HEART ALERT: ECG SONIFICATION FOR SUPPORTING THE DETECTION AND DIAGNOSIS OF ST SEGMENT DEVIATIONS

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ABSTRACT

This paper presents two novel sonification designs for Electrocardiography (ECG) data: (a) *Water Ambience soundscapes* aim at turning heart activity into an ambience which exhibits salient patterns as specific ECG properties deviate from a normal heartbeat, (b) *Timbre Morphing sonification* aims at supporting analysts to quickly assess if an abnormality in terms of the frequency, rhythm or amplitude in the signal occurs. Both methods are embedded into an interactive setting where the users can upload a dataset and interactively adjust sonification parameters, for instance in search of settings that optimize the contrast between a baseline (regular) and abnormal (ST deviated) case, based on pre-recorded real ECG data sets. In result, we qualitatively analyze how a small group of users interacts with the system and what their overview regarding the proposed methods is. Also, we conduct a study with eight participants in which they are asked to classify a set of sonifications according to two categories; healthy or unhealthy. The study results suggest that the proposed sonification designs allow users to correctly classify the datasets without having prior knowledge about ECG signals.

1. INTRODUCTION

In recent years, the interest for using sonification as a method for exploring ECG signal features has increased. Researchers had exposed the advantages of using heart rate sonification to support medical diagnosis [1], and they have proposed sound designs to guide attention to the specific ECG segments [2]. Additionally, part of the research efforts focused on improving the detection of the ECG components of a signal [3], in order to provide accurate segmentations that result in better starting points for the sonification method definition.

One of the challenges when analyzing ECG recordings is to determine which parts of the signal are meaningful data, and which others are the result of noises and artifacts. Moreover, a difficulty for accurate diagnostics is given by the fact that an abnormality in the ECG might be present in only a specific subset of leads, while other leads remain closer to a healthy signal. Sonification appears to be a good approach to help clinicians in the analysis and identification of important variations of the signal. First, because the human ear has the capability to rapidly and robustly detect changes and patterns even in very noisy signals, and second, because by giving the users the possibility to interact with the resulting sonifications, they could refine the sonifications themselves in order to enhance any pattern they regard as relevant, thus increasing the saliency of patterns. For example, if an abnormal and normal signal would differ in rhythmical features, the adjustment of parameters that control a nonlinear time warping might increase the perceptual difference between the sonifications of these datasets and thus help to better distinguish patterns.

The paper will first provide some background on ECG in Section 2. After presenting the used data (Section 3) and methods to extract relevant features (Section 4) the paper introduces the two new sonification approaches in Section 5. A pilot study with discussion and conclusion complete and summarize the paper.

2. BACKGROUND ON ECG

The electrocardiogram was first developed and introduced in the year 1903 by Willem Einthoven. An ECG is a visual representation of the electrical potentials generated by the cells of the heart muscle [1] during the depolarization and repolarization process of each cardiac cycle.

The resulting ECG signal is structured into intervals or segments that represent the electrical current flow within the heart over a period of time. A standard ECG recording contains 12 leads, which allow to measure the electrical potentials in distinct heart walls.

From the 12 standard leads, a few subgroups are formed. Their division depends on the heart's wall they measure. As a result, the standard leads are divided in lateral, inferior, septal and anterior leads. When a set of leads belong to the same subgroup it is said that they are contiguous.

2.1. ECG reference points and intervals

An ECG signal is typically analyzed by looking at six standard reference points [2], which are produced in every heartbeat. The references are shown in Figure 1.

The P wave represents the process of atrial depolarization, while the T wave occurs during ventricular repolarization. The U wave is normally not seen because of its low amplitude; however, it also takes place during ventricular repolarization. The J-point is located where the QRS complex finishes and the ST segment begins.

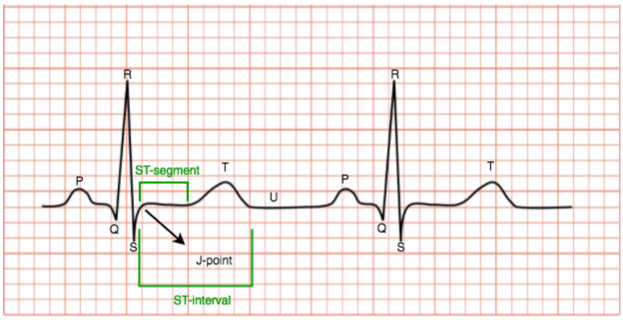

Figure 1. *ECG standard reference points (P, Q, R, S, J-point, T and U), ST-segment and ST-interval. This image is a derivative of 'Normal ECG 2' by Madhero88*[1]

Additional to the standard reference points, there are general segments in the signal that are important for its analysis. First, the PQ segment, followed by the QRS complex that represents ventricular activation. Right after the QRS complex there is the ST segment. It appears when the heart muscle contracts, which is the time between depolarization and repolarization of the ventricles. In healthy patients, this segment should be isoelectric, which means that the potential difference is zero. Finally, between the T wave and the P wave, the TP segments appears.

The most common ECG intervals and their normal durations for a heart rate of 60 beats per minute (bpm) are listed in Table 1 [2].

Interval	**Duration**
PQ/PR Interval	160 ms ± 40 ms
QRS	100 ms ± 20 ms
QT	400 ms ± 40 ms

Table 1. *ECG standard interval durations for a heart rate of 60 bpm.*

2.2. Importance of the ST-Segment

The ST segment is an isoelectric part of the healthy ECG. During that period of time there is normally no electric activity in healthy subjects. The ventricular depolarization has reached its maximum and the repolarization has not started yet. Therefore, no current is flowing during that time frame. The ST segment begins with the so-called J-point which is succeeding the QRS complex, the J-point represents the end of ventricular depolarization. The end of the ST segment is the beginning of the T wave corresponding to the ventricular repolarization.

Under certain conditions the ST segment can vary its appearance. The most important ST segment abnormalities are ST elevation or ST depression. These can be due to an ischemia of the coronaries, the vessels that are necessary for direct oxygen supply of the heart. ST segment elevation occurs in an event of sudden closure of these vessels. In this situation a myocardial infarction is present, because the tissue of the heart is in constant need of oxygen supply. Medical doctors use the ST segment evaluation as a major tool to decide whether the patient needs urgent intervention for recanalization of the coronaries.

According to the guidelines of the European Society of Cardiology, patients presenting with ECGs containing an ST segment elevation at the J-point of greater than 0.1 mV in two contiguous leads are ruling in as a so-called ST elevation myocardial infarction (STEMI) [4]. Slightly varying rules exist, depending on age and sex of the patient. The elevation at the J-point should be compared to either the PQ segment or the TP segment, which are both supposed to be isoelectric. The repolarization of the atrium occurs during the PQ segment [5], this segment can show variants and might lose its isoelectricity if there is pathologic involvement of the atrium, e.g. perimyocarditis [6].

If the above mentioned criteria of ST segment elevation are met the patient will undergo a heart catheterization, because described ST segment changes are most likely due to a STEMI. In case of a STEMI the shape of the ST segment elevation can even hint to the time of onset of the infarction. By evaluating the ECG and the localization of the ST segment elevations medical doctors can distinguish which coronary vessel is acutely affected.

The ST segment is a very important part of the ECG, because disturbances of this segment are evaluated for different pathologies, the most important pathology being myocardial infarction.

2.3. Overview of ECG Sonifications

State of the art methods for analyzing ECG signals rely merely on visual representations. Nevertheless, the interest for sonifying ECG signals has been growing in recent times. Some efforts are focused on detecting the main components of the ECG signal for further use in the sonifications [3], and some others had proposed sonification designs to represent the data, either implementing audification methods [7, 9] or parameter mapping sonification techniques [1,9, 7, 8].

So far, the sonifications were mainly focused on heart rate representation and the pathologies that derive from abnormal heart rate values or rhythmical patterns. For example, Ballora et al. [1] carried out a study in which they sonified the heart rate variability in four cardiac states. Additionally, Mihalas et al. [10] proposed sonification designs to monitor heart rate during exercise. Also, Terasawa et al. [9] directed their work towards making ECG components such as the T and P waves more salient.

3. ECG DATA AND PREPROCESSING

To develop our sonification designs described below in Section 5, we utilize two ECG data sources. The first one is the publicly available PTB (Physikalisch-Technische Bundesanstalt) diagnostic database [11] from Physionet[2], and the second one is own data recorded via a General Electric's MAC2000 Resting ECG System[3] in the hospital.

3.1. Physionet dataset – PTB diagnostic database

The PTB database is composed of 549 files sampled at 1000 Hz, each recording contains the standard 12 leads plus three Frank leads. We use only the first 12 leads for our sonifications. Along with each ECG recording, a clinical summary is included, which encloses information such as age, gender and

[1] *Licensed under CC BY-SA 3.0. https://commons.wikimedia.org/wiki/File:Normal_ECG_2.svg*

[2] https://www.physionet.org/physiobank/database/ptbdb/

[3] http://www3.gehealthcare.com/en/products/categories/diagnostic_ecg/resting/mac_2000

diagnosis. From the total number of files, there are 148 patients whose diagnostic was Myocardial Infarction. Additionally, 52 cases are included as healthy controls.

3.2. MAC2000 Resting ECG System

The files from the MAC2000 Resting system are provided by our clinical partner. Since the system outputs the recordings in XML format, we first extract the relevant leads into a CSV-formatted file.

The database built from the Hospital's system contains files from patients diagnosed with myocardial infarction and subjects that are considered healthy. All recordings include the standard 12 leads sampled at 500 Hz.

4. ESTIMATION OF ST-SEGMENT DEVIATION

In order to calculate the ST-segment deviation, first we estimate the location and duration of the sections and standard reference points of the ECG signal. Initially, we carry out the R peaks detection and subsequently, based on this information we define the other segments.

4.1. R Peaks detection

The R wave is the standard point with the biggest amplitude in the ECG signal over a heartbeat cycle (Figure 2). The detection of the R peaks is commonly used to determine the heart rate.

We perform the R peak detection of every lead implementing the procedure proposed by Worrall et al. [3] as follows: First, we remove the DC component from the signal and apply a high-pass filter to remove the lower frequency P and T waves. Subsequently the envelope is estimated using the Hilbert transform operation and the resulting signal is non-linearly scaled. Finally, the R peaks are detected and grouped when the time difference Δt among them is lower than 300 ms (corresponding to a rate of 180 bpm). The R peak with the higher amplitude among the grouped peaks, was chosen as the peak for the analyzed heartbeat. We chose to use a lower Δt, than the one proposed in [3] for grouping the peaks because we observed that when there is an ST deviation the heart rate could be higher than 60 bpm, leading to a lower duration of the QT interval and the other segments. Hence, setting a smaller Δt diminished the risk of missing peaks and increased the performance of the R peak detection algorithm.

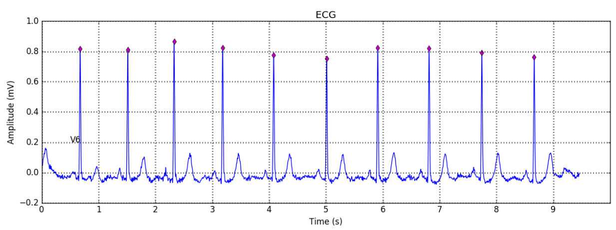

Figure 2. *R peaks detection.*

4.2. ECG Segments detection

Once the R peaks are detected, we determine the heart rate of every lead (as 60/RRinterval$_{lead}$, where RRinterval$_{lead}$ $= \frac{1}{n}\sum_{k=1}^{n} RRinterval_k, k$ is the kth heartbeat) and subsequently the duration of each segment. For the latter calculation, we normalized the ratio of the ECG parts in relation to the RR interval duration when the heart rate is 60 bpm. We take as a reference the values initially presented in Table 1.

Typical interval duration for a healthy adult (60 bpm). RR Interval duration = 1000 ms		Ratio of ECG Intervals in relation to RR interval duration when the heart rate is 60 bpm
QRS Width	100 ms	$\frac{RR\ interval}{10.0}$
QT Interval	400 ms	$\frac{RR\ interval}{2.5}$
PQ/PR Interval	160 ms	$\frac{RR\ interval}{6.25}$

Table 2. Ratio of *ECG intervals in relation to the RR interval when the heart rate is 60 bpm.*

Together with the peak's location and the estimation of the segments shown in Table 2, we determine the location of the J point, which happens right after the QRS complex ends (cf. Figure 4). Additionally, we calculate the ST interval duration as

$$ST_{dur} = QT_{dur} - QRS_{dur} \quad (1)$$

Finally, we determine the duration and location of the TP segment as

$$TP_{dur} = RR_{dur} - QT_{dur} - PQ_{dur} \quad (2)$$

As was mentioned in Section 2.2, the estimation of the TP segment is important because it provides the interval from which we estimate the isoelectric reference. Figure 3 shows the estimation of the points and segments that are necessary to calculate the ST segment deviation. Although the end of the T wave (that marks the end of the ST interval) is not exactly determined, the estimation of the J point and the TP are better achieved.

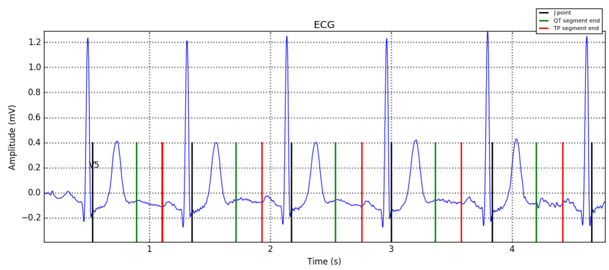

Figure 3. *ECG segments estimation for one lead (black line: J point, green line: end of ST interval, red line: end of TP segment).*

There are other methods that focus on a more accurate detection of the segments [12, 13, 14], yet we postpone such improvements as our current approach is sufficient for the development of the presented sonification designs.

4.3. ST-Segment deviation estimation

With our previously estimated J point and ST interval duration per lead, we can proceed to calculate the amplitude difference with respect to the TP segment (which we assume to define isoelectric) in every heartbeat of the analyzed lead.

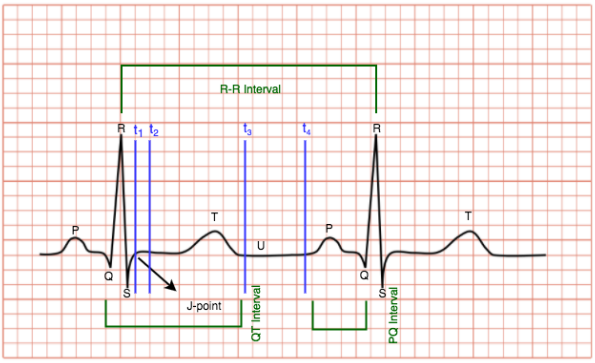

Figure 4. *ECG segments detection. This image is a derivative of 'Normal ECG 2' by Madhero88*[4]

First, we apply a band-pass filter to remove frequencies below 0.6 Hz and above 70 Hz in order to remove frequencies out of the accepted range for ECG diagnostic [2]. Then we calculate the average amplitude within the TP segment, which ideally should be 0 mV, and serves as DC-offset or isoelectricity reference. Practically we compute

$$\overline{TP} = \frac{1}{t_4 - t_3}\int_{t_3}^{t_4} g(t)\, dt \tag{3}$$

by summing the sampled signal *g(t)* between the segment borders t_3 and t_4, using

$t_3 = Rpeak + \frac{1}{2}QRS_{dur} + ST_{dur}$ and $t_4 = ST_{dur} + TP_{dur}$. Likewise we calculate the amplitude at the J point as the average from the J point until a time t_2.

$$\overline{ST} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} g(t)\, dt \tag{4}$$

where $t_2 = t_1 + \frac{1}{2}QRS_{dur}$.

Finally, the average ST-segment deviation with reference to the isoelectric reference results in

$$ST_{amp} = \overline{ST} - \overline{TP} \tag{5}$$

For the proposed sonifications we consider only the absolute value of the ST deviation $ST_{abs,amp} = |\, ST_{amp}\,|$. Next to the ST elevation calculated per heartbeat we determine the overall elevation per lead by

$$ST_{ampLead} = \frac{1}{n}\sum_{k=1}^{n} |\, ST_k - TP_k| \tag{6}$$

Where, n is the number of heartbeats per lead, and k is the index for the heartbeat in the data recording.

4.4. ST deviation in contiguous leads

Besides estimating the ST deviation, it is important to detect if an abnormal value of the deviation is present in contiguous leads (as defined in Section 2) to determine the heart's zone where problems occur. For this, we take as a reference the set of the 12 standard leads and cluster them into three groups. We don't include the aVR lead as part of the subgroups[5].

- Anterior leads (joining septal and anterior leads): V1, V2, V3, V4.
- Inferior leads: II, III, aVF.
- Lateral leads: I, aVL, V5, V6.

Then, if in any of these three groups a deviation exceeds a threshold $\theta = 0.1$ mV [4] in two or more leads, we conclude that the ECG signal exhibits ST deviation in contiguous leads and thus the corresponding section/s of the heart is/are affected.

5. SONIFICATION DESIGNS

We propose two sonifications, *water ambience* sonification and *timbre morphing* sonification, that can be used in different medical scenarios. The first one is meant to be used as a monitoring tool, which implies that when a signal is characterized as healthy, the sound should not be intrusive nor distract the doctors from any activities they are performing. The idea is to turn the ECG signals systematically into a soundscape that can be constantly played in the monitoring room, leading to audible sound events as soon as the signal exhibits abnormal behavior, from weak cues to a number of sounds appearing simultaneously in the soundscape to make the ECG features more salient.

The timbre morphing sonification is intended to work as an emergency signal that produces very clearly distinguishable sounds between ST-isoelectric (healthy) and ST-deviated (pathological) signals. The motivation is to provide an auditory cue that allows doctors to quickly assess the overall state of the main ECG components.

5.1. Water ambience sonification sound design

The idea of using water sounds for representing the ECG starts by considering that the heart itself works as a pump that sends blood (fluid) to the body tissues. Therefore, we can expect that water flow provides a metaphoric association to facilitate its interpretation as blood flow across the heart. However, we propose two variations in comparison to the real blood flow model: (i) *Discrete representation of blood flow*: instead of using a continuous sound stream for water flow we quantize the stream into perceptual units, i.e. water drop sounds as basic elements. (ii) Opposite representation of *Healthy vs. Pathological ECG*: rather than representing the blood flow of a healthy signal triggering several sound events, we propose an inverted approach where a healthy signal is represented with the least possible amount of sounds. In this way, the listener only receives auditory cues when the signal presents abnormal variations that call for attention. Thus, during each heartbeat a number of drop sound events are triggered if the calculated ST-deviation is greater than 0.05 mV; otherwise no sound is produced. We chose to trigger the drops from a 0.05 mV threshold in order to subtly start calling the attention from the

[4] *Licensed under CC BY-SA 3.0. <https://commons.wikimedia.org/wiki/File:Normal_ECG_2.svg>*

[5] The aVR lead is not normally included as part of any subgroup.

listener before an amplitude value catalogued as ST deviated (0.1 mV) is reached.

We propose a parameter-mapping sonification [15] where we determine the number of drops within each ST deviated heartbeat by linearly scaling the amplitude of each ST segment (input values) to the number of drops (target values). Based on the ST amplitude characteristics that we have observed in the ECG data, we define the range (min, max) of the source values to (0, 0.5) and the output (min, max) is set to (0, x, where x is the maximum number of drops defined by the user (cf. Table 4).

Data Feature	**Data Range (min, max)**	**Parameter**	**Parameter range (min, max)**
ST deviation of heartbeat	(0mV, 0.5 mV)	Number of drops per heartbeat	(0, x) x is defined by the user, according to: $1 \leq x \leq 10$

Table 4. Linear mapping of data features used in the *water ambience* parameter-mapping sonification.

In order to avoid wrong interpretations of the number of drops due to their temporal coincidence, but also to provide the listener with a cue for the heart rate even if a high number of drops is triggered, the sound events can be evenly distributed over the RR peak duration, or they can be distributed over α of the RR interval ($\alpha \cdot RR_{dur}$, Figure 5). We set the possible minimum duration for the drops distribution parameter to $\alpha = 0.4$ and the maximum to the full RR interval ($\alpha = 1.0$).

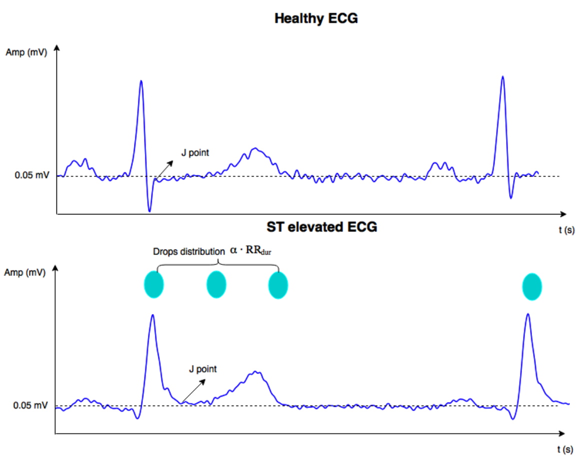

Figure 5. *Water Ambience sound design of healthy ECG and ST elevated ECG.*

Finally, we use the information from the ST deviation in contiguous leads to add selected ambience sounds. When the inferior, lateral or anterior leads present a deviation, a new sound event is triggered. Each of the three groups is assigned to a specific sound: the group of lateral leads is assigned to thunder sound, inferior leads to wind sounds, and anterior leads to rain sounds. All these sounds are added by playing recorded sound samples of few seconds duration. They are not meant to be played as long as the groups' deviation prevails, but occur only once every 10 seconds duration if the ST deviation is present.

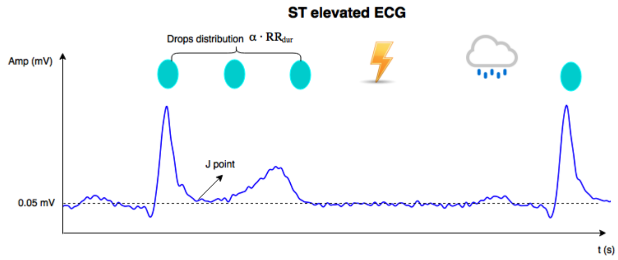

Figure 6. *Water Ambience sound design drops and extra ambience sounds representing contiguous leads.*

5.2. Timbre morphing sonification sound design

For the *timbre morphing* sonification, we introduce a parameter-mapping sonification that represents abnormality via an interpolation between two different waveforms, so that the degree of deviation becomes salient as a morphed timbre.

The sound is synthesized by superimposing two oscillators over different wave tables, specifically (*i*) a sine wave and (*ii*) a square wave. For this sonification we wanted to interpolate between a sinusoidal waveform to one of the other three most common audio wave shapes (Triangle wave, Square wave, and Sawtooth wave). We chose the sine wave as the starting point in order to represent healthy signals with the most spectrally simple sound, a pure tone, and then interpolate to a more complex tone. We chose the square wave. We did not use the triangle wave because it is perceptually too close to the sine wave and we also ruled out the sawtooth wave because it was perceived as too sharp as it contains all harmonics.

As a result, the overall timbre can be produced only by a sinusoidal wave, a square wave, or a combination of the two. The cross-fading weighting factor α between the waves depends on the ST deviation value, thus when the ECG is considered healthy and the amplitude in the J point is low, the sinusoidal wave is predominant. On the contrary, when the deviation is high the square wave is more noticeable. The cross-fading between the waveforms is given by,

$$W(t) = \alpha \cdot W_a(t) + (1 - \alpha) \cdot W_b(t) \quad (7)$$

As mentioned before, we intend that this sonification provides cues for clinicians to assess the overall state of the ECG components, thus besides representing the ST elevation we wanted the sonification to also represent the amplitude and location features of the R peak and the T wave in every heartbeat. For this, we trigger sound events of the synthesized sound only when the R peak and the T wave occur in each cardiac cycle (Figure 7). The duration of the two sound events is initially set to 600 ms but can be modified by the user within a range from 0 ms to 1000 ms.

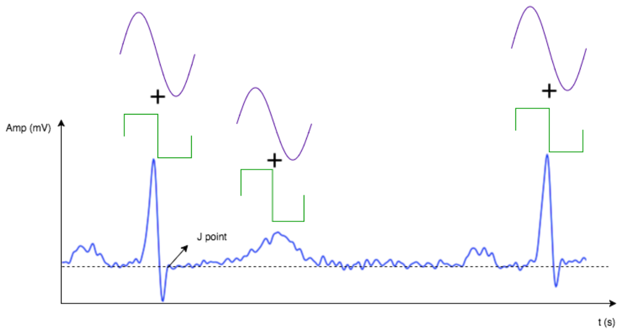

Figure 7. *Timbre morphing sound design.*

The frequency of the synthesized sound is modulated by a sine oscillation resulting in an audible effect of vibrato. We use a linear mapping function (eq. 10) to map the amplitude of the R peak to the fundamental frequency of the synthesized sound. We take the same approach for the sound event triggered when the T wave appears but in this case the data feature we map is the maximum amplitude value of the T wave. Furthermore, we count the number of leads that are catalogued as ST deviated and map this value to the depth parameter of the vibrato (cf. Table 5).

$$y = (x - x_a)/(x_b - x_a) \cdot (y_b - y_a) + y_a \qquad (8)$$

where, x is the value to be mapped. The source range is given by (x_a, x_b) and the destination range by (y_a, y_b).

Data Feature	**Data Range (min, max)**	**Parameter**	**Parameter range (min, max)**
Amplitude R peak	(0 mV, 2.0 mV)	Fundamental frequency	(100, x) x is defined by the user, according to: $100 \leq x \leq 1000$
Amplitude T peak	(0 mV, 0.8 mV)	Fundamental frequency	(200, x) x is defined by the user, according to: $200 \leq x \leq 1000$
Number of leads catalogued as ST elevated	(0, 12)	Depth of vibrato	(0, 1)

Table 5. Linear mapping of data features used in the *timbre morphing* parameter-mapping sonification.

Lastly, we take the value of the RR segment duration and use it as the rate parameter of the vibrato.

6. INTERACTIVE ECG SONIFICATION

Interactive sonification can provide tools for the user to have a better understanding of the data and to make features of interest more noticeable. The advantages of using interactive sonification for exploratory data analysis has been discussed by Herman and Hunt in 2004 [16]. Since one of the goals of our research is to provide sonification tools that can be used in medical scenarios as a supporting tool for diagnosis and monitoring, and given the fact that clinicians are normally used to work with medical devices that present data on a visual form, we decided to develop a Graphical User Interface (GUI) where users can interact with the sonifications and at the same time have a visual feedback of the data that is currently being played.

6.1. Heart Alert GUI

The Heart Alert GUI is divided into four modules; the first one allows the user to select an ECG file and it's basic properties (sampling rate, etc.). Then the user can select a group of leads or an individual lead for plotting and sonifying. Module 2 contains a menu for selecting the type of sonification and a 'play' and 'stop' button. The third module plots the selected leads of the ECG signal and when the sonification is triggered, provides visual feedback about the current time in the data. The last module includes controls for interacting with the sonifications.

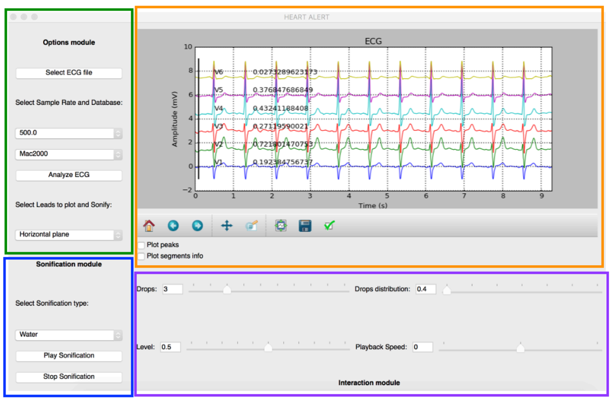

Figure 5. *Heart alert GUI (Green rectangle: Options module, blue: Sonification module, orange: Plot module, purple: Interaction module).*

6.2. Interacting with the sonifications

The user can interact with the sonifications by adjusting the sliders of the GUI that control the parameters of each sound design and selecting the leads to plot and sonify.

From the available parameters that determine the *water ambience* sonification, the two parameters *maximum number of drops* and *drops distribution* were chosen for the GUI, using sliders as shown in Figure 6. Additionally, we include three more sliders, one to control the level of the ambience sounds that represent ST elevation in contiguous leads, another one for the level of the drops sound, and the last one to control the playback speed.

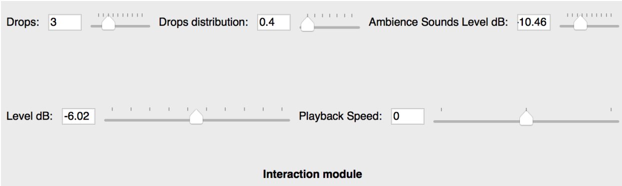

Figure 6. *Interaction Module of the Water ambience sonification.*

For the *timbre morphing* sonification, we chose three parameters: (*i*) *max fundamental frequency* that the R peak amplitude can be mapped to, (*ii*) *maximum fundamental frequency* that the T peak can be mapped to, and (*iii*) the *sound event duration*. The interaction module (see Fig. 7) also includes a slider to control the level of the sonification and one for the playback speed.

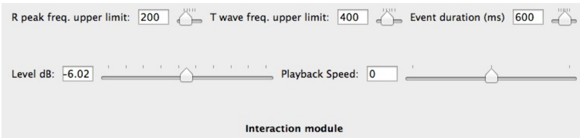

Figure 7. *Interaction Module of Timbre morphing sonification.*

7. USER FEEDBACK AND STUDY RESULTS

As a first preliminary qualitative assessment of the new designs, we asked three subjects to comment on the insight provided by the sonifications when comparing healthy and non-healthy datasets. They also provided feedback regarding the graphical user interface and the interaction tools. At the time of this evaluation the current version of Heart Alert did not allow to alter the generated sonifications in real-time, but instead required to trigger a new sonification by pressing the play button in order to apply the changes produced by the interaction module sliders.

During the pre-test the users stated that the morphed sound worked closer to an alarm requiring their immediate attention, while the *water ambience* sound felt more calm and didn't evoke the same level of urgency compared to the *timbre morphing* sonification. We also noticed, that for the *water ambient* sonification the wind and rain sounds were often confused by the users, which made difficult to identify the role of this sounds when they appeared. Concerning the GUI, they indicated to feel comfortable with the interaction elements provided and one of them suggested to include a set of presets in the interaction module that could be used as a starting point to interact with the sonifications.

After conducting the preliminary test, we improved the interactivity of the system so that the changes in the sonifications were produced immediately when the sliders were modified without having to trigger the sonification again. Also we selected new rain and wind samples to allow the users to better identify when these sounds appeared.

After this iterative improvement, we carried out a second study in which eight participants were asked to listen to ECG sonifications (each with 10 seconds duration) and classify them in one of two possible categories; healthy or unhealthy. Four users evaluated the *water ambience* sonification first (the classification task included 10 audio files), followed by the *timbre morphing* sonification (10 audio files). For the other four users the sonification designs were presented in the opposite order. We also asked the users to select on a six-points Likert scale (1 being the lowest score and 6 the highest score) if the sonification was pleasant to listen to and if they found the sound acceptable to be listened to for a longer period of time. At the end they were asked to select their preferred sonification.

The classification accuracy (i.e. the fraction of examples correctly classified as healthy or ST elevated, reported as $\mu \pm \sigma$) is 0.975 ± 0.046 for the *water ambience* sonification and 0.9 ± 0.093 for the *timbre morphing* sonification. A two-sided t-test shows that this difference is significant ($t(18) = 3.0$, $p< 0.0199$. Even do the high classification scores for both sonifications suggest a ceiling effect, the water ambience sonification allowed a more accurate classification.

Pleasantness of each sonification was rated from 1 to 6, where 1 refers to 'strongly disagree' and 6 refers to 'strongly agree' (results are reported as $\mu \pm \sigma$). The *water ambience* sonification was rated as 5.12 ± 0.64 and the *timbre morphing* sonification as 3.5 ± 1.69.

When the users were asked about the sonifications being acceptable to listen to for a long period of time, they rated the *water ambience* as 4.88 ± 1.13 and the *timbre morphing* as 3.5 ± 1.93. Finally, all users selected the *water ambience* design as they preferred sonification.

8. DISCUSSION

This work presents a sonification system for ECG signals that is meant to be used as a supporting tool in the diagnosis of ST segment deviations. We propose two sonification designs, one for monitoring the patient and one for providing quick insight on the state of the ECG segments. Furthermore, we provide tools for visualizing and sonifying a specific lead or a set of leads, which allow users to focus their attention on the heart's zone they are more interested in, or to have a general idea on the characteristics of the signal. Presently the sonifications are stereo, but the playback capabilities of the actual system can be extended to generate multi-channel sonifications which can be played over *N* loudspeakers for a more spatialized sonification.

The interaction module provides clinicians with tools that can be used to adjust the sonifications based on the needs and preferences of the user and at the same time find the sounds that are more meaningful to them when analyzing and exploring clinical data. These sonifications should differ from already used auditory displays (e.g pulse oximeter), because it is possible to modify the sounds and assign them to a different spectral bandwidth that doesn't interfere with the sounds produced by existing auditory devices or soundscape components in a regular medical scene. For future system implementations we think it would be interesting to implement the control of the Heart Alert features using mobile devices that clinicians already use on a daily basis.

Currently the estimation of the ECG segments is implemented under a basic approach that leaves room for improving the detection methods. Also the peak detection algorithm can be further improved to yield better performance on ECG files with distinct rhythm pathologies. Improving the R peaks and segments detection would open a door for using the system as a supporting tool in the diagnosis of other heart abnormalities.

The study results showed that the proposed sonifications provide a functional first approach to ST-segment elevation sonification since it is already makes it possible for users with no previous ECG experience to differentiate healthy datasets from ST-elevated ECG. A significant difference was found in the classification task, however the classification scores are considerably high for both sonifications, which suggest a ceiling effect that would not make possible to select one of the two sonifications as a conclusive winner. The ceiling effect can be the result of an easy classification task; this means that the complexity of the task needs to be increased for future studies.

9. CONCLUSIONS

We have introduced an ECG sonification system that uses real medical data to provide information on the overall state of the signal an its variations. According to the study results obtained, the sonifications showed to offer interesting insight on the data when a healthy dataset is compared to an ST elevated one. However, further work needs to be done in order to improve the segment estimation so that the sonifications better convey information regarding changes in the leads that conform a standard ECG.

We consider ECG sonification research to be promising and able to provide meaningful insight on several features of the heart's signal. Not only could it be used for diagnostic, but also as an educational tool for medicine students that are in the process of learning how to interpret the variations in the signal, and for whom an auditory-type feedback could be useful.

We aim to improve the methods presented in this work and to use sonification to further represent and explore the characteristics of the ECG signal. For example, one of the following steps in ECG sonification, would be to explore methods for sonifying the polarity of the ECG axis.

10. RESOURCES

Examples of the sonifications are provided in
http://dx.doi.org/10.4119/unibi/2907475

ACKNOWLEDGMENTS

This work has been supported by the German Academic Research Service (DAAD) and the Cluster of Excellence Cognitive Interaction Technology 'CITEC' (EXC 277) at Bielefeld University, which is funded by the German Research Foundation (DFG).

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