ARTÍCULO ORIGINAL

Heart Rate Variability analysis as a tool for assessing the effects of chi meditation on cardiovascular regulation

El análisis de la variabilidad de frecuencia cardiaca como una herramienta para evaluar los efectos de la meditación chi sobre la regulación cardiovascular

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ABSTRACT

Approximately 30 indices have been proposed for assessing heart rate variability (HRV). Some are mathematically identical or very closely related to each other, and results can be interpreted from completely different viewpoints. Comparing various indices from a tachogram, and combining statistical significance with physiological plausibility could improve the result's interpretation. Using the "KubiosHRV" package, we studied the "*chi*-meditation" R-R database available at "Physionet.org", addressing the following questions: i) Which HRV indices are the most suitable for describing meditation effects? ii) Are the effects of meditation beneficial, harmful or insubstantial? iii) Which are the most likely physiological events associated to meditation? It was concluded that power spectrum low frequency component (LF), LF/HF ratio, and nonlinear indices α 1 and α 2, recurrence rate and Shannon entropy performed the best ($p<0.05$). Observed changes suggest that they harmonize with changes observed in other health-pursuing circumstances as physical training, stress combating; whereas they are in the opposite tendency of changes associated to aging, heavy smoking, high blood glucose levels, autonomic heart denervation and congestive heart failure. Changes induced by *chi* meditation seem to be associated to increases in respiratory component around0.04 Hz, lower entropy and reduced long-term correlation with higher cardio vascular complexity.

Keywords: heart Rate variability, cardiovascular complexity, *chi* meditation, heart rhythm modulation by respiration.

RESUMEN

Alrededor de 30 índices han sido propuestos para evaluar la Variabilidad de la Frecuencia Cardiaca. Algunos de esos índices son matemáticamente idénticos o muy semejantes a otros y los resultados pueden ser interpretados desde puntos de vista completamente distintos. Al comparar varios índices estimados a partir de un tacograma y combinando la significación estadística con la plausibilidad biológica pudiera mejorarse la interpretación de los resultados. Utilizando el paquete de análisis "KubiosHRV" estudiamos la base de datos de señales R-R "Chi meditation", disponible en el portal "Physionet.org", centrándonos en las interrogantes siguientes: i) ¿cuáles índices son los más adecuados para describir los efectos de la meditación? ii) ¿son los efectos de la meditación beneficiosos, nocivos o insustanciales? iii) ¿cuáles son los eventos fisiológicos asociados a la meditación? Se concluye que el componente de baja frecuencia del espectro de potencia (LF), la relación LF/HF y los índices no lineales $\alpha 1$ y $\alpha 2$, la razón de recurrencia y la entropía de Shannon, fueron los indicadores más apropiados ($p < 0.05$). Los cambios observados parecen armonizar con cambios observados en otras acciones promotoras de salud como entrenamiento físico, combatir el estrés, mientras que exhiben una tendencia opuesta a los cambios asociados al envejecimiento, hábito de fumar, elevados niveles de glucosa, denervación cardiaca, e insuficiencia cardiaca congestiva. Los cambios inducidos por la meditación chi parecen estar asociados a incrementos en el componente respiratorio próximo a los 0.04 hertzios, a una menor entropía y una menor correlación a largo término combinadas a una mayor complejidad cardiovascular.

Palabras Claves: variabilidad de la frecuencia cardiaca, complejidad cardiovascular, meditación chi, modulación del ritmo cardiaco por la respiración.

INTRODUCTION

Meditation refers to a family of mental training practices that is designed to familiarize the practitioner with specific types of mental processes.[1] In addition, meditation is considered an ancient spiritual practice that has potential benefit on health and well-being.[2,3] It is a complex physiological process, which affects neural, psychological, behavioral, and autonomic functions.[4]

With advances in multivariate statistics, nonlinear science, Bayesian methods, pattern recognition and other approaches, extracting meaningful information from complex physiological signals is becoming a tangible possibility. For some signals (e. g. electrocardiograms), visual inspection by trained experts still remains the main diagnostic criterion. For others, automated analysis emerging from a set of indices obtained from a complex physiological signal is becoming a weighty contribution into the diagnostic practice, as happens with quantitative electroencephalography (EEG) or heart rate variability (HRV) analysis.

In the case of HRV, at least 28 indices have been proposed, not mentioning other specific suggestions made by different authors in the last 30 years. These indices can be grouped into three broad divisions: "time domain", "frequency domain" and "nonlinear".[5]

Researchers are still striving to find possible correspondence between the different indices and physiologically interpretable activity. In this regard, frequency domain indices (figure 1), are illustrative. Traditionally there has been agreement that the area under the power spectrum in the low frequency (LF) band (LF, 0.04 - 0.15 Hz) is associated with both sympathetic and parasympathetic activities; on the other hand the high frequency (HF) power (HF, 0.15 - 0.4 Hz) is associated with parasympathetic activity. Accordingly, the ratio LF/HF is regarded as a measure of sympatho-vagal balance. The abrupt downhill power decline in the very low frequency (VLF) band (VLF, 0-0.04Hz) suggests the presence of nonlinear self-organizing mechanisms on the long-range time scale, and justifies the introduction of different indices purportedly assessing the nonlinear phenomena underlying HRV. Depending on respiration rate, both LF and VLF may convey an important respiration-related component.[6]

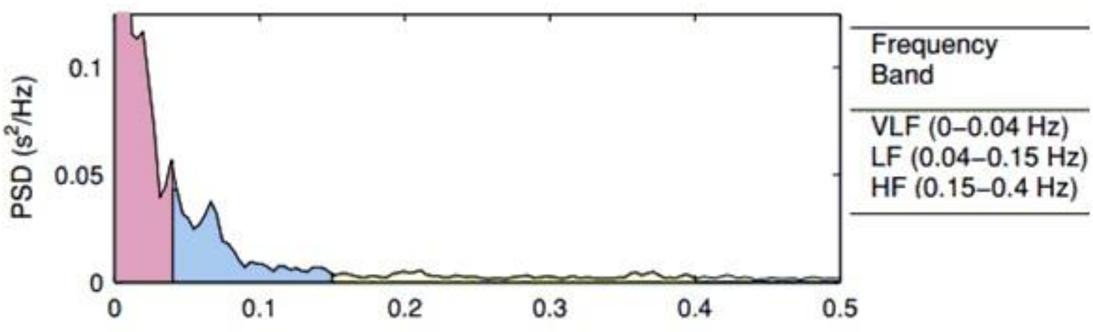

Fig. 1. Typical power spectrum from a 30-min HRV recording with indication of different frequency bands

However, a brief review of literature suggests that some of those indices to which different physiological roles were attributed; can be numerically derived from others and may become redundant and physiologically misleading. Moreover, some of the previously coined indices referring to "sympathetic", "parasympathetic", "sympatho-vagal balance", etc., have been put into doubt in light of recent research.[7] Thus, it has been shown that frequency domain "total power" is highly correlated with the square power of Standard Deviation of Normal to Normal (SDNN), as expected from the definition of power spectrum. Percentage of differences between adjacent normal R-R intervals >50 milliseconds (pNN50) was found to be highly correlated with the power spectrum HF component (as expected from the parasympathetic nature of pNN50 proportion of successive decelerations of the heart rhythm), but also has proven to be of little use when heart rate variability is either too high or too low.[8] Poincare plot is reminiscent of the phase portrait, a key concept associated to the Takens theorem, and thus has been viewed as a reflection of chaotic nonlinear processes in cardiac rhythmogenesis. Simple mathematical manipulations reveal that Poincare's SD1 exactly abides to equation.[1]

$$SD1 = \sqrt{2} * RMSSD$$

As is widely known, "Root Mean Square of Successive Differences" (RMSSD) has never been associated with nonlinear processes. A similar derivation is found for SD2.[9]

Special relevance finds the demonstration that parameters derived from Detrended Fluctuation Analysis (DFA) can be theoretically derived from a combination of VLF, LF, and HF.[10]

$$\alpha_1 \approx 2\left(\frac{\mathbf{LF}}{\mathbf{HF}+\mathbf{LF}}\right)$$

$$\alpha_2 \approx 2\left(\frac{\mathbf{VLF}}{\mathbf{LF}+\mathbf{VLF}}\right)$$

Being the different spectral bands consensually associated to autonomic nerve system (ANS) activity and in light of the conception that power spectrum retain information about linear processes only, the validity of DFA as a reliable way of exploring fractal properties of cardiovascular dynamics might be questionable.

As it can be expected, there is still no golden rule suggesting which are the best indices to use in different HRV studies; moreover, in light of discrepancies about physiological bases of different indices obstacles appear when it comes to interpreting results.

We hope that applying publicly available and well standardized estimation packages and testing them with publicly available datasets is a good way to come to a better agreement on the diagnostic value of different HRV indices.

Here we use the "Kubios HRV" analysis package developed at the University of Eastern Finland to analyze the data set of HRV changes induced by c*hi* meditation in a group of healthy young adults; original HRV data are available at the Physionet.org portal.

Qigong or Chi meditation is a practice of aligning breath, movement, and awareness for exercise, healing, and meditation. With roots in Chinese medicine, martial arts, and philosophy, qigong is traditionally viewed as a practice to balance qi (Chi) or what has been translated as "intrinsic life energy." Typically a qigong practice involves rhythmic breathing, coordinated with slow stylized repetition of fluid movement, and a calm mindful state.[11]The *chi* meditation data set is particularly curious. On one hand, it is among the best documented evidence of physiologic changes induced by meditation. In light of scarcity of scientific evidences for such changes this can be regarded as a valuable set. On the other hand, the authors of the original publication associated with this dataset reported the presence of prominent heart rate oscillations associated with slow breathing during meditation. The lack of any reference to nonlinear phenomena may be interpreted as a non-finding of interesting results on this area. Since nonlinear measures have dealt with non-periodic components of HRV this might bring to light the presence of a mechanism independent from respiration-associated changes. Another report suggests that HRV complexity of trained *Zen* meditation practitioners is drastically reduced when compared to beginners.[12] We hope that the present study can help in understanding changes induced by *chi* meditation upon the basic physiological mechanisms of HRV. Perhaps our approach can be useful for other HRV studies as well.

Here we are trying to approach the following three questions:
1. Which indices are the most predictable for describing the effect of meditation on HRV?
2. On the basis of observed changes, are the effects of meditation beneficial, harmful or insubstantial?
3. Which are the most likely physiological events associated to meditation?

Methods HRV data

Heart Rate Variability data were downloaded from the "Physionet" portal at http://www.physionet.org/physiobank/database/#rr. The data set (8 sujects) corresponds to the recordings on *Chi* meditation mentioned by Peng et al.[13] Subjects were at an advanced level of meditation training. All Chi meditators, were graduate and post-doctoral students. In addition, they were relative novices in Chi meditation, most of them having begun their practice in meditation about 1-3 months before the data collection. The subjects were in good general health and did not follow any specific exercise routines. The eight Chi meditators, five women and three men (age range 26-35, mean 29 years), wore a Holter recorder for about 10 h and did their ordinary daily activities. Roughly 5 h in the recording, each subject practiced 1 h of meditation. Meditation's beginning and ending times were delineated with event marks. During these sessions, the Chi meditators were asked to sit quietly and listen to the taped guidance of the Master. The meditators were instructed to breathe spontaneously while visualizing the opening and closing of a perfect lotus in their stomach. The meditation session lasted about 1 h. The sampling rate was 360 Hz. Analysis was performed offline and meditations' beginning and ending times were determined with event marks. Each original data file in ASCII format is presented as a two-column array (time vs. duration, in hundredths of second, of R-R intervals). The first 30mins of the recording (about 20,000 data points), were saved for further analysis. For standard presentation, R-R intervals were expressed in milliseconds.

Signal Analysis

For signal processing, we used the Kubios HRV 2.2 analysis software,[14] developed by Biosignal Analysis and Medical Imaging Group (BSAMIG)), at the Department of Applied Physics, University of Eastern Finland, Kuopio, and freely available at http://kubios.uef.fi. Before processing, data were corrected with a 3rd order detrending algorithm in the software.

Indices used Time Domain Indices

pNN50*.* The percentage of differences between successive R-R intervals over the recording time that are longer than 50ms. It has been proposed that pNN50 reflects alterations in autonomic function that are primarily vagally mediated.

Triangular Index*.* The integral of the density distribution. Triangular index expresses overall HRV and is more influenced by the lower than by the higher frequencies.

RMSSD. The square root of the mean squared differences of successive R-R intervals. RMSSD is related to high-frequency variations in heart rate and is often interpreted as an estimate of parasympathetic regulation of the heart. RMSSD is measured in milliseconds.

Frequency Domain Indices

Total Power. An estimate of the total power of power spectral density in the range of frequencies between 0 and 0.5 Hz. This measure is sometimes interpreted as overall autonomic activity where sympathetic activity is a primary contributor. Total Power is calculated in milliseconds squared (ms2). Mathematically it is identical to the standard deviation of RR intervals (SDNN).

Very Low Frequency (VLF). Corresponds to the integral of power spectrum in a frequency band from 0.00 to 0.04 Hz. Generally it is agreed that this parameter reflects overall activity of various slow mechanisms of sympathetic function. At the same time, it is associated with some purportedly nonlinear processes, given its fractal-like '1/f' behavior. Very Low Frequency band is calculated in milliseconds squared (ms^2).

Low Frequency (LF). A band of power spectrum range between 0.04 and 0.15 Hz. This measure is confirmed by both sympathetic and parasympathetic influences, but generally it is regarded as an indicator of sympathetic activity. Parasympathetic influence is represented by LF when respiration rate is lower than 7 breaths per minute or during taking a deep breath. Accordingly, when subject is in the state of relaxation with a slow and even breathing, the LF values can be very high indicating increased parasympathetic activity rather than increase of sympathetic regulation.[15,16] Low Frequency band is calculated in milliseconds squared (ms^2).

High Frequency (HF). A band of power spectrum range between 0.15 and 0.5Hz usually associated to parasympathetic (vagal) activity. HF is also known as a 'respiratory' band because it corresponds to the RR variations caused by respiration (respiratory sinus arrhythmia (RSA)). Heart rate is increased during inhalation and dropped during exhalation. High Frequency band is calculated in milliseconds squared (ms^2).

LF/HF ratio. The ratio between the power of Low Frequency and High Frequency bands. This measure could indicate overall balance between sympathetic and parasympathetic systems. Higher values reflect domination of the sympathetic system, while lower ones -domination of the parasympathetic system. This ratio can be used to help quantify the overall balance between the sympathetic and parasympathetic systems. This measure minimizes an effect of changes in Very Low Frequency power and emphasizes changes in sympathetic regulation. Normalized LF is calculated in percentile units. Recent research stresses the serious limitations of LF/HF as a synonym of Sympatho-vagal balance.[7]

Nonlinear Indices

$\alpha 1$ and α 2. DFA indices were obtained from linear fits to log-log plots of F (n) versus n in the range $4 < n < 16$ for α 1 and the range $16 < n < 64$ for $\alpha 2$

Hurst Exponent (H).Closely related to α 2, H quantifies the loss of order in the R-R sequence. H indicates whether an increase in the value of a measure taken now is likely to be followed by an increase or a decrease in that measure taken later. When H = 0.5, the measurements are not correlated. When H > 0.5, the measurements are positively correlated. This is called persistence. An increase now is more likely followed by an increase at all-time scales later. When H < 0.5, the measurements are negatively correlated. This is called anti- persistence. Parameter α 2 from DFA is directly related to the self-similarity scaling Hurst exponent.[17]

Recurrent Plot Analysis (RPA*).*The following indices were computed: Recurrence rate, Percent of determinism and Shannon entropy.[18]

SD1 and SD2*.*Derived from Poincare plot were estimated*.* The Poincare Plot Analysis (PPA) is a quantitative visual technique, whereby the shape of the plot is categorized into functional classes and provides detailed beat-to-beat information on the behavior of the heart. Usually, Poincare plots are applied for a two-dimensional graphical and quantitative representation (scatter plots), where n^{th} R-R interval ($R\text{-}R_n$) is plotted against the following one ($R\text{-}R_{n+1}$). Generally, three indices are calculated from Poincare plots: the standard deviation of the short-term R-R interval variability (minor axis of the cloud, SD1), the standard deviation of the long-term R-Rinterval variability (major axis of the cloud, SD2) and the axes ratio (SD1/SD2). For the healthy heart, the PPA graph shows a cigar-shaped cloud of points oriented along the line of identity. These indices are mathematically identical to certain combinations of time domain indices. At the same time, Laitio et al[19] showed that an increased SD1/SD2 ratio was the most powerful predictor of post-operative ischemia.

Correlation Dimension (D2) and Approximate Entropy (ApEnt). Correlation dimension is a theoretically sound concept for low-dimensional deterministic chaotic systems. Since HRV can be viewed as a fractal motion with uncorrelated noise plus periodic perturbances, correlation dimension values in HRV studies cannot be taken at face value. ApEnt is a measure that quantifies the amount of overall regularity or predictability in time-series data. Lower ApEnt values indicate a more regular signal; higher values indicate more irregularity at the same time theoretical studies revealed that Fractal dimension and entropy exhibit a negative correlation.[20]

Details about computation algorithms for each index are described in the Kubios technical manual.[20]

Statistical processing

For comparing effects induced by meditation, paired t-test was applied; correlation coefficients were also obtained for assessing between different HRV indices.

RESULTS

Comparison of pre-meditation and meditation recordings revealed that significant changes were observed in nine of the seventeen indices explored ($p<0.05$, paired t-test, table 1)

Table 1. Indices showing significant differences between pre-mediation and meditation ($p<0.05$)

Test Type	MeanPre-Meditation	Standard Deviation Pre-Meditation	Mean Meditation	Standard Deviation Meditation	Paired t-test
pNN50	16.56	8.57	13.70	9.07	0.01
LF	1012.37	417.40	2692.00	1976.56	0.02
VLF	5109.25	3862.37	1453.00	908.16	0.02
LF/HF	2.42	1.0721	10.0321	7.8920	0.03
α 1	1.21	0.16	1.48	0.29	0.003
α 2	1.023	0.149	0.691	0.211	0.012
Recurrence Rate	39.770	5.470	32.799	2.287	0.005
Shannon Entropy	3.607	0.335	3.260	0.123	0.010
D2	3.469	0.730	3.007	0.568	0.04

As it can be noticed, significant changes were found in 5 nonlinear measures, (α 1, α 2, Recurrence Rate, Shannon entropy and correlation dimension (D2)).

Correlation between variables, of the 9 variables that changed significantly with meditation, five of them exhibited significant correlations with others. In table 2 there were included those indices that changed significantly with meditation, as well as those that exhibited significant correlation to other indices.

Table 2. Correlations between relevant HRV indices. Only significant values ($p<0.05$) are shown

	VLF	α 2	Recurrence Rate	Shannon Entropy	LF/HF	α 1
VLF	-	0.75	0.90	0.88		
α 2		-	0.78			
Recurrence Rate			-	0.95		
Shannon Entropy				-		
LF/HF					-	0.85
α 1						-

DISCUSSION

For the sake of reproducibility, it seems plausible to apply a publicly available software to the study of a publicly available dataset. Also, the comparison of the two conditions with a broad assortment of time-domain frequency domain and nonlinear indices seems advisable and, considering today's computer and software capabilities, easy to perform. Perhaps one of the major drawbacks of the majority of published reports on HRV is that they are centered on the estimation of a few indices.

We obtained that among *chi* meditation beginners, this condition induces changes in 9 indices, five of them belonging to "nonlinear analysis" category.

A relevant question pertains to the reliability of obtained results, considering that artifacts can arise either from software hitches or data quality issues. Mounting evidence indicates that previous commonly accepted assertions as "LF/HF being associated to sympatho-vagal balance" and "pNN50 associated to parasympathetic activity " cannot be taken as true in all cases.

Hoshiyama and Hoshiyama[12] compared HRV indices from meditating beginning and trained Zen practitioners. Comparison of trained vs. beginners obtained by these authors parallels the results of comparing premeditation and *chi* meditation results obtained from present study. Similar to our results, trained Zen meditators exhibited increased LF, whereas pNN50, VLH, and α 2 were reduced.[12] No contradicting results were found among both studies. We interpret the outcome of this comparison as a support for consistency of these two meditation techniques as well as a confirmation of the adequacy of Kubios HRV as a tool for assessing HRV.

Interpretation of our results can be made through comparison with pathology and health-seeking actions associated changes, as well as in light of present knowledge about physiological bases of these indices.

Thus, unlike meditation, pNN50 is increased among trained skiers and reduced among diabetes patients; otherwise, and similar to meditation, LF/HF is increased during stress combating actions as well as among athletes.[22] LF is increased in stress reduction maneuvers and among vigorous exercise practitioners, while reduced in diabetes, poor diet, low job control, among smokers, among high alcohol consumers and in old age, in presence of image-confirmed cardiac sympathetic denervation as well as experimentally induced congestive heart failure in dogs.

Contrary to observedchanges with meditation, Shannon entropy is increased among elderly healthy persons[8] and exhibit increases linearly associated to blood glucose levels.[18]

Similar to the effect of meditation, VLF is decreased among the elderly, whereas it is increased among patients suffering from obstructive sleep apnea. DFA index α 1, contrary to meditation, is reduced in elderly persons, as well as in diabetes mellitus and atrial fibrillation whereas α 2 is increased with age.

Recurrence rate, oppose to meditation, is increased among the elderly.[8] Finally, similar to meditation, but contrary to expected, is reduced after cardiac transplant and is slowly recovered with tears after transplant.[23]

Taken together, these comparison suggests that meditation seems to bring cardiovascular system away from changes associated to different pathological conditions

A fundamental question looms regarding physiological interpretation of our results. Thus, for example, Peng et al,[13] working with this dataset remarked that observed changes in LF are greatly influenced by the respiration component associated to *chi* meditation.[13] This could also be true for α1, given the observed high correlation with LF/HF (see equation 1 above) as well as the observed excellent correlation we found between α1 and the theoretically predicted ratio using this data set.

$$(\alpha\ 1_{predicted}=1.12*\alpha\ 1_{observed},\ r=0.94)$$

The pNN50 index, despite its widespreaduse and proven predictive capacity, can be flawed when HRV is very high, as in the case of *chi* meditation. Accordingly, in present study's context, suggestions about associated physiological changes can be misleading (24Garcia and Pallas 2001).

Nonlinear measures are worthy of special mention, taking into account that nonlinear indices performed nicely in discriminating between pre- and meditation states. Literature suggests that indices such as power law spectral slope beta (positively correlated to α 2), α 1 and recurrent plot analysis indices exhibit the higher discrimination power in a group of conditions.[8]

Even when nonlinear indices are recognized to perform better, whether this is due to technical aspects or reflect processes that are inherent to nonlinear dynamical systems and/or fractal time series remains an open question.

Thus the better performance of nonlinear indices has been attributed to the potential of capturing non-periodic aspects of heart rate generation,[8] as well as to their capability of excluding respiration-related influences.[12] After showing that DFA indices may be derived from the power spectrum, provide the following physiological interpretation of them: "We can now understand fractal manifestations of physiological abnormalities: depressed baroreflex sensitivity implies low LF/HF which implies low LF/(HF + LF) resultingin low α 1 , while periodic breathing implies high VLF/LF which implies high VLF/(LF + VLF) resulting in high α 2. Prognostic associations of alpha are no longer mysterious.".[10] Nevertheless, we consider that at least a part of HRV is associated to scale-invariant nonlinear phenomena intervening in cardiac rhythm conformation.

As is known, the HRV series is not a pure fractal. DFA analysis woks properly for pure fractals, not for signals with non-fractal components. However, there are indications that DFA analysis is quite robust respect to the presence of non-fractal influences.[25]

The presence of long term correlations (as indicated by α 2) is regarded as a hallmark of self-organized criticality.

As Riley and Van Orden[17] state, "Self-organization implies global emergence. Global emergence is collective behavior that depends on the interdependence among a system's parts. Interdependence implies that each part may reflect something of the behavior of the whole; the behavior of the whole is present, in some sense, in each of its parts". In heart rhythm regulation, self-organized behavior has been found at different spatial and time scales, including ion channels, calcium release mechanisms, isolated hearts, and innervated hearts. Heart rate has shown scale independence fat second, minute, hour and circadian time scales.

Thus taken together, this study suggests that *chi* meditation leads to a reduction in long-range correlation, a reduction in entropy and a reduction in correlation dimension. These changes are in the opposite direction to those observed in a group of pathological conditions, suggesting a beneficial effect on cardiovascular dynamics.

CONCLUSION

We would answer the above-posed questions as follows.

I. Power spectrum low frequency component (LF), LF/HF ratio, and the nonlinear indices α 1and α 2, recurrence rate and Shannon Entropy are the most information-carrying indices. Due to well-known limitations as well as due to incongruences with literature reported changes, pNN50 and D2 areincluded into the list.

II. Observed changes with above-mentioned indices suggest that they harmonize with changes observed in other health- pursuing circumstances as physical training, stress combating strategies; whereas they are in the opposite direction of old age, poor job management, heavy smoking, diabetes, blood glucose levels, autonomic denervation of the heart, congestive heart failure. Thus meditation induced changes "drive" the human body away from disease/deterioration associated changes, and, accordingly, they are mainly beneficial. The question of sustainability of these changes cannot be assessed from this dataset.

III. Observed changes seem to be associated to an increase in respiratory influences around F=0.04 Hz, a reduction in system's entropy and a reduction in the strength of long-term correlation with a concomitant increase in cardio vascular system's complexity.

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