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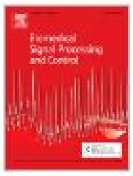

Effect of fractal quality of Indian classical music on autonomic function

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Highlights

The objective of our study was to compare the response of autonomic system parameters (blood pressure, ECG, heart • rate variability) in healthy subjects while listening to Indian classical music of different fractal qualities.

- To quantify the complexity of a musical phrase we have used the Higuchi fractal dimension.
- Indian classical music has the unique quality of slow transition betwen notes, with consequent changes in dimensions of the string being played, which we have quantified in the study.
- 25 healthy volunteers were recruited, all between 18 and 35 years of age. The subjects were randomised into three groups: sinewave, low fractal music and high fractal music.
- Electrocardiogram (ECG) and Non invasive BP (NIBP) leads were placed and continuous measurements started 10 min prior to intervention. At 0 min, the standardised musical intervention/ control was played.
- During intervention, the fractal dimension of the BP waveform showed a significant difference between subjects of high fractal group and low fractal group. The Hurst exponent and sample entropy of the waveform was also measured.
- In addition, the increment in heart rate variability during intervention showed an increasing trend from high to low fractal to sinewave.
- Whether the changes are due to direct contact with source of music or through a cerebral mechanism can be ascertained by further studies.

Abstract

Music is an external stimulus that affects physiological systems; both the quality of music and the resultant physiological changes can be quantified, which presents an unique opportunity. To quantify the complexity of a musical phrase we have used the Higuchi fractal dimension. We then compared the response of autonomic system (blood pressure, ECG, heart rate variability) in healthy subjects while listening to Indian classical music of different fractal qualities. Indian classical music has the unique quality of slow transition between notes, with consequent changes in dimensions of the string being played, which we have quantified. 25 healthy volunteers were recruited, all 18–35 years of age; the subjects were randomised into three groups: sinewave, low fractal and high fractal, depending on the type of musical intervention. The subjects were placed in a quiet room and asked to perform deep breathing exercises for relaxation. Electrocardiogram (ECG) and Non invasive BP (NIBP) leads were placed and continuous measurements started 10 min prior to intervention. At 0 min, the standardised musical intervention/ control was played. During intervention, the fractal dimension of the BP waveform showed a significant difference between subjects of high fractal group and low fractal group. In addition, the increment in heart rate variability (measured by standard parameters) during intervention showed an increasing trend from high to low fractal to sinewave. Whether the changes are due to direct contact with source of music or through a cerebral mechanism can be ascertained by further studies.

Keywords

Indian classical music; Autonomic nervous system; Fractal; Heart rate variability; Blood pressure waveform

1. Introduction

Physiological systems have varying frequencies and periodicities [1] (i.e. pulse, blood pressure, electrical activity of brain, electrical activity at neuromuscular junctions, the movements of gastro intestinal tract etc); these rhythms arise from our internal, non linear systems while interacting with the external environment. The regulatory mechanisms of such systems are a combination of local and central control. Both the voluntary (i.e. skeletal muscles) and the involuntary (i.e. gastro intestinal tract, respiratory tract) muscles can carry out movements on their own; however, the central nervous system is involved in fine control and coordination of movements in both cases. External environmental stimuli may interact at both levels to modulate these rhythms. For example, the normal motility of the gastrointestinal tract is maintained by the autonomic nervous system (the sympathetic and parasympathetic system) as well as local hormones (i.e. ghrelin and motilin) [2]. During an acute stress response the colonic motility increases, both by central (i.e. sympathetic over-activity, action of hormones such as corticotrophin releasing factor) as well as peripheral (mast cell activation[3]) mechanisms.

Music is an external stimulus that is ubiquitous, rhythmic and can be quantified to a certain extent. The rhythm in music is not just related to the tempo and percussion of the piece, *but* *the very tunes themselves*, which are no more than oscillations at a certain frequency. The objectives of the present study was to investigate the effects of music of a particular complexity on autonomic functions. Music can only be perceived by *peripheral* vibration receptors (either in ears or other body parts, i.e. skin and joints); however, they have widespread effects on central nervous system, In the present study we planned to study whether it has any effects on the rhythm of autonomic functions – which are, by definition, *centrally* regulated.

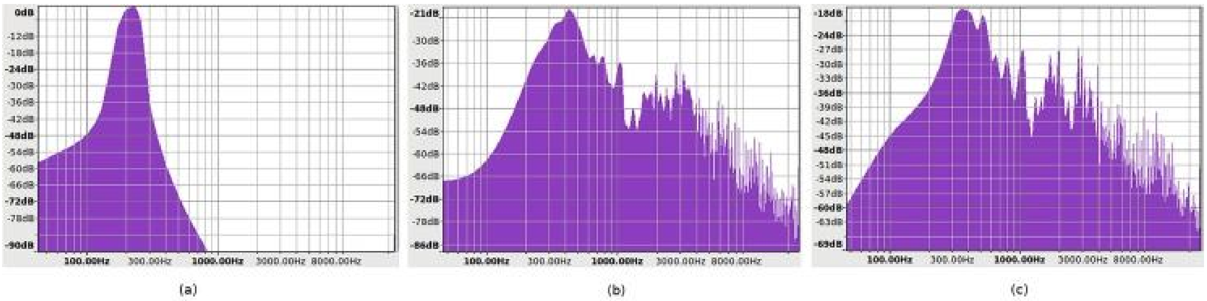
It is known that music can synchronize autonomic functions of listeners to some degree [4]. In a well-designed experiment, Muller et al. demonstrated that phase synchronization both within and between brains (measured by EEG, electroencephalography) increased significantly during the periods of preparatory metronome tempo setting and coordinated play onset between two guitarists [5]. This finding hints at deeper, underlying mechanisms, which are poorly understood. Whereas the broad health benefits of music listening and music-making are increasingly well acknowledged, the evidence around it is mediocre at best [6], [7]. The 'music' in most published studies is often unquantified, making the results statistically untenable. Unlike pure sounds, 'music' is often a complex amalgam of various frequencies and tempos, originating from different instruments and/ or human voice. There does not seem to be one single metric to 'measure' music. We thus introduce a singular metric, complexity (measured by the fractal dimension) to quantify music and study its effects on autonomic nervous system in humans. The objective of our present study was to compare the response of autonomic system parameters (blood pressure, electrocardiogram and heart rate variability) in healthy subjects with Indian classical music of different fractal qualities.

2. Method

For the purpose of the study, specially designed sounds were recorded in a studio by playing a Sitar, an Indian Classical string instrument. The recording was made using a Neumann (U87) microphone (Georg Neumann GmbH, Berlin), Hawk Professional Low Noise Recording Cable (Hawk Proaudio India), using NUENDO 8 (Steinberg Media Technologies GmbH, Germany) recording suite on a Macintosh running Apple macOS High Sierra, Version 10.13.6. Studio Live 32 Digital mixer (PreSonus Audio Electronics, Inc) was used for recording. The sounds incorporated phrases of Indian *rāga Bilawal,* which is roughly equivalent to the Ionian mode of Western classical. The two distinct sounds, SBPC752 LT (low fractal) and SBPC752 HT (high fractal) were recorded in the study, and is attached as additional material.

The functioning of a Sitar is based on smooth transitions between notes (*'mīr'*). A musician stretches the strings, using fingers on various frets, thick and thin strings, as well as *changing the thickness of a particular string during playing*. Supplementary table S1 shows the range of frequencies from a single string of the Sitar, as well as physical measurements of the string (diameter and length) while smoothly transitioning from one note to the next. This particular characteristic of Indian music contribute to its unique tonal texture. Supplementary figure S1 shows the process of measurement by screw gauge.

In addition, two sinewaves were prepared with Audacity software package, with 220 Hz and 440 Hz frequencies. However, during the pilot run of our study, the 440 Hz sound was associated with uneasiness and discomfort among subjects, thus we re-recorded sinewave of 220 Hz, which was well tolerated by subjects. The spectrograms of the three pieces are shown in Fig. 1, their Higuchi fractal dimensions in Fig. 2 along with a sample of their waveforms (not to scale) and Fourier transforms.



Spectrograms of the three kinds of music used in the study: (a) Sinewave (b) Low fractal (c) High fractal

Fig. 1. Fourier spectrum of the three different music pieces used in the study (a) Artificially generated sinewave of 220 Hz (b) Indian classical music of low fractal and (c) high fractal.

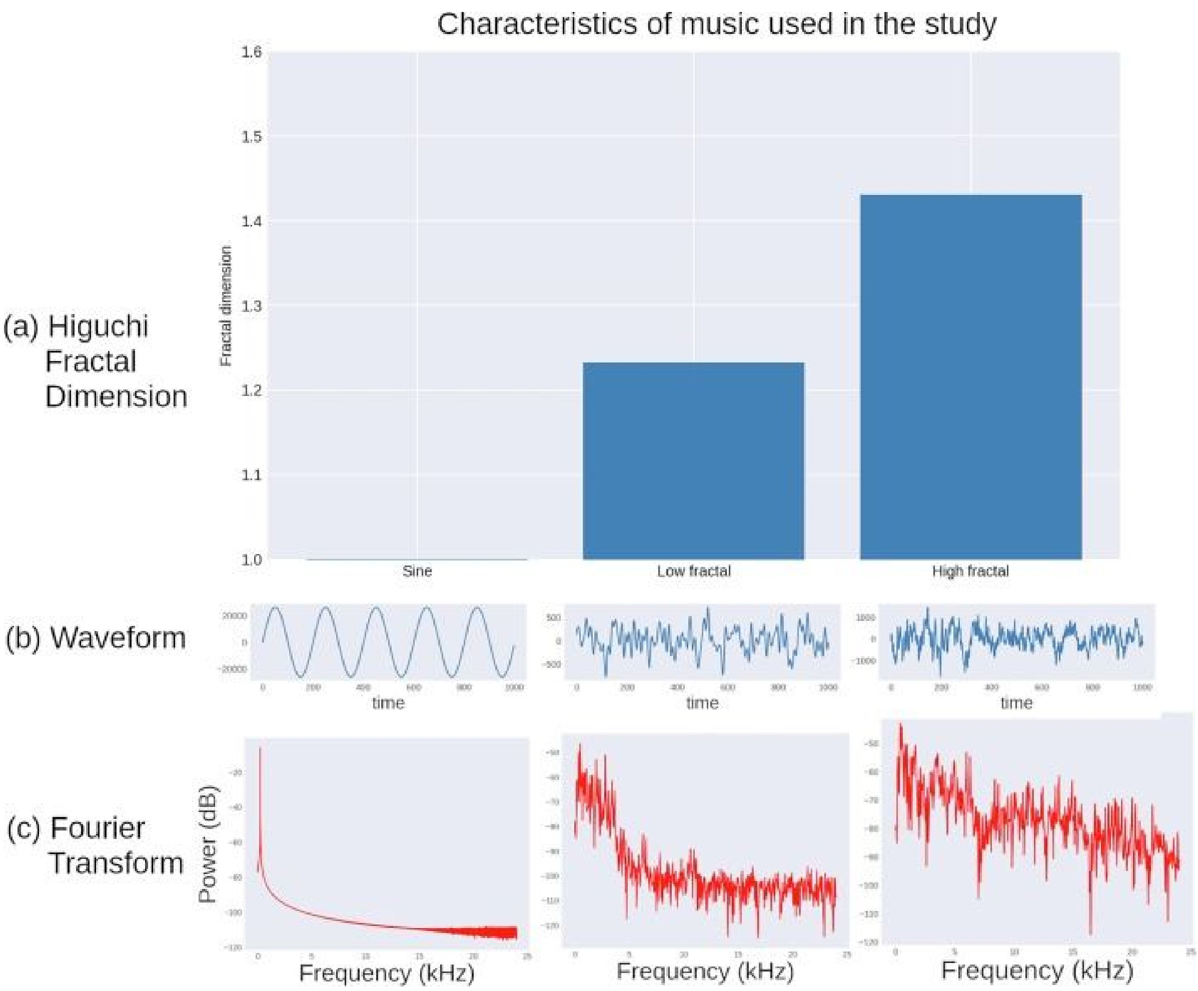


Fig. 2. (a) Higuchi Fractal dimensions of three different music pieces used in the study, showing increasing fractal complexity from sinewave, to low fractal and high fractal.

The Higuchi Fractal Dimension (HFD) is a method used to analyze the fractal properties of time series data, particularly in the context of physiological signals like Heart Rate Variability (HRV). It's commonly employed to quantify the complexity or irregularity of a signal. The steps for computing the Higuchi Fractal Dimension are as follows:

1. Resampling: First, the time series data (in our study, blood pressure or ECG data) is resampled to create a set of subseries. This involves dividing the time series into a number of segments by applying a sampling interval (*k*). Basically, R wave peaks are detected and then uniformly sampled.

2. Curve Length Calculation: For each subseries, the curve length L(*k*) is computed. The curve length is determined by connecting the data points within each subseries with straight line segments and then summing the lengths of these line segments.

3. Higuchi fractal dimension Calculation: The Higuchi fractal dimension (HFD) is then calculated using the formula

$$D_{HFD} = \log\left(L\left(k\right)\right)/\log\left(k\right)$$

where *k* is the number of subdivisions (sampling interval) and L(*k*) is the average length of the curve after *k* subdivisions. The process involves repeating steps 2 and 3 for different values of *k* and then fitting a line to the plot of log(L(*k*)) versus log(*k*). The slope of this line gives the estimate of the fractal dimension.

The Higuchi Fractal Dimension quantifies the irregularity or complexity of the signal. Higher values of D_{HFD} indicate more irregular or complex signals, while lower values indicate more regular or predictable signals.

25 healthy volunteers were recruited for the study, all between the age groups of 18–35, of either gender. The subjects were counseled and written informed consent was obtained (Participant Information Sheet & Participant Informed Consent Form had received prior approval from Institutional Ethical Committee).

The subjects were randomized into three groups: sinewave (‘sine’) – 08, low fractal (‘low’) – 09 and high fractal (‘high’) – 08. We used sinewave of 220 Hz (i.e. the middle ‘A’ key of piano) as control because it has a musical quality – and is thus similar to the intervention music - but very low fractal dimension. A period of silence was already included in the study protocol before commencement of actual music; thus, silence was not used as control. White noise was not used as control as it has proven effects on levels of anxiety and autonomic function [8].

The protocol for intervention is shown in Table 1. The subjects were asked to refrain from caffeinated beverages from 12 h prior to intervention. Before 20 min of intervention, they were placed in a quiet room and asked to perform deep breathing exercises for relaxation. Electrocardiogram (ECG, from lead II) and Non invasive BP (NIBP) leads were placed and continuous measurements started 10 min prior to intervention. Continuous heart rate and blood pressure were recorded using Labchart Pro 8 ® (AD instruments, Australia) and Finometer® (Finometer® model 2, Finapress Medical Systems, Amsterdam, the Netherlands) respectively. The ECG and Blood pressure signals were analyzed for their variability (HRV, Heart rate variability; BPV, Blood pressure variability). For this the data was subjected to offline analysis using Nevrokard HRV analysis software.

Table 1. Intervention protocol.

Empty Cell	**TIME →**			
−20 min	**−10 min**	**0 min**	**+15 min**	**+25 min**
Arrival of subject	Relaxation by deep breathing exercises	Start of music	End of music	Relaxation by deep breathing
Attachment of leads	←Lead II ECG reccording → ←Beat to beat non invasive BP recording →			

At 0 min, the musical intervention/ control was played from a specific computer in the same volume setting, through a fixed headphone, delivering the music at a volume of 60 ± 10 dB [9] (standardised with Sound Meter android app). The eyes of the subject was covered to exclude any visual stimuli. The setup is shown in Fig. 3.

Fig. 3. Layout of the experimental setup with supine subject in a quite room, eyes covered with obscurer, Electrocardiogram (ECG, from lead II) and Non invasive BP monitoring.

3. Results

We analyzed the Fourier transform of blood pressure waveform from a selected duration (middle 5 min interval while the music was being played) using the method described by Coltrane[10], which uses the same unit of power (dB) as in analysis of sounds. The Fourier transform was distributed into five frequency bins (Fig. 4). Only the lowest frequency band (0–100 Hz) showed a significant difference in power between the three groups ($p = 0.04$), with an increasing trend from high fractal to low fractal & sinewave group. Table 2 shows the power distribution (in dB) of BP wave in different frequency bands (kHz) of the subjects (see Fig. 5).

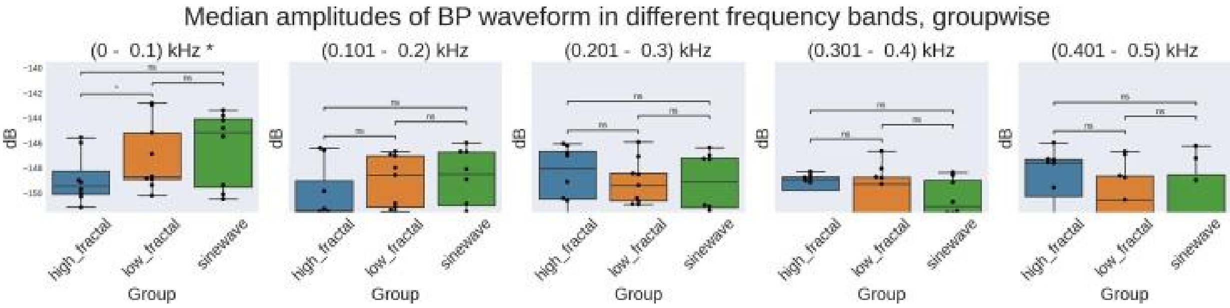


Fig. 4. After NIBP recording in all three groups, the Fourier transform of the blood pressure wave was performed and amplitude in different frequency bands is shown.

Table 2. Power of BP wave in subjects distributed in frequency bands (n = 25).

	Power (dB) in Frequency bands (kHz) of blood pressure wave					
Subject ID	**(0, 0.1)**	**(0.101, 0.2)**	**(0.201, 0.3)**	**(0.301, 0.4)**	**(0.401, 0.5)**	**Group**
1	−150.31255498638	−152.408216785685	−152.54699256107	−148.547199330165	−146.011900014243	high
2	−149.012828520986	−151.649938160115	−147.024941575449	−149.168719864912	−147.579182339271	high
3	−148.877190863653	−150.857520363999	−150.652913375413	−146.673841408016	−146.706022464491	low
4	−149.725593195461	−151.489184210913	−146.077851975795	−148.842967405604	−147.362597886192	high
5	−150.233941303288	−151.170665271063	−147.114498027623	−148.748438147003	−148.775175198377	low
6	−148.939279088155	−151.382130900336	−145.959748837198	−148.812463713072	−146.938055090445	low
7	−150.508819923791	−150.8777816695	−147.331159256111	−148.594651549233	−149.003144114785	sine
8	−151.179114680185	−149.857394771853	−149.14109400939	−148.304645965573	−149.59307296519	high
9	−150.055446836211	−151.496025884756	−146.238071145669	−149.042099092623	−147.632183586061	high
10	−149.405963120899	−151.52198223103	−148.463845349123	−149.317984770405	−148.651264491016	low
11	−149.166148014652	−151.303130845103	−146.804569094651	−148.785259697827	−147.306266402327	high
12	−149.392258585577	−151.505488592067	−146.409350504829	−149.167818190499	−147.250655858188	sine
13	−150.122777842553	−152.281957786784	−152.303133393291	−148.37133214403	−146.26654157409	sine
14	−145.507516260144	−148.952263472371	−147.28717082337	−151.481698412915	−151.773258544407	sine
15	−145.205909539482	−146.944439546484	−150.441710503417	−151.869444476687	−151.870428201955	low
16	−144.207248854041	−146.028362672212	−151.115247340209	−151.628671260444	−151.939047335137	sine
17	−148.713707818065	−147.998350135706	−149.416477038726	−148.073577042331	−150.57104899336	low
18	−145.592861870976	−146.597678896295	−150.464936894014	−151.791105871813	−152.376116320301	high

	Power (dB) in Frequency bands (kHz) of blood pressure wave					
Subject ID	**(0, 0.1)**	**(0.101, 0.2)**	**(0.201, 0.3)**	**(0.301, 0.4)**	**(0.401, 0.5)**	**Group**
19	−143.825511506232	−146.722754889984	−151.422219673838	−151.595082054507	−151.905206975054	sine
20	−144.83622913781	−148.116923024111	−147.027853646044	−150.737377025224	−152.158409483619	sine
21	−143.000954679944	−147.065362571451	−150.945272236978	−152.495741895997	−153.526520283843	low
22	−143.410781021691	−146.73307658507	−150.995213559874	−152.527879051779	−153.800918645934	sine
23	−142.832663097811	−146.702508573787	−150.918171409499	−152.246107112897	−153.067337638247	low
24	−146.890885468615	−148.595777180262	−148.542776326892	−152.496210891208	−153.005691030431	low
25	−146.014413117822	−146.434419713218	−150.623443713116	−151.757610980847	−152.807714064334	high

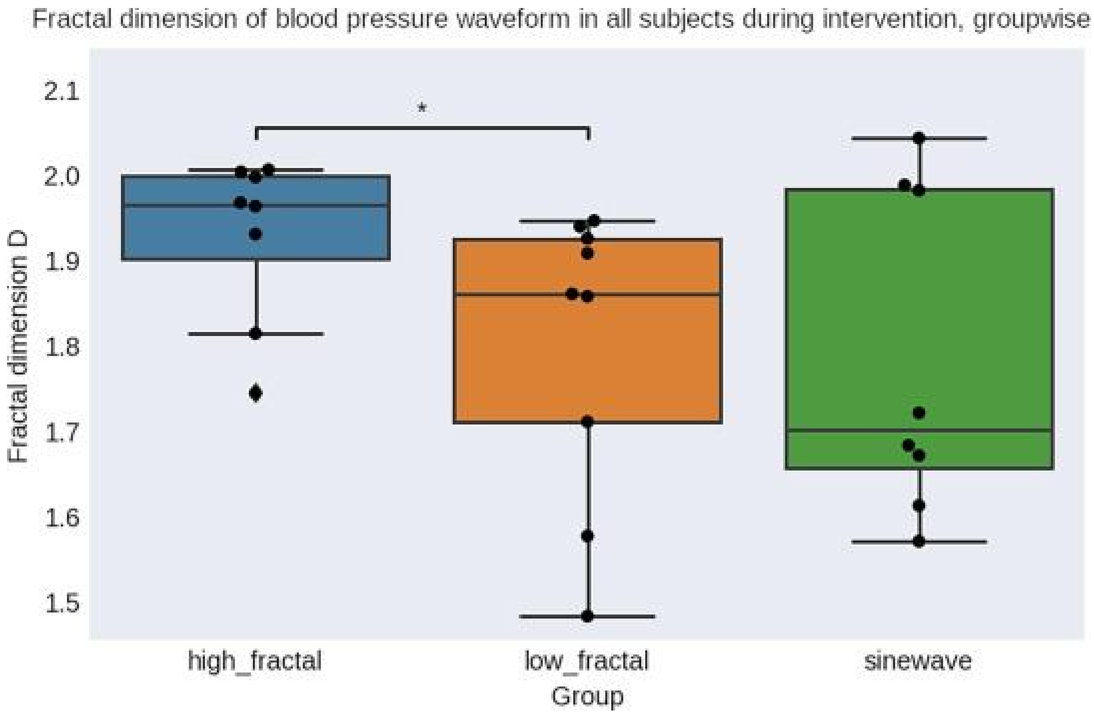


Fig. 5. Higuchi Fractal dimension of raw blood pressure waveform (n = 25) shows a significant difference between the groups subjected to low fractal music and high fractal music.

The fractal dimension of the BP waveform was measured from the same duration using Higuchi's fractal dimension [11] and the Python library HFDA [12], [13] (Fig. 4). The kMax parameter was selected as 5, based on previous applications of Higuchi Fractal Dimensions in biological rhythms [14]. A Mann-Whitney *U* test showed a difference between complexity of BP waveforms between high fractal and low fractal music (p = 0.03), with the high fractal group showing significantly more complexity of BP waveform, while the sinewave group showed mixed results. A second measure of complexity, the sample entropy (measured in the first 10 s of BP recording in the intervention period), did not show any statistical difference between the three groups. (Supplementary Fig. 2). This might indicate that the BP waveform is more self-similar in long term than short term fluctuations that were associated with the intervention.

The blood pressure waveforms were also analyzed using Hurst exponent (H), which provides insights into the long-term correlations and self-similarity present in the variability of blood pressure. A higher Hurst exponent (H > 0.5) indicates a persistent behavior, whereas a lower value (H < 0.5) suggests an anti-correlated or more random behavior. In all the subjects, the Hurst exponent H was found to be >0.7 (Table 3). This may indicate that over long term, the BP waveform shows greater consistency than short term, where stochastic behavior predominates.

Table 3. Fractal dimensions of BP and ECG waves (D) in subjects during intervention (n = 25).

ID	Group	Gender	Higuchi fractal dimension of BP waveform	Higuchi Fractal Dimension of ECG waveform	Sample entropy of BP waveform	Hurst exponent of BP waveform
1	high	M	2.00304062265591	1.0127975222448	1.87	0.73
2	high	F	1.96692860391589	1.00777534738205	1.92	0.72
3	low	M	1.90752863841027	1.01220855371016	1.87	0.71
4	high	M	2.00561959650366	1.01043872747509	1.8	0.72
5	low	M	1.9388941253483	1.00770578732022	1.81	0.74
6	low	M	1.92484970238381	1.01198806114323	1.83	0.72
7	sine	M	1.98123704010715	1.01077831902834	2.07	0.73
8	high	F	1.93004825597271	1.01120510572326	1.77	0.73
9	high	M	1.99694013740681	1.00521209928389	2.04	0.72
10	low	M	1.94570126323176	1.00607807791779	1.76	0.72
11	high	M	1.96272834651983	1.00848042293705	1.72	0.73
12	sine	M	1.98757450952874	1.00692658284379	1.93	0.73
13	sine	M	2.04265963868547	1.00688164620849	1.87	0.73
14	sine	M	1.68267230139908	1.00921450609399	1.76	0.71
15	low	M	1.71038439998941	1.00702953894485	2	0.71
16	sine	F	1.67075581426772	1.00906159175319	1.88	0.71
17	low	M	1.85701461503993	1.00757705042563	1.91	0.74
18	high	M	1.8133912137727	1.00759137210198	1.58	0.71
19	sine	F	1.61207983110524	1.01227159223879	1.93	0.73
20	sine	F	1.72076311682719	1.00605807167838	1.76	0.71
21	low	F	1.5763295254729	1.01004816522136	2	0.74
22	sine	M	1.57012136294021	1.0055820498341	1.7	0.72
23	low	F	1.48222786403265	1.00992815642882	2.03	0.7
24	low	M	1.85981570151466	1.00630144599237	1.81	0.72
25	high	F	1.74394823331254	1.01001439166231	2.04	0.72

High = high fractal music, low = low fractal music, sine = sinewave.

Sitar Measurement

The complexity of the ECG waveform (i.e. its Higuchi fractal dimension with kMax = 5) did not show any significant difference between the three groups (Fig. 6), although a decreasing trend in complexity was noted between high fractal to low fractal to sinewave group. Table 3 shows the fractal dimensions of BP and ECG waveforms of all subjects.

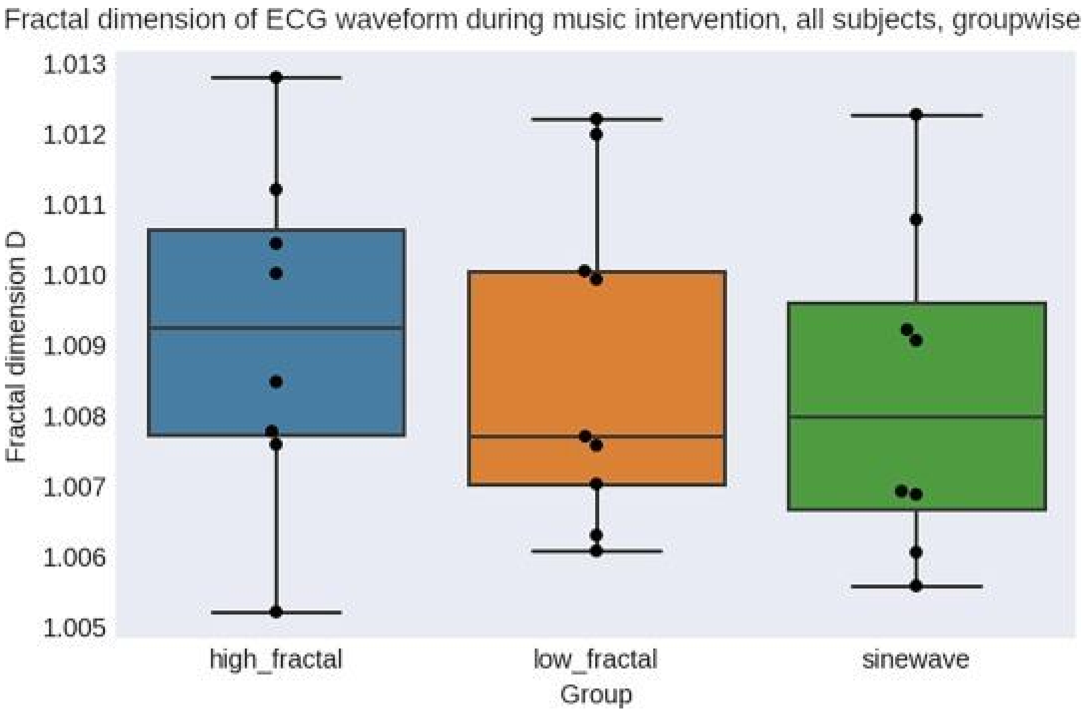
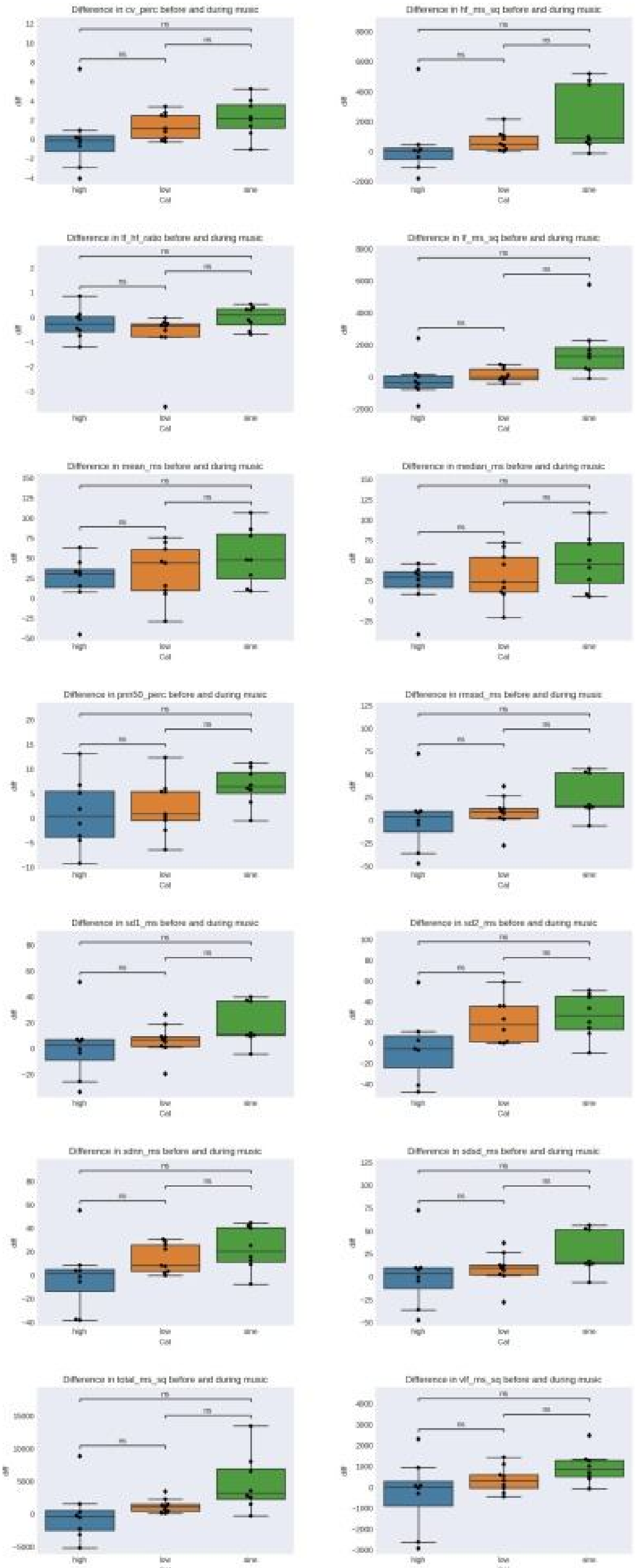


Fig. 6. Higuchi Fractal dimension of electrocardiogram ((ECG) waveform (n = 25)

shows no significant difference between different intervention groups.

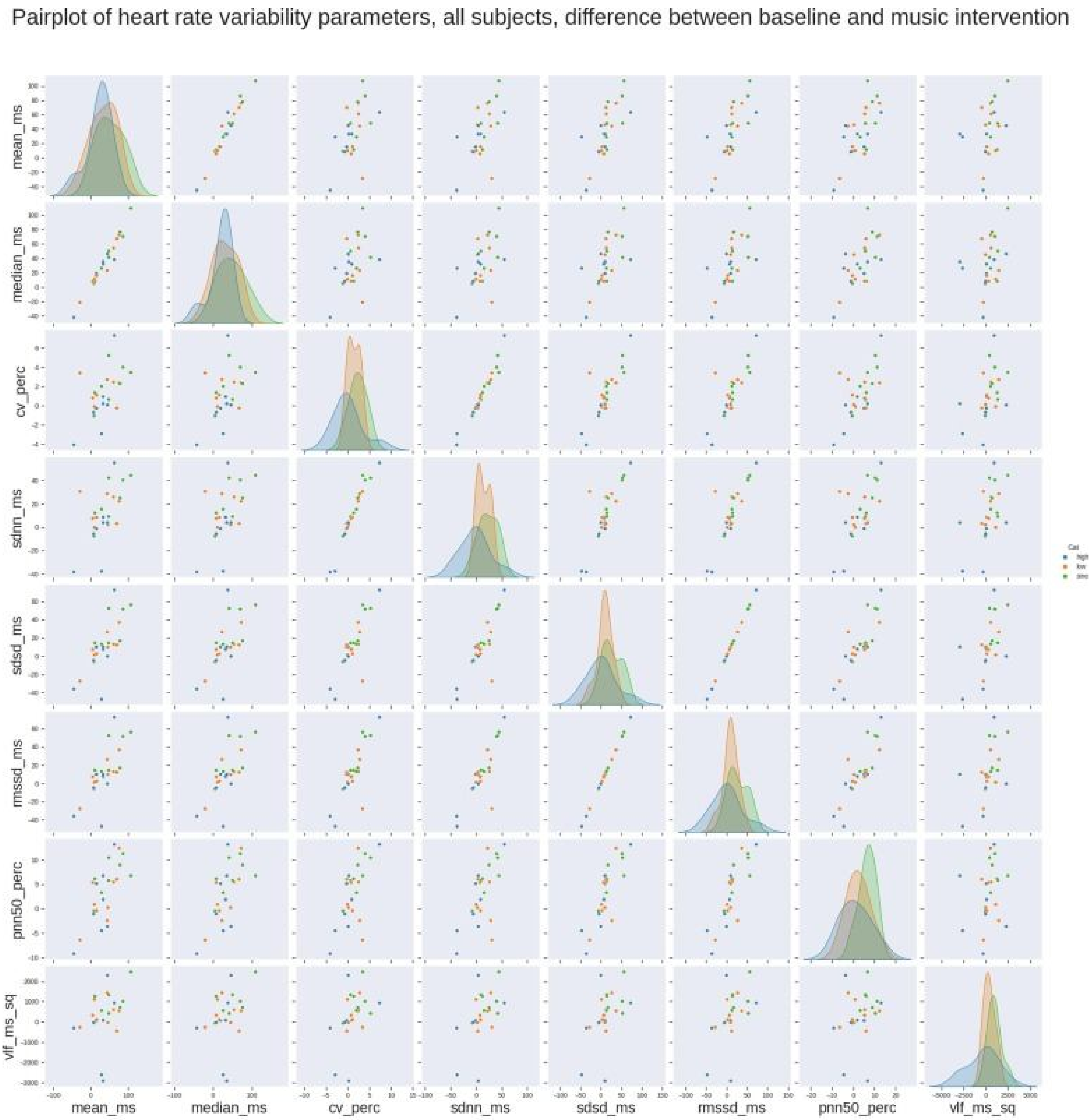
In addition to blood pressure waveform and ECG, we measured the heart rate variability (HRV) parameters of subjects, both at baseline (a 5 min interval before intervention) and during intervention (a 5 min interval in the middle of intervention). Fig. 7 shows difference in all the HRV parameters in both time and frequency domain: mean NN intervals (mean), median, coefficient of variation (CV%), standard deviation of NN intervals (SDNN), SDSD, root mean square of successive RR interval differences (RMSSD), percentage of successive RR intervals that differ by more than 50 ms (pNN50), Absolute power of the very-low-frequency band (0.0033–0.04 Hz) (VLF), absolute power of the low-frequency band (0.04–0.15 Hz) (LF), absolute power of the high-frequency band (0.15–0.4 Hz) (HF), LF/HF ratio. In addition, non linear parameters such as Total area of ellipse (Total), Poincaré plot standard deviations (SD1, SD2) used, between baseline and intervention. An increasing trend is seen from high to low fractal to sinewave group. The increase in trend is not, however, statistically significant, possibly due to the small number of subjects in each group. A pairplot of all parameters show none of the parameters are predictive of the intervention group (Fig. 8). Supplementary figure S4 shows the change in HRV parameters, groupwise, from baseline to intervention; the raw data is presented in supplementary tables S2, S3 and S4.

Calculated heart rate variability parameters, difference between baseline and intervention, all subjects, groupwise



Legend: mean of NN intervals (mean_ms), median NN (median_ms), coefficient of variation (cv_perc), standard deviation of NN intervals (sdnn_ms), root mean square of successive RR interval differences (rmssd_ms), percentage of successive RR intervals that differ by more than 50 ms (pNN50), Absolute power of the very-low-frequency band (0.0033–0.04 Hz) (vlf_ms_sq), absolute power of the low-frequency band (0.04–0.15 Hz) (lf_ms_sq), absolute power of the high-frequency band (0.15–0.4 Hz) (hf_ms_sq), LF/HF ratio (lf_hf_ratio), standard deviations of Poincare plots (SD1, SD2)

Fig. 7. Heart rate variability (HRV) parameters in subjects of three groups (n = 25); no significant difference is noted between groups.



Legend: mean of NN intervals (mean_ms), median NN (median_ms), coefficient of variation (cv_perc), standard deviation of NN intervals (sdnn_ms), root mean square of successive RR interval differences (rmssd_ms), percentage of successive RR intervals that differ by more than 50 ms (pNN50), Absolute power of the very-low-frequency band (0.0033–0.04 Hz) (vlf_ms_sq), absolute power of the low-frequency band (0.04–0.15 Hz) (lf_ms_sq), absolute power of the high-frequency band (0.15–0.4 Hz) (hf_ms_sq), LF/HF ratio (lf_hf_ratio), standard deviations of Poincare plots (SD1, SD2)

Fig. 8. Pairplot of heart rate variability (HRV) parameters in subjects (n = 25); no single parameter is discriminative of the type.

4. Discussion

The fractal dimension of a piece of music is a measure of the amount of complexity in the said piece. The technical framework of fractal analysis of musical pieces has been exemplified by Clark (2020) in his thesis [15]. Analysis of fractal dimension of a time series, such as music, is a difficult problem – because unlike a two dimensional image (i.e. a Sierpinski triangle), the X & Y axis of a time series do not represent the same physical quantity [16]. The method proposed by Hurst et al. [17] measures the randomness of a time series, which we have used in the present study to characterise the response in the blood pressure wave. We propose to use Higuchi's fractal-dimension D [18], [19], which is a variant of the usual box-counting fractal dimension suited for time-series analysis. In this method, sinewaves produce the lowest fractal dimension, followed by waves of regular shapes such as square waves. The highest fractal dimensions are observed in music with a complex waveform, such as combinations of human voice and a string instrument.

Several groups have studied the effects of music on autonomic function; Mojtabavi et al. [20], in their comprehensive review, reported 26 original studies that have found a positive impact of music on heart rate variability (HRV). The chief difficulty among all these studies seems to be quantifying the nature of 'music' which is used, as in the study by Escher et al, where 'relaxing music (Bach, Vivaldi, Mozart)' - a subjective parameter at best – was used [21]. Jia et al. (2016) reported increase in parasympathetic activity (with HRV) post listening to the subjects own 'favorite music' (again, a subjective parameter), as well as attenuation of exercise-induced decrease in parasympathetic activity [22]. Similarly, a number of studies refer to 'sedative' music that cause variable effects on heart rate [23]; qualifying music in such a manner is inadequate at most.

The simplest way to describe music is, of course, to use pure tones. There have been numerous, often contradictory reports regarding effect of pure tones on autonomic function. Veternik et al. (2018) concluded that sounds of 20 Hz, 50 Hz, 2 kHz and 15 kHz, even when played at a volume more than 65 dB, does not affect heart rate variability [24]. The other way of quantifying sound is by volume. Chang et al. (2015) concluded that 45 dB(A) of noise, 10 dB(A) higher than background noise, affects the ANS; additionally, the impact on HRV activity might differ according to the noise quality (i.e. traffic noise or speech noise) [25].

Majority of these studies have been carried out with western music/ music of the subjects own choice. Studies on Indian music and autonomic function have often focused on a particular musical mode, such as a defined *raga* [26], or one specific instrument [27]. No quantification of the music concerned have been reported in these studies.

There is one aspect of musical sound that can be measured by standardized method, that is its fractal dimension [28]. The fractal dimension is an indirect measure of the complexity of a piece of music. In this particular aspect, Indian classical music differs significantly from western music. The distinct fractal quality of Indian music has been demonstrated in several studies in the past. The fractal dimension of Tanpura music was extensively analyzed by Sengupta et al. [29]. Das et al. have shown a clear difference in fractal qualities in different genres of Indian music [30], that is, a simple $\bar{a}l\bar{a}p$ (slow simple movements between frequencies) has much lower fractal quality than a *thumri* (complex movements) recital. In addition, due to the very nature of Indian music, the smooth transition between notes ($m\bar{\imath}r$) causes quantitative changes in the string and tonal quality of the music, as described in the methods section. Whereas the diverse effects of music on autonomic function have been studied before [31], the effect of distinct subtypes of music based on their fractal quality is under-investigated. We aim to fill this research niche, especially with regards to Indian music.

The Higuchi fractal dimension (HFD) has been widely used in analyzing biological rhythms. Gomolka et al. used HFD to analyze HRV in healthy and diabetic subjects as a measure of autonomic nervous system dysfunction, and Kawe et al. have recently used the HFD in analysis of EEG waves to delineate mental states of anxiety and depression [32]. We have, however, used the HFD to quantify *both* the stimulus (music) and the response (blood pressure and ECG waveform). Although no direct correlation was found, music of higher complexity was seen to affect the complexity of blood pressure waves. Whether this response is due to the direct contact with the source of music or emerging from a higher neural center is not known. Further studies will be required to examine this phenomenon.

In addition, one other phenomenon was noted in the study, i.e. the response of HRV to sinewaves. The 'acoustic environment' is a known determinant of mental and physical state [33], [34]. Sound carries with it information about the environment, which alerts the organism through an intermediary emotion. Scahfer et al. [35] in a study in 2015 hypothesised that feeling 'safe' in an acoustic environment depends on the complexity, or the information density, of the sound – not too little or too much. However, admittedly, their data did not support this hypothesis. In the present study, the music of least complexity (sinewave) produced the most pronounced increase in heart rate variability. This might indicate that due to the lack of sinewaves in nature, humans are not conditioned to it and produce a panic response.
The present study is limited by the small sample size, because of which trends have not been found to be statistically significant. The subjects were not as homogeneous a group as desired, because subjective criterion such as musical preference differs between subjects, which might affect their autonomic response. We hope to overcome this with further studies which will employ (a) a larger but more uniform sample and (b) a further refinement on the phrases of music for intervention, particularly short term changes while listening to features unique to Indian music, such as smooth transitions between notes ($m\bar{\imath}r$) and fast complex movements ($t\bar{a}n$).
In conclusion, we demonstrated that Indian classical music of different fractal qualities has a bearing on the complexity of blood pressure waves, as well as heart rate variability. The findings on the present study may be further investigated to answer whether the effects are due to direct contact with the source of sound or a cerebral mechanism.

CRediT authorship contribution statement

Parikshit Sanyal: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Koushik Roy:** Software, Resources, Project administration, Methodology, Investigation, Data curation. **Sanjay Chakrabarty:** Resources, Methodology, Conceptualization. **Dinu S. Chandran:** Supervision, Resources, Project administration, Methodology. **K.K. Deepak:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Supplementary data 8.

Data availability

Data will be made available on request.

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