GENERAL ARTICLE

Heart Rate Sonification: A New Approach to Medical Diagnosis

Mark Ballora, Bruce Pennycook, Plamen C. Ivanov, Leon Glass and Ary L. Goldberger

ABSTRACT

Ever since 1819, when Theophile Laënnec first put a block of wood to a patient's chest in order to listen to her heartbeat, physicians have used auscultation to help diagnose cardiopulmonary disorders. Here the authors describe a novel diagnostic method based in music technology. Digital music-synthesis software is used to transform the sequence of time intervals between consecutive heartbeats into an electro-acoustic soundtrack. The results show promise as a diagnostic tool and also provide the basis of an interesting musical soundscape.

The term "biometric art" has been proposed to describe art derived from physiological measurements of living organisms [1,2]. While the term was coined to describe visual representations of cardiac activity and other physiological functions, it can also be extended to auditory representations. In a complementary manner, a number of composers have explored applications of complexity ("chaos") theory to music composition and synthesis [3]. Heart rhythms have also been used in musical contexts [4,5], and experiments have even been conducted that have mapped real-time heart rhythms to brief auditory displays for use in biofeedback [6]. This project, however, has a different focus. Rather than setting out to create musically interesting sounds, we explore whether physiological variations in heart rate dynamics over a period of hours could be a source of medically useful representations. In other words, can bedside diagnosis be aided by information taken from an auditory display of human heart rate variability?

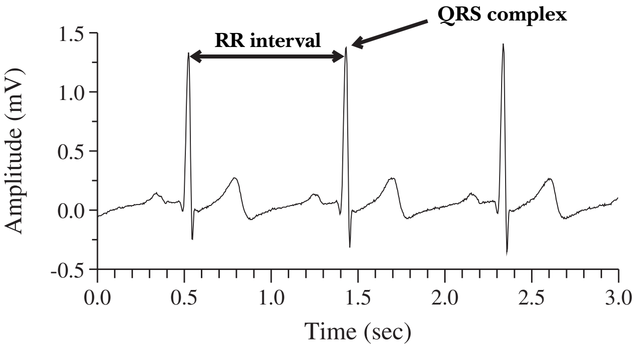
HEART RATE VARIABILITY

Heart rate fluctuations can be easily measured from an electrocardiogram (ECG), a graphical recording of the electrical potentials generated by cardiac muscle cells. While clinicians often refer to the healthy heartbeat as "regular sinus rhythm," healthy subjects typically display patterns more complex than those found in unhealthy ones [7–9]. For example, researchers have found that patients whose heart rates become overly regular following a heart attack may be at increased risk of fatal cardiac arrhythmias [10]. This loss of variability may be related to a decrease in the plasticity of the neural mechanisms that help regulate and "fine-tune" the heart's activity on a beat-to-beat basis. A fuller understanding of the dynamics of these kinds of cardiac signals in health and disease is the goal of contemporary heart rate variability research [11].

To measure heart rate over extended periods, physicians make use of Holter monitors, ECG devices that permit long-term ambulatory recording and storage of ECG waveforms for time periods on the order of 24 hours. Following the recording, the data can be processed via automated or semi-automated programs. Such programs detect the electrical pulses, termed QRS complexes, that trigger mechanical contraction of the heart's pumping chambers (ventricles). Further analysis of these waveforms can be used to generate a sequence of intervals (the intervals between QRS complexes, also called "NN intervals" or "RR intervals," shown in Fig. 1) that represent the time periods between consecutive normal beats. These NN intervals, representing heart rate fluctuations, are the datasets most often used in heart rate variability analysis.

The heart's normal beats are initiated by impulses from pacemaker cells in the sinus node, hence the term *normal sinus rhythm*. The sinus node frequency is modulated primarily by input from the autonomic (involuntary) nervous system. There are two major components of this system: the *sympa-*

Fig. 1. Electrocardiographic recording of the heartbeat. (Courtesy of Joseph E. Mietus, Margret and H.A. Rey Laboratory for Nonlinear Dynamics in Medicine) The QRS complexes represent electrical activation of the ventricles. The RR interval is the time between consecutive QRS complexes.



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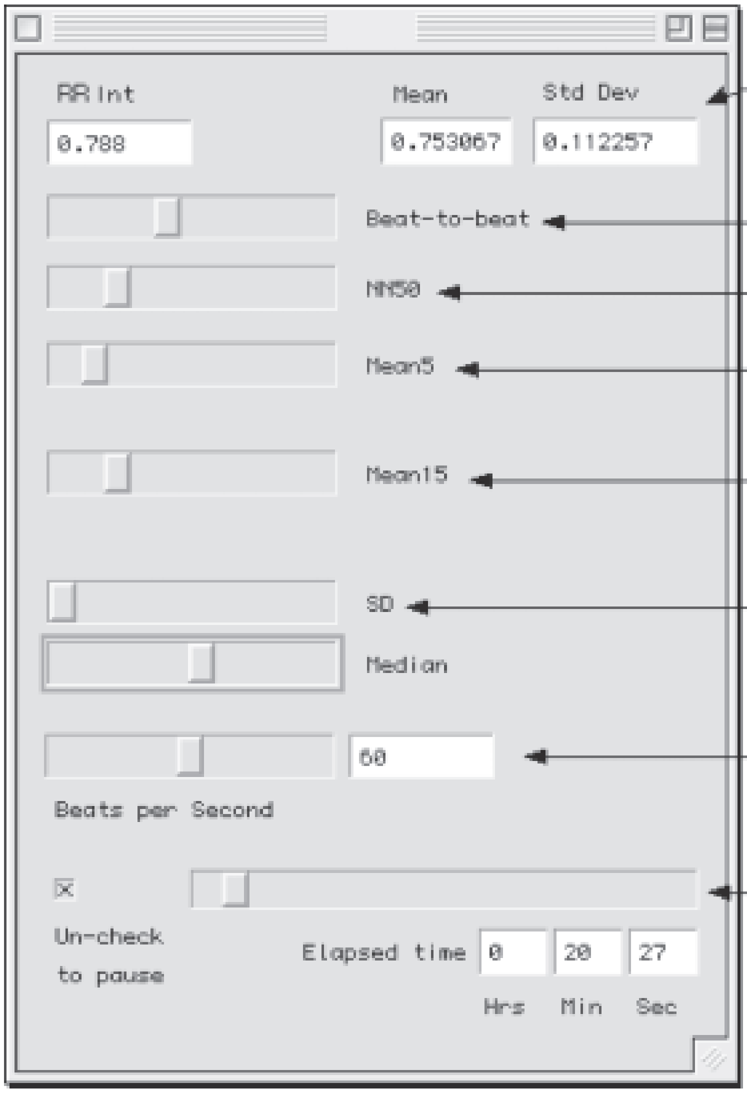


RR Int: 0.788

Mean: 0.753067

Std Dev: 0.112257

Beats per Second: 60

☒ Un-check to pause

Elapsed time: 0 Hrs 20 Min 27 Sec

Running displays of current values for the RR interval (Int), mean, and standard deviation (Std Dev), both based on window of 300 RR intervals

All tracks are based on the same pitch mapping

Each interbeat (RR) interval is mapped to a sine-like tone (“whistling”)

NN50, larger successive interval differences (>50 ms), have additional timbral annotation (“tinkling”)

A sliding window represents the mean of 5 intervals, with course resolution (“clarinet-like”)

A sliding window represents the mean of 15 intervals, with fine resolution (“glassy hum”)

A sliding window represents the standard deviation of 300 intervals, mapped to tremolo rate (“buzzing”)

The playback rate is adjustable during playback

Elapsed time represented by the data is shown by slider position and number boxes. Sonification may be paused at any point. The slider may be used to refer to another time in the data. When sonification is resumed, it will start from the selected time.

Fig. 2. The graphical user interface used in the sonifications. (© Mark Ballora)

thetic—which increases the heart rate—and the *parasympathetic* (or *vagal),* which decreases the heart rate. The nonlinear interaction between these two competing components is responsible for much of the heart rate’s intrinsically complex fluctuations [12]. Mechanical and metabolic influences may also contribute to heart rate variability. A major factor regulating heart rate variations over the short term involves the effects of respiration, which are mediated via the parasympathetic branch of the autonomic nervous system. During inspiration, heart rate typically increases, while during expiration it decreases. These oscillations are referred to as *respiratory sinus arrhythmia.* Pathologic breathing patterns, such as those seen with obstructive sleep apnea, may be associated with lower-frequency oscillations in the heart rate [13,14].

Diverse measures of heart rate variability have been proposed, and some may be associated with a variety of cardiopulmonary and systemic disorders [15,16]. However, implementation of such methods remains difficult to interpret on an individual basis and, in the absence of a consensus as to their utility, these measures have limited practical bedside applicability at present.

SONIFICATION

The auditory system is particularly well suited for following multiple streams of information [17–19] such as those contained in complex heartbeat time series. Sonification may thus offer an effective means for simultaneous display of many signal-processing operations. A heart rate variability dataset, which can be considered a one-dimensional vector, may be displayed as a multidimensional sonification. Such a means of display may allow correlations among analytic techniques—which might normally be difficult to detect—to be observed aurally. Further, such a technique might prove useful in screening long-term series records for clinically important dynamics.

SOFTWARE

We use a software sound synthesis (SWSS) program to sonify the heart rate variability data. Such programs, the basis of computer music [20], have existed since the 1950s. Music is represented digitally by converting the air pressure changes of musical events into a discrete series of numbers or samples. The samples are audified by being passed into a digital-to-audio converter (DAC), which converts the sample values into voltage values, which are used to vibrate the cone of a loudspeaker, thus producing the desired sound. For example, an audio CD contains a set of discrete samples. The CD player contains a DAC that feeds the

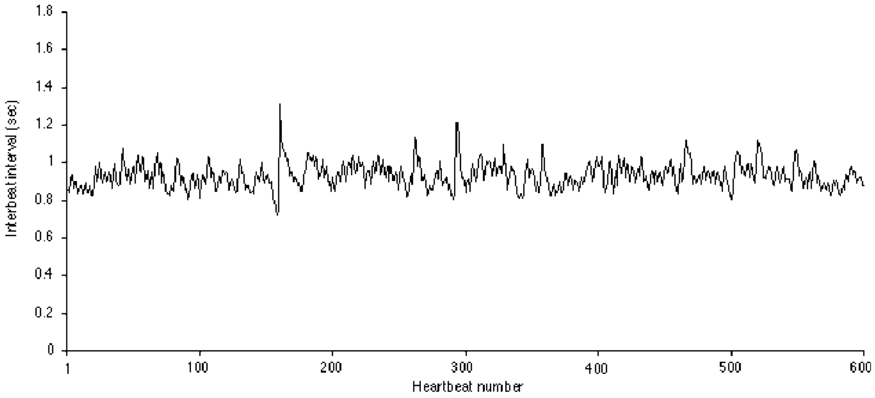


Fig. 3. Healthy subjects show a complex pattern of heart rate variability that is neither random nor periodic. (© Mark Ballora)

numbers to an amplifier, which in turn sends energy proportional to the discrete sample values to a loudspeaker. SWSS programs enable composers to create sets of samples so that compositions may be realized and stored digitally.

We sonify heart rate variability data with the synthesis program SuperCollider <www.audiosynth.com>, a specialized programming language designed for real-time audio applications. SuperCollider is well suited to our sonification model because of its computational efficiency, its array and list processing capability, its methodology for generating *(spawning)* musical events according to a programmer's instructions, and its interactive potential as realized through the use of custom-designed graphical user interfaces (GUIs).

In our procedure, a series of signal-processing operations are saved as separate files, loaded into SuperCollider and stored as array variables. The arrays are iterated simultaneously, with each successive value employed as a source of musical events. The model employs the following mappings:

- Each interbeat interval is mapped to a pitch, sounded by an oscillator that produces short sine-wave sounds ("grains"). Higher heart rates correspond to higher pitches. To produce a harmonious blend of sounds, the same pitch-mapping formula is used as the basis for all sonification tracks.
- Successive interbeat intervals differing by more than 50 msec are given an additional timbral annotation, a "tinkling" sound produced by phase modulation synthesis.
- The current interbeat interval is considered to be the center of a sliding window of 300 values. This value corresponds to roughly 5 minutes of cardiac activity, a time window used for some heart rate variability analyses [21]. The window's standard deviation is sonified by a pulsing, spectrally rich waveform with all harmonics at an amplitude equal to the fundamental. The standard deviation value is mapped to pulsing speed and number of harmonics.
- Two smaller sliding windows sonify running means. The windows are smaller than the standard deviation window in order to render changes on shorter time scales. The first is a window of 15 values, sounded by a glassy hum. The second, sounded with a clarinet-like timbre, is a window of five values, all of which are rounded to the nearest one-fifth of a second, so that cardiac changes are rendered with a lower degree of precision.

We have found a useful default playback rate to be 60 events per second, a number corresponding to roughly 1 minute of cardiac activity, since normal sinus rhythm in the resting state tends to produce one heartbeat per second. This pointillistic "sound cloud" of extremely short events is an example of granular synthesis, an approach explored by such composers as Iannis Xenakis, Barry Truax and Curtis Roads [22]. Via the interface, listeners may adjust relative volume levels among signal-processing operations, playback rate (data points per second) and the region of the file to be played. Thus, users may "zoom" in or out to focus on any dimension(s) of the data. The interface is shown in Fig. 2.

CASE STUDIES

In preliminary studies, we have studied heart rate dynamics for four cardiac states: good health, congestive heart failure, atrial fibrillation and obstructive sleep apnea. Audio examples of the sonifications may be heard at <www.music.psu.edu/Faculty%20Pages/Ballora/sonification/sonex.html>.

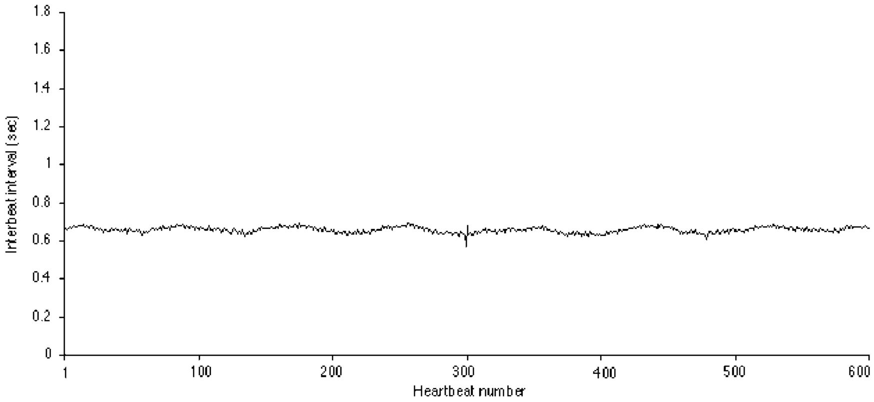
Good Health

The heart rate of healthy individuals shows subtle but complex variations with intermittent, but not extreme, fluctuations in all parameters (Fig. 3). Changes in the mean and standard deviation are easily perceived, reflecting physiologic nonstationarity (changeability of mean and standard deviation). Patches of higher variability produce clusters of the tinkling sound associated with larger interbeat intervals.

Congestive Heart Failure

Congestive heart failure is a syndrome characterized by a marked reduction in the pumping efficiency of one or both ventricles (low cardiac output) and by fluid retention (edema). Heart rate variability datasets from subjects with congestive heart failure (Fig. 4) often display reduced variability in sinus rhythm, in extreme cases displaying a nearly flat line. They also may display low-amplitude oscillations within a frequency range of approximately 0.01–0.02 Hz (50–100 seconds per cycle), corresponding to a pathological pattern of periodic breath-

Fig. 4. Severe congestive heart failure, a major cardiac pathology, may be associated with a striking loss of heart rate variability, producing a flat, monotonous pattern. (© Mark Ballora)



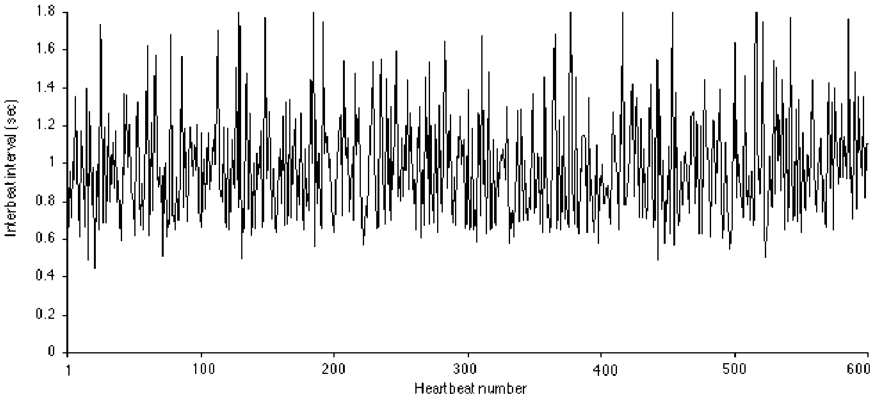


Fig. 5. The heart rate with the cardiac arrhythmia known as atrial fibrillation shows an erratic, uncorrelated response over short time scales, producing a white noise (static-like) output. (© Mark Ballora)

ing known as Cheyne-Stokes respiration. Individuals who suffer from congestive heart failure are at high risk for sudden cardiac death [23]. Congestive heart failure sonifications for subjects in sinus rhythm are typically extremely monotonous, reflecting greatly reduced variability. The interbeat interval pitches appear to be nearly constant, as does the running mean. The standard deviation sonification has such a low oscillation rate and such reduced harmonic content that it is almost inaudible. The "tinkling" from larger intervals is far less apparent than in sonifications of other cardiac states.

Atrial Fibrillation

Atrial fibrillation describes a cardiac rhythm that is no longer set by the sinus node, but rather by rapidly circulating waves (300–500/sec) originating in the upper chambers of the heart (the atria). The actual heartbeat does not result directly from each of these waves, but rather from a fraction that manage to reach the lower chambers of the heart, the ventricles, which pump the blood to the rest of the body. In atrial fibrillation, the heart rate is highly irregular, with no obvious patterns (Fig. 5). Due to the high levels of variability, the cardiac interbeat interval sonifications in atrial fibrillation jump discontinuously between high and low pitches, and the tinkling sounds are relatively constant throughout. Despite such ongoing variability, the mean does not change markedly, and the standard deviation stays at a consistently high value.

Obstructive Sleep Apnea

Obstructive sleep apnea is associated with excessive relaxation of muscles in the back of the throat during sleep. The airway becomes intermittently closed, and breathing can stop for time periods on the order of a minute or so. Breathing then suddenly resumes, often accompanied by a loud snorting. These episodes may occur 20 to 30 times per hour, hundreds of times in a night, without the sufferer even being aware of them. The daytime result may be loss of alertness, even to the point of suddenly falling asleep. In the long term, obstructive sleep apnea increases risk of high blood pressure, heart attack and stroke. People with obstructive sleep apnea are also at increased risk of involvement in traffic accidents [24].

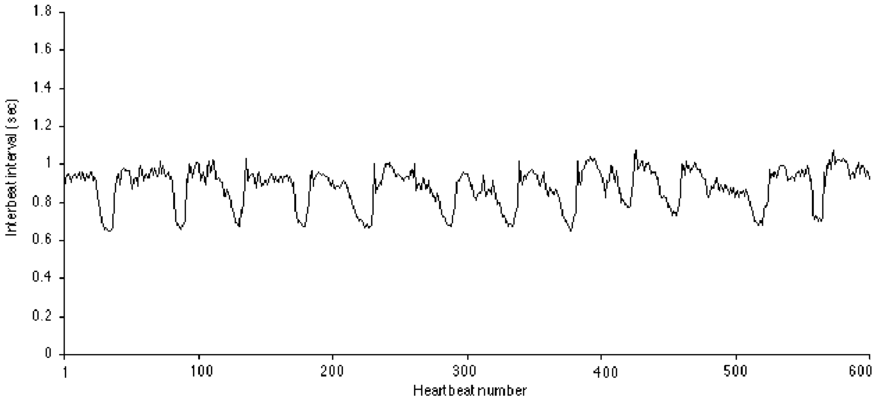
While sleep apnea is typically diagnosed via polysomnographic analysis (an expensive and often burdensome procedure), the syndrome can also often be observed indirectly by periodic changes in the heart rate associated with cessation and resumption of breathing [25,26]. Sonifications of apneic variability data may sound similar to healthy sets, particularly in milder cases, due to the sporadic nature of apneic episodes. Severe cases, characterized by a high density of apneic episodes, are quite perceptible and have a siren-like sound corresponding to the recurring, relatively low-frequency heart rate oscillations (0.01–0.04 Hz) with relatively large amplitude [27,28] (Fig. 6). This oscillating tone is also apparent in the two running mean sonifications. Furthermore, often the heart rate oscillations are also perceptible in the tinkling sounds of the larger intervals, which are heard in regular "clumps" associated with the oscillations.

While some heart rate variability plots of subjects with sleep apnea are straightforward, others are "noisy," displaying no clear oscillations (Fig. 7). However, by using the sonification interface described above to "fine tune" a sonification of the data, the oscillations may become audible, allowing a diagnosis to be made.

CLINICAL APPLICATION

Preliminary studies with undergraduate volunteers without biomedical expertise suggested that auditory displays were more useful than visual representations in differentiating obstructive sleep apnea from healthy states. We tested this observation further in an international physiologic signal analysis data competition <www.physionet.org/physiobank/database/apnea-ecg/> in which 30 ECG datasets from subjects with moderate to severe sleep apnea and 30 datasets from healthy control subjects needed to be differentiated. By transposing these records into auditory signals, one of us (MB) was able to achieve a 90% correct identification rate. The identifications were achieved not by automatic recognition, but by adjusting the volume balances of the various properties shown in Fig. 2 to "tune in" telltale oscillations. The results suggest the potential for diagnosis of sleep apnea through heart rate variability data taken from an ambulatory (Holter) or bedside heart monitor and mapped to an auditory display [29].

Fig. 6. Subjects with obstructive sleep apnea typically show periodic heart rate oscillations that correspond to repetitive cycles of apnea and arousal during sleep. (© Mark Ballora)



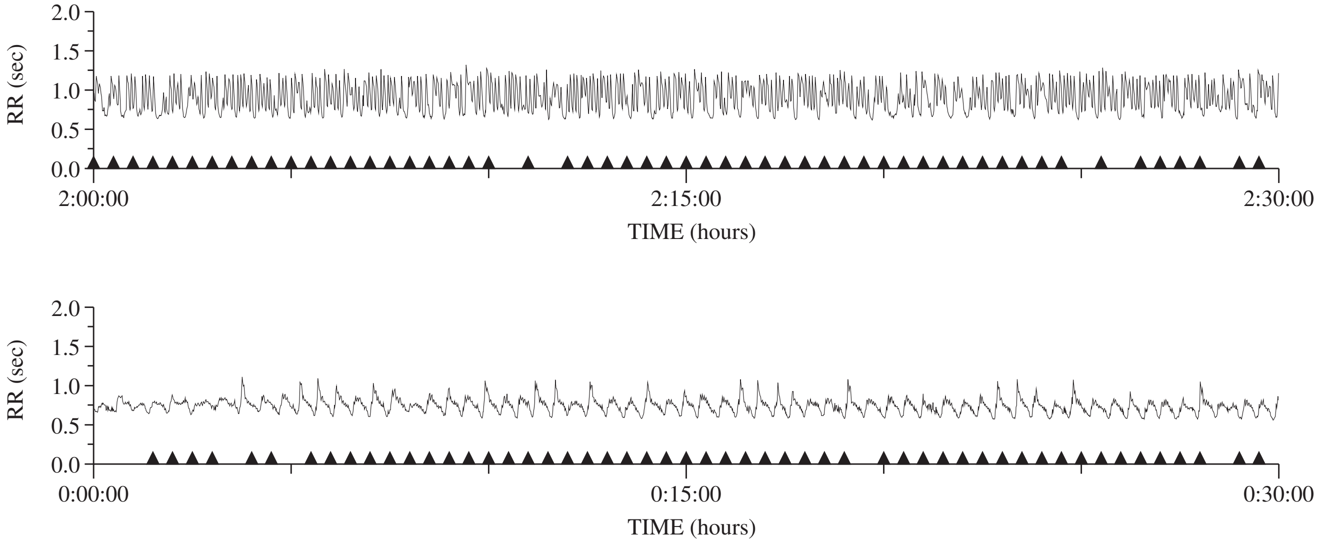


Fig. 7. Comparison of straightforward and "noisy" heart rate variability plots during apneic episodes (records from different subjects). (Courtesy of Joseph E. Mietus, Margret and H.A. Rey Laboratory for Nonlinear Dynamics in Medicine) In the top record, the dark triangles along the time axis indicate apneic episodes identified through standard polysomnographic analysis. The heart-rate oscillations clearly correspond with the triangles, making this example easy to diagnose visually with a heart rate variability plot. In the bottom record, there is no visually clear correlation between the heart rate plot and the apneic episodes. However, the sonification interface effectively filters the "noise" out, allowing the "hidden" oscillations to be heard and enabling a diagnosis.

Based on the experiences described above, sonifications could be employed in two ways. The sonification model could be adjusted to register known conditions automatically—for example, if a certain number of intervals within a given range occurred within a certain number of successive beats, a warning tone could sound. Alternatively, the model could be used as is, with the possibility of adding more operations as separate audio "tracks." This second model would allow a more open-ended investigation that could reveal unexpected phenomena.

MUSICAL APPLICATION

To explore musical applications, we chose a greater variety of mappings than those used in the diagnostic tests, with the goal of creating a soundscape of continually shifting timbral elements. We used some of the same external files as for the diagnostic sonifications: the cardiac interbeat interval and a series of standard deviation values corresponding to window sizes of 300 data points. The piece *Heart Rhythms: Healthy* was played at the 2002 conference of the Society for ElectroAcoustic Music in the United States (SEAMUS). An excerpt can be heard on-line at <www.music.psu.edu/Faculty%20Pages/Ballora/sonification/hrhythms.html>. It employs the following mappings:

- Each cardiac interbeat interval is mapped to a pitch sounded by an oscillator that produces short sine wave sounds ("grains"), as with the diagnostic sonifications. The interbeat intervals were also used as a clock to provide the timing for each granular event.
- A bell-like sound was synthesized based on the values of the differences between successive interbeat data values. The sound was created by sending impulses to a filter bank with adjustable center frequencies and ring times. The frequency at which the impulses were generated was based on the current standard deviation window value. The center frequencies and ring times were based on the global mean of the data points, plus minimum, maximum and mean values from the list of standard deviation values.
- A vocal chorus sound was synthesized by sending a rich harmonic wave and noise through a set of bandpass filters and setting center frequencies and their amplitude values to correspond with formant regions used in vocal synthesis [30]. The values for center frequencies and amplitudes were mappings of the standard deviation values of the inter-beat intervals in windows of 300 beats.
- The set of inter-beat intervals was subdivided into six equal subdivisions; each subdivision was successively divided in half, creating subdivisions of $\frac{1}{12}$ the set's length, $\frac{1}{24}$ the length, and so on to $\frac{1}{768}$ the dataset's length. The median of each subdivision was taken and mapped to a frequency and stereo pan position. The frequencies were assigned to a variety of synthesized sounds resembling a sitar, wooden wind chimes, plucked strings and a number of abstract timbres. These sounds were generated at time intervals corresponding to the proportion of the dataset they represented. A sitar-like tone was heard every time $\frac{1}{6}$ of the dataset was iterated (approximately every 40 seconds), another drone was heard every $\frac{1}{12}$ of the set's iteration, and so on. The shortest subdivision was mapped to a plucked string sound that occurred approximately every 0.75 seconds, thus creating the piece's "melody."

AFTERWORD

Although Laënnec was not the first to listen to the human heart, his signal contribution was in demonstrating how to systematically interpret its sounds in terms of underlying health and pathology. Computer methods now enable us to generate new ways of listening to the heart and even to compose music from its workings. But we are still at the early stages of learning how to interpret the resulting sonifications and how to compose music based on complex physiologic datasets. The creation of music from biologic templates remains a fascinating and incompletely explored compositional challenge. Little, if any, music created from real-world data approaches the compelling beauty of the popular visual representations of fractal and chaotic phenomena [31,32]. Future work could evolve in two directions—one toward new forms of "biometric music," the other toward new modalities of medical diagnosis.

Acknowledgments

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