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Physiological Effects of Bioceramic Material: Harvard Step, Resting Metabolic Rate and Treadmill Running Assessments

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Abstract

Previous biomolecular and animal studies have shown that a room-temperature far-infrared-ray-emitting ceramic material (bioceramic) demonstrates physical-biological effects, including the normalization of psychologically induced stress-conditioned elevated heart rate in animals. In this clinical study, the Harvard step test, the resting metabolic rate (RMR) assessment and the treadmill running test were conducted to evaluate possible physiological effects of the bioceramic material in human patients. The analysis of heart rate variability (HRV) during the Harvard step test indicated that the bioceramic material significantly increased the high-frequency (HF) power spectrum. In addition, the results of RMR analysis suggest that the bioceramic material reduced oxygen consumption (VO_2). Our results demonstrate that the bioceramic material has the tendency to stimulate parasympathetic responses, which may reduce resting energy expenditure and improve cardiorespiratory recovery following exercise.

Key Words: bioceramic, Harvard step test, oxygen consumption, parasympathetic, resting metabolic rate (RMR)

Introduction

The autonomic nervous system is typically divided into 2 branches: the sympathetic and the parasympathetic nervous systems. The two systems tend to balance each other, offering opposite and yet complementary effects reflective of the Chinese philosophy of Yin and Yang (30). The sympathetic nervous system manages responses to stress and danger, releasing adrenaline that stimulates *fight-or-flight* responses that are characterized by increases in heart rate, metabolic rate and O_2 consumption (VO_2). The parasympathetic nervous system is responsible for the stimulation of *rest-and-digest* or *feed-and-breed* activities that occur when the body is at rest, including vagal tone, increased gastrointestinal activity and the stimulation of reproductive processes. Proper functioning of the sympathetic and parasympathetic systems is necessary for an overall physiological balance (1, 30).

As a reliable noninvasive measure of autonomic-nervous-system function and an indicator of the

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neurological-cardiac-health condition of living animals, the application of heart rate variability (HRV) is a measure of the beat-to-beat changes in the heart rate. Because HRV varies with age, gender and health conditions, HRV analysis has become widely used for assessing perturbations of autonomic responses and other conditions, such as panic disorder and chronic fatigue.

Whole-body VO_2 is another measurement that is used for assessing autonomic function. VO_2 values reflect the cellular respiration rate in the various metabolically active organs of a living animal. The processes involved in the supply of O_2 and its consumption at the cellular level are usually driven by the respiratory and cardiac systems, which are regulated by parasympathetic and sympathetic stimuli through the autonomic nervous system (9, 34).

Bioceramic material is a type of ceramic solid that emits high-energy far-infrared (FIR) rays. In our previous studies, bioceramic irradiation provided a non-thermal support without external electrical support to promote physical-biological effects, such as increased microcirculation (28) and upregulation of calcium-dependent nitric oxide (NO) and calmodulin in different cell lines (17, 21). Our prior investigations have also demonstrated that bioceramic irradiation promotes NO enhancement through a calcium-dependent NO synthetase-mediated mechanism (17, 21). The antioxidant effects of bioceramic irradiation include the stimulation of hydrogen peroxide scavenging in murine macrophages (RAW264.7) (22), murine calvaria-derived MC3T3-E1 osteoblast-like cells (14, 24), NIH3T3 fibroblasts (24) and murine C2C12 myoblasts (18) in the cell culture. Bioceramic irradiation produces significant *in vivo* decreases in the heart rates of stress-conditioned rats and in isolated frog hearts with or without adrenaline-induced stress. Bioceramic may also affect calcium ion movement, which influences central nervous system (CNS) regulation of the cardiovascular and endocrine organ systems and alters cardiovascular hemodynamic parameters (15). Based on the results of animal studies, bioceramic materials may be beneficial for normalizing the psychologically induced stress-conditioned elevated heart rate and oxidative stress-suppressed cardiac contractility (15).

In our current study, we evaluated the physiological effects of bioceramic material on parasympathetic or sympathetic regulation in participants during exercise using the Harvard step test (HST), the resting metabolic rate (RMR) assessment and the treadmill running test (TRT).

Materials and Methods

Study Participants

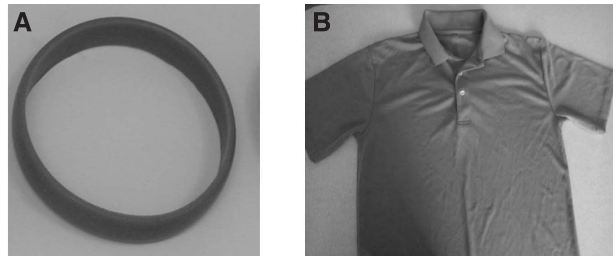

Fig. 1. (A) A bioceramic silicon rubber bracelet and (B) a bioceramic shirt.

Participants were recruited for our study through posted advertisements. Our study was approved by the Ethics Committee of Taipei Medical University Hospital with certification by the Institutional Review Board (approval no. 201105006). Twenty-six men and 5 women (ages 18 to 22 years) were enrolled in 3 independent clinical trials. All participants provided a signed consent document before participation in the experiments.

Bioceramic Material

The bioceramic material (obtained from the Department of Radiology, Taipei Medical University Hospital, Taipei) that was used in our study was composed of micro-sized particles produced from several ingredients, mainly different elemental components. The average emissivity of the ceramic powder was determined to be 0.98 at wavelengths of 6 to 14 μm using a CI SR5000 spectroradiometer, indicating an extremely high ratio of FIR intensity. Two types of bioceramic devices were used in this study, including a silicon rubber bracelet containing bioceramic powder (YY Rubber company, Foshan, PRC; Fig. 1A) and a shirt (Fig. 1B) made of polyester with bioceramic powder (Grand Textile Corporation, New Taipei City, Taiwan). The bioceramic devices underwent specific physical-chemical tests at room temperature in the laboratory of the Radiology Department of Taipei Medical University Hospital to ensure FIR ray-emitting functions (13-26, 28).

HST on HRV

The HST is a convenient and widely used method for evaluating cardiopulmonary functions. The participant is asked to step up and down on a 45-cm-high platform at a rate of 30 steps/min for 5 min or until exhaustion. The HRV represents the change in heart rate in response to the physiological states induced during the exercise and resting periods, and can be used to assess the activity of the autonomic nervous system through quantification of sinus rhythm variability. The sinus rhythm time series is derived from the RR interval sequence of the electrocardiogram (ECG) by extracting only the NN intervals.

Relatively high-frequency variations in sinus rhythm reflect parasympathetic (vagal) modulation, and slower variations result from a combination of parasympathetic, sympathetic and non-autonomic regulatory factors. Standard spectral analysis was applied on a 5-min interval for both high frequency (HF) and low frequency (LF) to provide indices of autonomic function. The HF power spectrum was evaluated from 0.15 to 0.4 Hz to assess the parasympathetic (vagal) tone and fluctuations caused by respiratory sinus arrhythmia. The LF power spectrum was evaluated from 0.04 to 0.15 Hz to assess both the sympathetic and parasympathetic tone.

Eight non-athletes and 8 junior-college athletes were recruited for the HST analysis. HSTs were conducted using a random-crossover and double-blind design in which the participants were assigned to either the control group (wearing a control bracelet on one wrist) or the experiment group (wearing a bioceramic bracelet on one wrist). Each participant's HRV was assessed 5 min before, during and after HST.

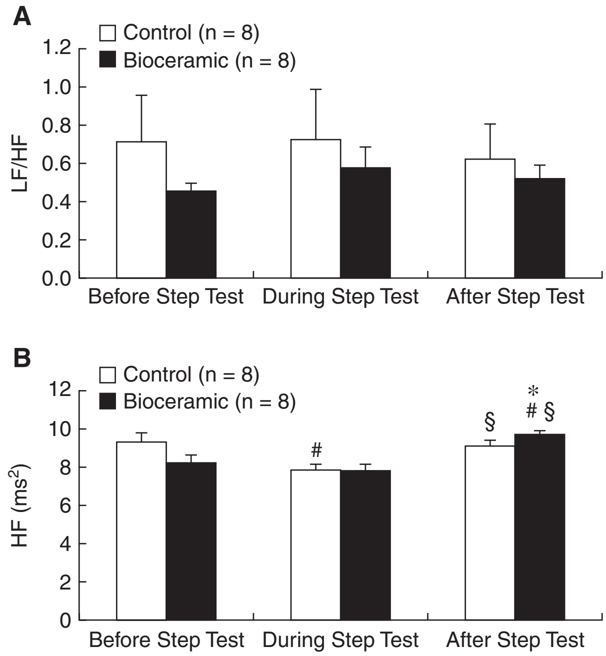

Fig. 2. HST analysis of HRV in non-athletes for (A) the sympathetic response and (B) the parasympathetic response. *Represent significant difference from control. #Represent significant difference from before step test. §Represent significant difference from during step test.

Whole-Body VO_2 and Resting Metabolic Rate (RMR) Assessments

The RMR assessment quantifies resting energy expenditure, which represents the minimum amount of energy required to maintain homeostasis at rest, including cardiovascular and respiratory functions and thermal regulation. Ten non-athlete participants wore the control or bioceramic shirts during the RMR assessment during two 24-h periods using a randomized double-blind cross-over design. All assessments were performed from 8:00 AM to 10:00 AM after a 12-h fasting period and a minimum of 8 h of sleep. Strenuous exercise was avoided at least 12 h before testing. The bioceramic shirt was worn for 10 min before RMR was assessed at 23°C using a MetaMax 3B portable indirect calorimeter (Cortex, Leipzig, Germany) in a supine position for 10 min. The calorimeter measurements were used to determine VO_2.

Treadmill Running Test (TRT)

For TRT, 5 non-athlete participants wore a control or a bioceramic shirt while running at a steady velocity of 6 km/h on a 6300HR motorized treadmill (Sportsart Fitness, Tainan, Taiwan, R.O.C.) with 2% inclination for 30 min on 2 separate days using a randomized double-blind cross-over design (4, 5). All assessments were performed from 8:00 AM to 10:00 AM after a 12-h fasting period and a minimum of 8 h of sleep. Strenuous exercise was avoided at least 12 h before testing. Tiredness, skin temperature, respiration rate and heart rate were recorded every 3 min using a BioHarness (BIOPAC Systems, Goleta, CA, USA). The BioHarness monitors, analyzes, and records various physiological parameters including ECG, respiration, temperature, posture and acceleration. Tiredness was measured using a 7- to 20-point scale, with 7 indicating no tiredness and 20 indicating complete exhaustion.

Statistical Analysis

The difference of sympathetic or parasympathetic activation at three different periods within group was compared by one-way ANOVA. A paired *t*-test was used to evaluate significant differences between the results of the experimental and control groups using the SPSS computer software (IBM, Chicago, IL, USA). The results of comparisons with a P value less than 0.05 were considered statistically significant.

Results

HRV from the HST

For the non-athletes, the results of the HST indicated that there were no significant differences in sympathetic response between control and bioceramic groups before, during or after the step test (Fig. 2A).

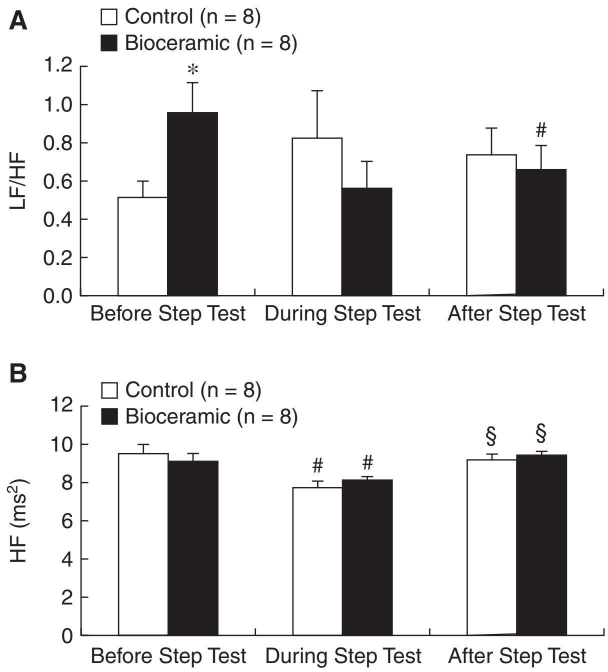

Fig. 3. HST analysis of HRV in athletes for (A) the sympathetic response and (B) the parasympathetic response. *Represent significant difference from control. #Represent significant difference from before step test. §Represent significant difference from during step test.

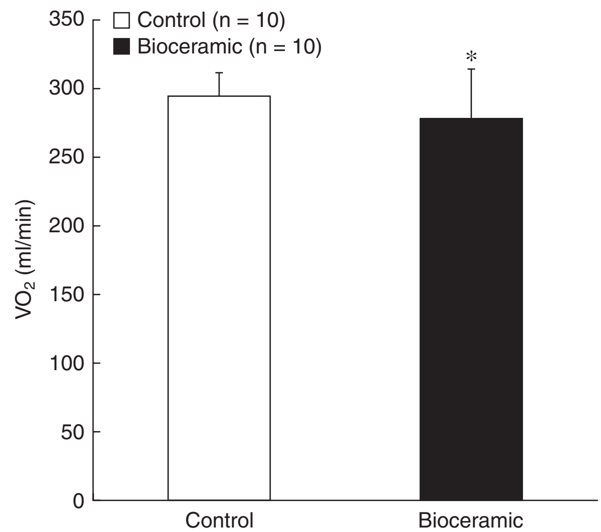

Fig. 4. VO_2 analysis based on the resting metabolic rate. Results showed that, during a 10-min period, the average VO_2 of the control group was significant higher than that of the bioceramic group. Asterisks (*) indicates significant difference.

Likewise, there were no significant differences in the HRT results among the participants of either the control or the experimental group. There was, however, a tendency toward decreased sympathetic stimulation before (38.7%), during (21.3%) and after the step test (19.4%) in the bioceramic group, compared with the results of the control group. A greater parasympathetic stimulation in the bioceramic group than in the control group after the step test was observed, and parasympathetic activation in the bioceramic group was significantly higher after the step test than in the periods before and during the step test (Fig. 2B).

In the athletes, the bioceramic group displayed significantly higher sympathetic activation than the control group during the period before the step test (Fig. 3A). A significantly lower sympathetic response was observed in the bioceramic group after the step test compared with their results taken before the step test. For athletes in both groups, the parasympathetic response decreased significantly during the step test, and the HF/LF ratios returned to levels that were similar to those observed before the test (Fig. 3B). There were no significant differences in parasympathetic response between the athletes in the control and bioceramic groups during 3 separate assessments.

Whole-Body VO_2 and RMR Assessments

The average VO_2 in the control and bioceramic groups was measured for 10 min after a 10-min steady-state period. Average VO_2 in the control group was higher than that in the bioceramic group based on a one-tailed paired *t*-test ($P < 0.05$; Fig. 4), but not on a two-tailed test ($P = 0.098$). Therefore, VO_2 measurements were divided into period sections for a refined analysis of the differences between the 2 groups. Average VO_2 during the first 3 to 5 min of testing was significantly lower ($P < 0.05$) in the bioceramic group (VO_2: 296 ± 25.93 ml/min) than in the control group (VO_2: 264 ± 42.10 ml/min). Calculations of the RMR of participants based on the average 10-min VO_2 showed that the RMRs of the control and bioceramic groups were 0.0216 kcal/kg/min and 0.0203 kcal/kg/min, respectively.

Treadmill Running Test

The results of the TRTs showed that there were tendencies toward decreased tiredness and reduced skin temperature in the bioceramic group compared with those of the control group (Fig. 5, A and B). The respiration and heart rates were relatively more stable in the bioceramic group than in the control group (Fig. 5, C and D).

Discussion

Measurements of HRV have been particularly useful in assessing parasympathetic activity, sympathetic function and overall sympatho-vagal balance

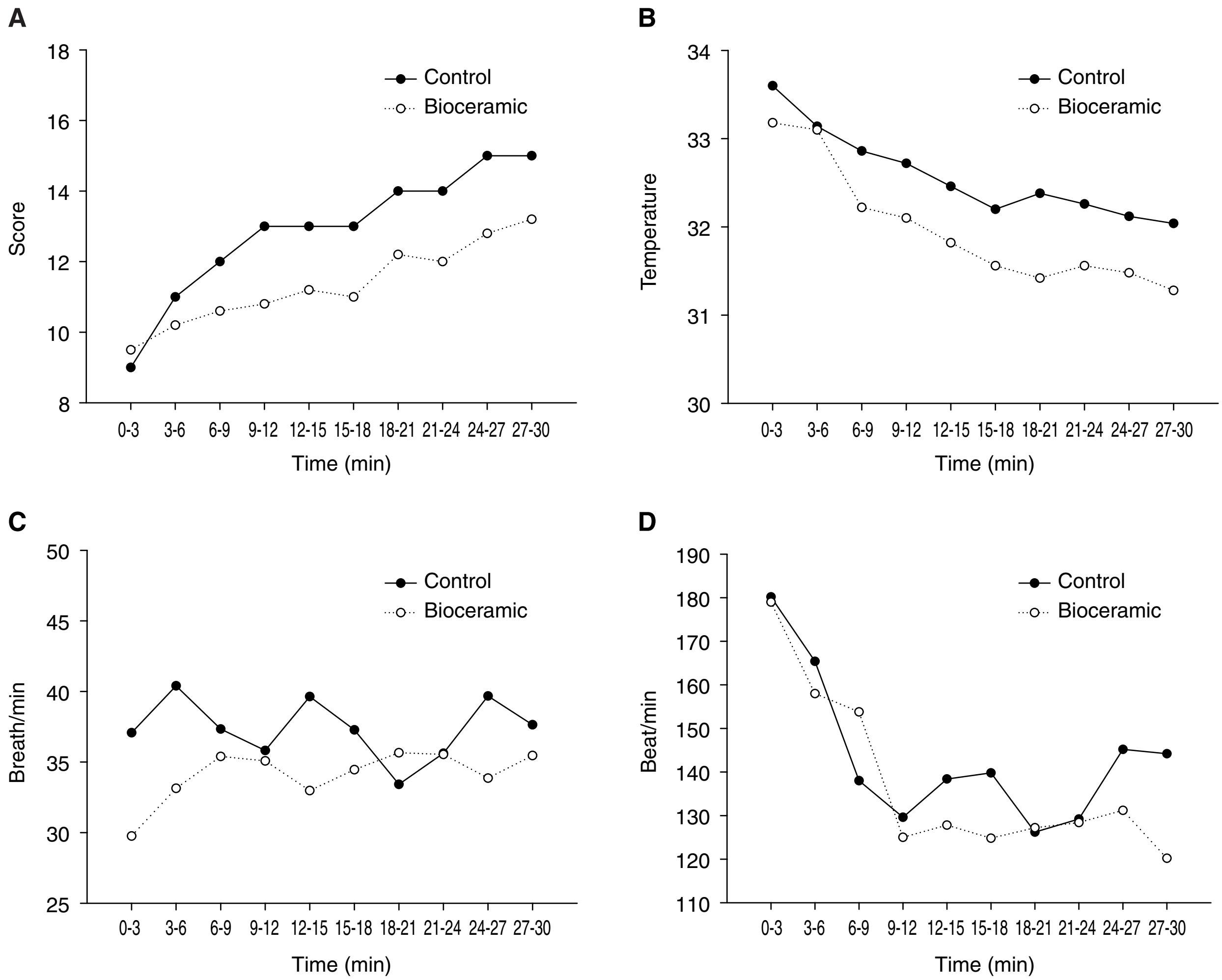

Fig. 5. Treadmill running test assessed using the BioHarness for (A) tiredness, (B) skin temperature, (C) respiration rate and (D) heart rate.

(32). HRV and parasympathetic power are closely related to well-being and health status in humans (6). Heart rate recovery after exercise represents the changes in autonomic tone that occur immediately following cessation of exercise. Recovery is characterized by parasympathetic activation followed by sympathetic withdrawal (32).

Generated by multiple factors, HRV is not exclusively limited to the effects of the autonomic nervous system. Simple statistical analyses of HRV, such as the standard deviation of R-R intervals in an ECG, can reliably assess a patient's health condition and serve as a predictor for prognosis in cardiovascular diseases (33). Because HRV conveys additional prognostic information, it is more useful than recording heart rate alone for the assessment of autonomic control of the heart rate, and HRV assessment of vagal tone has also been shown to have prognostic value (12).

Studies related spectral analysis of HRV during exercise indicated that parasympathetic and sympathetic indicators returned to pre-exercise levels by 15 min after exercise ceased (2) but the phenomenon after 30 min of intense treadmill running was suppressed up to 1 h (7). Other studies showed that parasympathetic nerve activation decreased during light or moderate exercise (31, 37). Out HST results are consistent with the above reported results. In this study, parts of parasympathetic and sympathetic indicators did not have enough time to return to baseline, because HRV was only assessed 5 min after exercise.

According to the results of HRV by HST presented in Figs. 2 and 3, we found that the effects of parasympathetic nerve activation by wearing a bioceramic bracelet for nonathletes were significantly better than those for athletes. Therefore, we infer that athletes may have more benefits of parasympathetic nerve activation from training than the effects from the bioceramic bracelet.

The decrease in VO_2 based on RMR assessments of the bioceramic group demonstrated negative effects on the sympathetic response and positive effects on the parasympathetic response. Physiological ageing is associated with a reduction in parasympathetic control of the heart, and this decline in parasympathetic activity can be reduced by endurance exercise (3). Endurance training has been shown to increase parasympathetic activity and reduce sympathetic activity at rest (3). The RMR in the control group (2, 117 kcal/d) was higher than that of the bioceramic group (1,997 kcal/d), suggesting a decrease in energy expenditure that is similar to the RMRs observed in athletes. The results of the TRTs indicated that the bioceramic shirt may reduce tiredness and skin temperature and stabilize respiration and heart rate, all of which reflect parasympathetic control (8, 10, 29, 35).

Previous researches have indicated individual differences, and a tendency toward increased parasympathetic and decreased sympathetic control of heart rate has been reported in women (3). Long-term endurance training also lowers exercise heart rate by reducing sympathetic stimulation (3). The ease with which the bioceramic material can be used to create platforms for conveniently providing physical-biological effects, such as silicon bracelets and shirts, ensures that more applications for balancing the autonomic nervous system in human participants are possible. The results of our study also suggest that bioceramic material may be used to provide the so-called HRV biofeedback, a technique for training people to change the variability and dominant rhythms of their heart activity. The use of HRV biofeedback began in Russia (11), and it has been applied to the treatment of various medical and psychiatric conditions, including anger, anxiety disorders, asthma, cardiovascular conditions, chronic obstructive pulmonary disorder, irritable bowel syndrome, chronic fatigue and chronic pain (27, 36).

Based on the three individual experiments of HRV assessment, RMR analysis of VO_2, and the TRT, the use of bioceramic material in non-athlete cohort showed that it had a tendency to activate parasympathetic responses in resting or after exercise, reduce resting metabolic rate, even have possible tendency to decrease skin temperature or tiredness during sustained exercise. Consequently, the bioceramic material may also help reduce resting energy expenditure and improve cardiorespiratory recovery following exercise by stimulating parasympathetic responses.

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