into consideration that we aim for a real-time approach, we expect an analysis window shorter than 5 minutes. For this reason, we don't estimate the HRV from the previously explained methods, but instead estimate the HRV calculating the Δt_{RR} value of the last detected peak. Then, we can compare our calculation to the Δt_{RR} of the penultimate peak and determine if the time difference is within a healthy or pathological range.

ST segment amplitude estimation

From the R peaks detection, we can estimate the duration of the other intervals that shape the ECG signal and extract features such as the amplitude in the ST segment. Detecting the amplitude in the ST segment provides an important cue on whether an artery in the heart is blocked [1]. In order to calculate the amplitude in the ST segment we implement the method proposed in our previous work [1] where we find an isoelectric reference in the TP segment and then calculate the elevation in the ST segment with respect to isoelectricity.

4 SONIFICATION DESIGNS

We propose two sonification designs: (i) The auditory magnification loupe sonification, a method to sonify the beat-to-beat variation in the ECG signal, and (ii) the water ambience sonification, a real-time implementation based on our previous ST segment elevation sonification method [1].

Auditory Magnification Loupe

Same as our eyes have limited resolution and need a loupe to distinguish tiny details, our ears can't differentiate if changes are below just noticeable differences. Despite our high resolution in perceiving changes in rhythm, we may overhear and miss subtle but relevant changes in rhythm. The Auditory Magnification Loupe (AML) is a mapping that magnifies such subtle changes that might fall below the just noticeable difference in one perceptual quality so that the information can be clearly discerned. Applied to rhythm sonification, variations such as heart rate fluctuations might be, despite our high sensitivity for discerning irregularities in rhythms, difficult to perceive. Instead of warping the temporal rhythm to apply the loupe only in the original domain (i.e. time),

[4]Interval from a QRS complex to the next one.

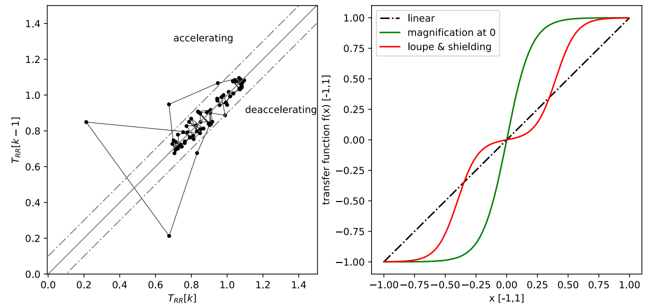

Figure 2: Auditory magnification loupe sonification. Left: Delay embedding of the heartbeat interval series, Right: Transfer functions for selective magnification transfer functions.

sonification allows to accentuate the variations by mapping to another perceptual quality where we can better attend to subtle variations, for instance pitch. In result, we obtain a 1-to-many mapping where a transfer function while mapping to pitch assures that a high (and low) sensitivity is obtained where needed.

Specifically for heart rate variability, we take the tuple of two successive heart rate intervals $(t_{RR}[k], t_{RR}[k+1])$ as a 2D point in a delay embedding. If the heart rate remains constant, the point will stay on a fixed point on the $x = y$ diagonal. A heart dysrhythmia would appear as a bouncing back-and-forth between two points on a line perpendicular to the diagonal.

With this intermediate representation we can now define a transfer function to realize our intended magnification. Choosing $f(x, y) = \tanh(\lambda \cdot (x - y))$, we obtain a mapping that accentuates deviations from the diagonal by a warping factor λ, allowing to magnify subtle differences around the diagonal until they result in clearly noticeable changes. For instance, mapping $f(t_{RR}[k], t_{RR}[k-1]$ from $[-1, 1]$ to the pitch of tone events, e.g. in [C4, C6] (i.e. 261 Hz, 1046 Hz), will result in C5 (i.e. 523 Hz) tones for heart beats as they are regular and higher or lower tones as the beat accelerates or slows down.

However, assume we wish to achieve a demagnification (or downsizing) of sensitivity within an ϵ-margin around the diagonal yet higher sensitivity outside the margin. This is for instance useful if regular heart beat variations regarded as healthy should not cause salient changes, yet variability beyond that should significantly stand out in the display. Then we can simply use a transfer function whose slope is low around 0 and large beyond ϵ, e.g. by using $f_{\epsilon,\lambda}(x - y) = 0.5 \cdot (\tanh(\lambda \cdot (x - y - \epsilon)) + \tanh(\lambda \cdot (x - y + \epsilon)))$ shown in Fig. 2 in the right plot.

Sonification example S1 [5] illustrates the auditory magnification loupe at hand of a dataset with important rhythm variations. It can be clearly heard how the frequency of the emited sound changes according to the interheart rate intervals. On the contrary, sonification S2 corresponds to an ECG without rhythm disturbances. Applications are in scenarios involving sport activities, because users receive clearly discernable auditory feedback when relevant rhythm disturbances occur. This is particularly relevant for patients recovering from myocardial infarction (MI) who are eager to monitor their heart activity while doing sports. In particular, for post-MI patients, it is important to monitor arrhythmias like ventricular tachycardia [6] because the patients are in danger of developing ventricular fibrillation [7], a life-threatening cardiac rhythm disturbance.

ST segment water ambience sonification

The ST segment water ambience sonification is a real-time implementation of our previous ST segment elevation sonification work [1]. This sonification is meant to be used as a monitoring tool in medical scenarios where sounds are triggered only when the ECG signal presents an abnormality in the ST segment. We use water drops sound as the main auditory cue. The idea behind this is to metaphorically represent blood flow in the heart. However, in our implementation the representation of blood flow is discrete (water drops) and in contrast to the real functioning where a healthy heart continuously pumps blood, a healthy ECG signal is represented by zero (or very few) sound events.

In this sonification we trigger a number of sound events (water drops) within R peak occurrences depending on the amplitude in the ST segment. The higher the amplitude, the more drops sound.

Sonification example S3 and sonification example S4 represent a healthy and an ST-elevated ECG respectively.

5 DISCUSSION AND CONCLUSIONS

This work presents a real-time sonification system aimed to assist cardiac diagnostic and monitoring. The current implementation allows to sonify one ECG lead that, depending on the electrodes placement chosen by the user, results in the recording of Lead I, Lead II or Lead III[8]. Nevertheless, we plan to expand the system for multivariate sonification. Recording multiple leads would allow to extract and sonify features that rely on multiple leads for their calculation (e.g. Cardiac axis). In the near future, we plan for CardioSounds to be a portable system that embeds signal acquisition, processing and sonification.

We consider that the proposed sonifications provide an interesting insight regarding rhythm variations and amplitude changes in the ST segment of an ECG signal, which would make ECG sonification a promising tool for clinicians and patients to monitor ECG signals of their interest in medical or everyday scenarios.

6 RESOURCES

Examples of the sonifications are provided in: http://dx.doi.org/10.4119/unibi/2912994

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[5] see section 6 for supplementary material.

[6] A heart dysrhythmia at a fast heart rate

[7] A heart abnormality that prevents the heart of pumping blood due to quivering.

[8] The standard ECG is composed by 12 leads (channels) that measure the electrical activity of the heart from 12 distinct angles.