Methods for Sonic Representation of Heart Rate During Exercise

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Abstract. Sonic display of HR changes during exercise helps both the patient and the investigator to better identify the transition from rest values to “exercise” zone, then crossing the “attention” threshold and reaching the “alert” threshold. Three types of sonic display were tested, based on combinations of saccadic sounds, different intensities and different pitch. The results indicate a clear preference towards a display marking each of the four zones by a specific pitch.

Keywords: sonification, heart rate, exercise, Karvonen Tanaka thresholds

1. Introduction

This work is a part of a larger project on “adding sound to medical data” [1]. In our previous works we have developed a toolkit for sonification of biological signals [2] and analyzed and tested various types of acoustic display procedures (tempo lenses, pitch scales etc) for emphasizing different events within pulse waves, heart rate, or ECG signals. The present study describes the first module (HR) of the ASET package (Adding Sound to Exercise Tests) – a toolkit focused on a practical application in a frequent investigation procedure for cardiac patients – the exercise test. It can be also useful in monitoring HR changes in any kind of physical exercise.

The value of exercise tests for prognosis in cardiac patients [3] generated a widespread of this method in current practice. Professional equipment for such investigations has been developed, which offer the physician the possibility to follow-up the evolution of cardiac parameters during exercise. It should be mentioned that the exercise test is not a “non-invasive” investigation but some risks can arise during the test: blood-pressure (BP) and heart rate (HR) increase, a most frequent occurrence of extra systoles and a depression of the ST segment of the ECG (especially in the ischemic patients). There are well defined values for these parameters indicating endpoints of the exercise test. Hence, the investigating physician has to pay attention all the time the evolution of all these parameters, to gaze at the screen for long minutes. The modern equipment has introduced a color warning when some parameters do exceed the predefined thresholds. However, most information is mostly visually displayed; keeping the physician’s attention to the screen. Moreover, due to the complexity of the information displayed on the screen. There are some devices giving
an information represented by sounds, as short beeps associated with each heart beat. The patient is usually kept passive.

The sonic representation of the heart rate was one of the early attempts to add sound to biological signals [4]. However, it has not been extended to HR changes during exercise tests and most often biased towards musical representation.

The purpose of this study was to improve the perception of cardiac parameters evolution during the exercise by adding appropriate sonic representation of the major parameters – HR (first module – described in this paper) and ST depression (second module). As the number of different sonic representations for the same set of data is huge, a limited set significant parameters has been chosen. The goal of this phase was to develop a flexible tool to allow a variety of sonic representations and determine users’ preferences for a representation with best perception of transitions between various exercise zones.

2. Material and Method

2.1 Signals and Parameters

(a) Signals. We have used two types of signals: (1) from Physiobank [5] and (2) from our recordings. The parameter considered in this study were the heart rate (HR) in beats/min computed for each beat as the inverse of the RR interval detected from the first ECG lead.

(b) Thresholds. A comprehensive study made by American Heart Association [6] and American Council on Exercise [7] yielded a guideline covering a large variety of risks to be considered during exercise. For the present stage of our study we have used a simplified risk representation, preserving three major levels of warning: transition from “rest” to exercise, attention level (getting close to risk threshold) and alert (reaching the HRmax threshold), which is usually visually represented on the screen of exercise monitoring devices by a light red background where that parameter is displayed. The thresholds for HR (starting “exercise” = \text{hrk1}, attention threshold = \text{hrk2} and alert threshold = \text{hrmx}) were computed according to Karvonen relations [7]:

\[
\text{hrmx} = (220 - \text{age}), \text{hr1} = 0.5 (\text{hrmx} - \text{mr}) + \text{mr}, \text{hr2} = 0.85 (\text{hrmx} - \text{mr}) + \text{mr}
\]

where \text{mr} represents morning rest heart rate.

2.2 Sonification procedures

From the large variety of possible sonic representations, based on our experience [1, 2], we have selected the following criteria:

- **duration**: equal to the RR interval for each beat,
- **pitch**: the reference frequency (f0) was 440 Hz (A4 on musical scale), corresponding to RR = 1s, HR0 = 60 beats/min. For the three sounds + alert displays, the coefficients k used were 6/5, 4/3 and 3/2. For the multiple sounds display, we expressed the increase of HR as a factor \( m = \frac{\text{HR}}{\text{HR0}} \); this factor was used for computing the sound pitch. The usual logarithmic scale was used [2]:
\[ f = f_0 \times 2^{(m-1)} \quad \text{and} \quad f_i = f_0 \times 2^{(k-1)} \quad (2) \]

- **saccadic sounds:** we tried both continuous and saccadic sounds; a “saccade” was defined as a sound of short duration (0.1 RR) followed by a still shorter pause, of 0.02 RR. The saccadic display was introduced to represent the warning levels: 1 saccade for attention level and three saccades for alert level;

- **loudness (intensity):** four levels of intensity have been also introduced for adding additional information about the exercise intensity. According to Weber-Fechner relation, a logarithmic scale was introduced; thus, the coefficients were defined by:

\[ \text{loud-}k = b^{(z-1)} / b^3 \quad (3) \]

where \( z = 1, 2, 3, 4 \), corresponding to the four exercise intensity zones, separated by the thresholds \( hr1, hr2 \) and \( hrmx \) and \( b \) = base of logarithmic scale; we worked with \( b = 2 \), but increasing it would yield a larger loudness scale.

Three types of sonic display were tested:
- saccadic sounds only (“1S”) – no pitch variation (all A4);
- saccadic display (“3S”) of three sounds (A4/B4/C#5/E5): no saccade on \( f_0 \) - for normal (rest) range of HR, 1 saccade on \( f_1 \) for exercise zone, 2 saccades on \( f_2 \) for crossing attention level and 3 saccades on \( f_3 \) for alert zone,
- saccadic display on a continuous scale of sounds (“MS”): having the pitch computed as a function of the corresponding value of HR, as in formula (2).

### 2.3 Preference selection procedure

In order to select the sonic display with highest discrimination power between the major stages of the exercise test – rest / exercise / attention / alert and to select the most appropriate sonic display for further use, we made a survey on a group of 20 subjects. The survey had two phases:
- **supervised learning:** two records have been used as example; the subjects were exposed to the sounds and explained the three sonic representations (named 1S, 3S and MS). The HR graph was also provided; thus they could also follow the sound change during transitions from one zone to the other. The same record was conveyed for each type of sonic representation, yielding a total of three sonic exposures per signal
- **testing phase:** the subjects were asked to listen to each record and score it with marks between 10 and 0, for the capacity to distinguish the transition between different exercise zones. 10 was for perfect distinction between rest / exercise / attention / alert periods and 0 is for no distinction at all. At the end of the three displays of a record the subject can also mention his preference for one or other type of sonic display. Each subject had his own time to estimate and fill in his scores; he also could ask repetition of a sonic display or could move to any other representation.

For shortening the testing time, each record was trimmed from the original length of 7 - 30 minutes to 50 – 90 seconds.

### 2.4 Software

The ASET package (Adding Sound in Exercise Tests) consists of two main scripts (in MATLAB 2011b), and several functions. Each main script has with two modules, one for HR and one for ST depression; we present here only the HR modules. First script was dedicated to prepare the signals for sonification, depending on the signal source.
The second script was the core of our study. Each signal was transformed according to the three sonic representations (1S, 3S and MS), using also a function for introducing the saccades. The generated sound was a pure sine wave, with a sampling frequency of 8 kHz. The sonic output could also be stored as a .wav files generated in MATLAB.

The program is flexible, one can easily change the thresholds, adopting Tanaka’s exercise zones [7]. It is also possible to change the number of exercise zones, as often recommended for fitness training (split exercise zone, defined by Karvunen thresholds between 50% and 85% of (hrmx – mr) into two “weak exercise” and “hard exercise”, with Tanaka’s thresholds of 60% - 70% and 70% - 80%., including redefinition of hrmx by [7]:

\[ hrmx = 208 - 0.7 \times \text{age} \] (4)

The loudness scale can be also changed, lowering the sound intensity for resting zone down by increasing the base “b”.

3. Results and Discussions

3.1. Sonic files

The files used for testing, with their graphical display and the corresponding sounds can be found on our website [8] in the section dedicated to ASET (Adding Sound to Exercise Test). Text

3.2. Discrimination power and preferences

Our results about the discriminant power of the three types of sonic display are presented in Table 1 (n = 20).

<table>
<thead>
<tr>
<th>Method</th>
<th>1S</th>
<th>3S</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean discrimination score (10-0)</td>
<td>7.85±1.23</td>
<td>9.55±1.05</td>
<td>5.40±1.43</td>
</tr>
<tr>
<td>Preference (%)</td>
<td>15</td>
<td>80</td>
<td>5</td>
</tr>
</tbody>
</table>

The results show that all sonic representations used in this study have a very good discriminant power and the selection for further use would mostly be motivated by the preferences. As expected, the 1S display was not preferred when the 3S display was also available, even it had a good discriminant power; it can be kept in simple devices. It was surprising that the multiple scale MS representation, despite its capacity to offer more details about the evolution of the heart rate, by raising the pitch progressively, had a lower preference. However, it was preferred for representing the variability of HR in rest conditions.

Comments about the observations made by the subjects:
- some subjects argued that the raised pitches or too loud sounds can introduce a supplementary stress during the test and would not prefer the MS display;
Others subjects claimed that the information about crossing thresholds is enough and there is no need to have more details (like in MS), which was confirmed by the high preference to representation 3S.

4. Conclusions

Despite the high potential of representing information by sounds and simplicity of such systems, the currently used equipment ignore it. We tried to demonstrate that such simple apps can add significant value in monitoring any kind of exercise, useful for both the patient (subject) and investigator. Our study can help future developers to use a similar methodology to select the functional parameters for sonic display of patient/subject physiological parameters.

For our specific case of heart rate monitoring during exercise, these results and comments show the major preference towards simple displays (without many details), focused mainly on revealing threshold crossing, with a clear transmitted message and user friendly sounds.

The potential impact of our study goes beyond the very monitoring of cardiac performance during the exercise tests. Simple devices can be developed for monitoring cardiac parameters (HR would be the simplest, but there are already available wearable devices for ECG, blood pressure, pulse waves, respiratory parameters), and a simple sonic warning system like the one described here would be welcome.

References