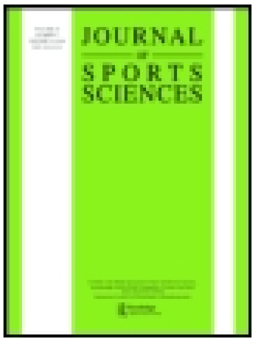


Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: http://www.tandfonline.com/loi/rjsp20

Cardiodynamicsgram: a novel tool for monitoring cardiac function in exercise training

Xu Wen, Bokai Guo, Yinglan Gong, Ling Xia & Jie Yu

JOURNAL OF SPORTS SCIENCES, 2018
https://doi.org/10.1080/02640414.2018.1470070

Cardiodynamicsgram: a novel tool for monitoring cardiac function in exercise training

Xu Wen[a], Bokai Guo[a], Yinglan Gong[b], Ling Xia[b] and Jie Yu[c]

[a]Department of Sports Science, College of Education, Zhejiang University, Hangzhou, P. R. China; [b]College of Biomedical Engineering & Instrument Science, Zhejiang University, Hangzhou, P. R. China; [c]Sports Science Research Center, Zhejiang College of Sports, Hangzhou, P. R. China

ABSTRACT

This study evaluated the feasibility of cardiodynamicsgram (CDG) for monitoring the cardiac functions of athletes and exercisers. CDG could provide an effective, simple, and economical tool for exercise training. Seventeen middle-distance race athletes aged 14–28 years old were recruited. CDG tests and blood test including creatine kinase (CK), CK-MB isoenzyme, and high-sensitivity troponin I (hsTnI) were performed before a high-intensity prolonged training, as well as 2 and 14 h after training, respectively. The CDG test result was unsatisfactory when the CK test result was used as standard. However, the accuracy of CDG test was about 80% when CK-MB and hsTnI were used as standards. Thus, CDG offers a noninvasive, simple, and economical approach for monitoring the cardiac function of athletes and exercisers during exercise training. Nonetheless, the applicability of CDG needs further investigation.

ARTICLE HISTORY
Accepted 22 April 2018

KEYWORDS
Cardiodynamicsgram; exercise training; monitoring; cardiac function

Introduction

Since Morris and his colleagues found that the risk of double-decker bus driver suffering from cardiovascular diseases was higher than that of the conductor in the 1950s (Morris, Heady, Raffle, Roberts, & Parks, 1953), many studies have shown that regular and moderate physical activity could help improve heart function and reduce the incidence of coronary heart disease (Lee, Rexrode, Cook, Manson, & Buring, 2001; Swift et al., 2013; Tanasescu et al., 2002). However, the prolonged, high-intensity exercise may also increase the risks of acute myocardial infarction (AMI) and sudden cardiac death (SCD) (Giri et al., 1999; Mittleman et al., 1993). In recent years, many scholars are also appealing to address the negative effects of high-intensity exercise on the heart (Merghani, Malhotra, & Sharma, 2015; Sharma, Merghani, & Mont, 2015). The joint scientific statement by the American College of Sports Medicine and the American Heart Association also pointed out that preparticipation screening for cardiovascular abnormalities is important to avoid sudden cardiac death (Thompson et al., 2007). However, simple and effective mean of risk assessment was absent.

On the other hand, several physiological and biochemical indicators are used to monitor exercise training, to help adjust the training program, to improve exercise performance, and to prevent exercise injury (Banfi, Colombini, Lombardi, & Lubkowska, 2012). For example, creatine kinase (CK), as an indicator of muscle fiber damage, is widely used to monitor muscle performance and exercise training recovery (Baird, Graham, Baker, & Bickerstaff, 2012; Banfi et al., 2012). CK-MB, troponin (cTn), and high-sensitivity cTn I (hsTnI) are common biomarkers to detect myocardial cell damage and diagnose acute coronary syndromes (Keller et al., 2011; Schneider, Dennehy, Rodearmel, & Hayward, 1995; Thygesen, Alpert, Jaffe, Simoons, & Chaitman, 2012). A study showed that cTn significantly increase in healthy individuals after long-term, high-intensity exercise training (Shave et al., 2007). CK-MB and cTn have been used as indicators of heart function test in sports medicine. Although CK and cTns are sensitive and effective indicators, the test methods are invasive, complex, and expensive. Therefore, CK and cTns cannot be used frequently by sports teams.

In the past few years, electrocardiograph (ECG) technology has made some important progress (Sullivan, Xia, Mcbride, & Zhao, 2010; Xia, Garcia, Bains, Wortham, & Zhao, 2012). Among the innovative ECG techniques, a novel method called cardiodynamicsgram (CDG) has been applied for early screening of myocardial ischemia by using deterministic learning algorithm (Wang et al., 2016). This noninvasive method extracts subtle cardiodynamics information from the ST-T segments in standard 12-lead ECG and plots the extracted cardiodynamics information into three-dimensional graphics. A recent paper reported that, with "coronary angiogram" as the gold standard to evaluate coronary heart disease, the accuracy of CDG for the early detection of coronary heart disease was 84.6%, sensitivity of 84.7%, and specificity of 83.7% (Deng et al., 2017). Moreover, CDG is noninvasive, comfortable, and economical. Nonetheless, the application of CDG has not been investigated in monitoring the cardiac functions of athletes and exercise training.

This study evaluated the feasibility of CDG for monitoring the cardiac functions of athletes and exercisers using CK and cTn as the standards, in order to provide a simple, effective, noninvasive, and economical monitoring tool for sports training.

CONTACT Xu Wen wenxu@zju.edu.cn Department of Sports Science, College of Education, Zhejiang University, 148 Tianmushan Road, Hangzhou, Zhejiang Province 310028 P. R. China

Research methods

Participants

Seventeen middle-distance race athletes (14–28 years old) from Zhejiang province in China were recruited in this study. Basic information of athletes was shown in Table 1.

Testing process and indicators

The recruited athletes underwent a high-intensity, long-term training. The training included: (1) in situ preparation activities and joint warm-up activities, (2) warm-up running for 4–5 km, (3) warm-up exercise for 15 min, (4) intermittent training, and (5) jogging to relax the muscles. Four groups of high-intensity runners were tested with an interval of 10 min. For each group, six sets of 250 m run were performed, each set had to be completed within 42 s with an interval of 45 s between sets.

Blood analysis and CDG test were performed before a high-intensity, prolonged training (no training for at least 48 h), after a 2 h training, and in the next morning after a 14 h training. Peripheral venous blood (5 ml) was collected, stood for 15 min, and centrifuged for 10 min at 2800 r/min. The serum was separated, and then CK, CK-MB, and hsTnI levels were detected using an immunoassay analyzer (Beckman Access II, United States) and an automatic biochemical analyzer (Johnson VITROS-5600, United States). CK, CK-MB, and hsTnI levels higher than 300 U/L, 24 U/L, and 32.4 ng/L, respectively, were considered positive (Feng & Zhang, 2007).

CDG test

Twelve lead ECG data were gathered using a commercially available ECG (Aikang, AIKD-B12 V3.0, Changsha, China). The participants were in supine position. Talking, limb movement, and excessive breathing were forbidden. The ambient temperature was set to 22–25 °C to avoid muscle tremor and artifacts. Twenty seconds of ECG data were recorded for further analysis.

The CDG, which is the three-dimensional graphical representation of cardiodynamics information extracted from the ST-T segments of ECG, was generated through the dynamic pattern recognition. The modeling method was performed in three steps: (1) transformation of the 12-lead ECG signals to three-dimensional vectorcardiography (VCG) signals; (2) application of an extension of the deterministic learning algorithm model to the cardiodynamics of the transformed VCG; and (3) plotting of the cardiodynamics information in a three-dimensional XYZ coordinate system along the trajectories of the transformed VCG. The details have been reported in previous studies (Deng et al., 2017; Wang et al., 2016).

Informed consent for both ECG and blood test was obtained from all the participants before the test. The study was approved by the Ethics Committee of College of Education at Zhejiang University.

Table 1. Basic information of participants.

Age (y)	18.2 ± 3.1
Height(cm)	179.0 ± 3.2
Weight (kg)	59.1 ± 4.9
BMI (kg/m^2)	19.8 ± 1.2

Table 2. Changes of CK, CK-MB, and hsTnI before training and 2 and 14 h after training.

	Pre-training	2 h after training	14 h after training
CK	263.4 ± 178.2$^{*\#}$	395.5 ± 127.5*	410.7 ± 145.8$^{\#}$
CK-MB	9.8 ± 2.6*	16.7 ± 4.3$^{*\square}$	11.3 ± 3.1$^{\square}$
hsTnI	14.6 ± 11.2	45.6 ± 66.0	22.4 ± 35.9
Positive rate of CK	1 (5.9%)$^{*\#}$	9 (52.9%)*	9 (52.9%)$^{\#}$
Positive rate of CK-MB	0 (0%)	4 (23.5%)	1 (5.9%)
Positive rate of hsTnI	0 (0%)	4 (23.5%)	3 (17.6%)
Positive rate of CDG	1 (5.9%)	7 (41.2%)	5 (29.4%)

* indicates significant difference between pre-training and 2 h after training, $p < 0.05$; # indicates significant difference between pre-training and 14 h after training, $p < 0.05$; □ indicates significant difference between 2 h after training and 14 h after training, $p < 0.05$.

Data analysis

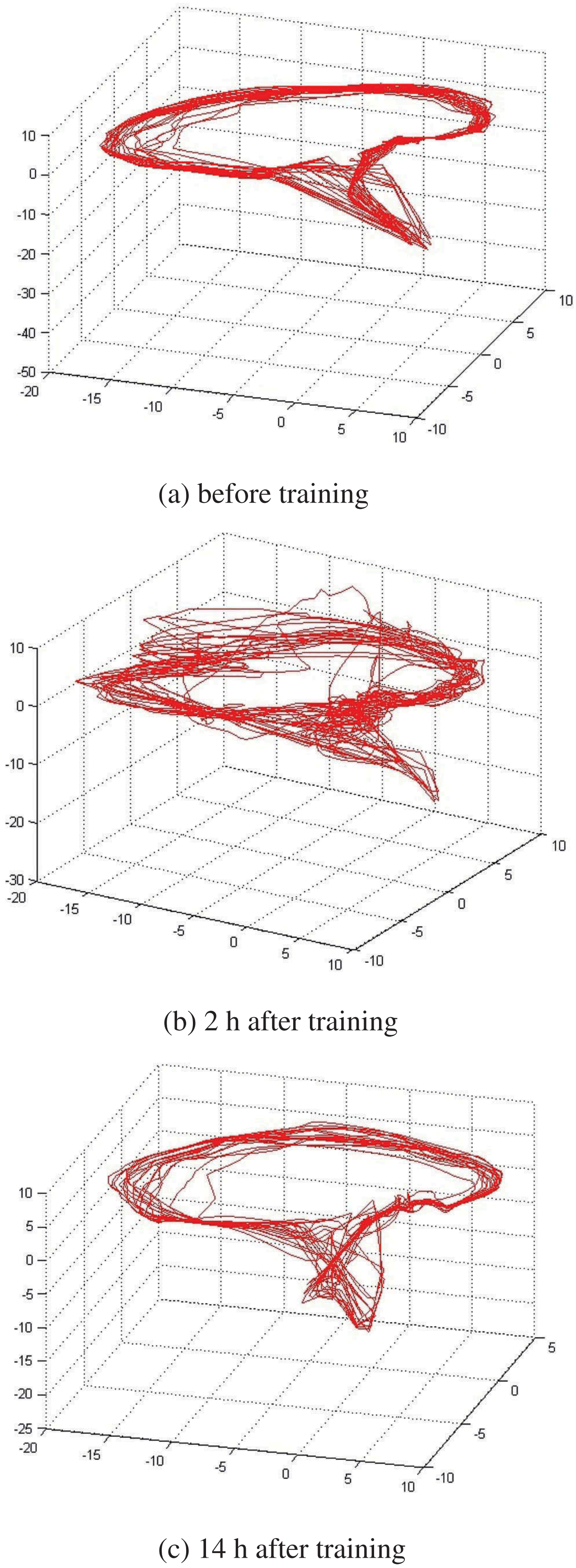
The CK, CK-MB, and hsTnI of the participants were compared using the repeated measure ANOVA between pre-training and 2 and 14 h after training. The accuracy, sensitivity, and specificity of CDG test were calculated using the test results of CK, CK-MB, and hsTnI as standards.

Results

After a high-intensity, long-term training, the athletes' CK level significantly increased (Table 2). Thereinto, the CK level was more than 300U/L in more than half of the participants after training for 2 h, which did not decrease after training for 14 h. CK-MB also increased after training for 2 h. However, after resting for 14 h, CK-MB showed a significant decline. The HsTnI also increased after training for 2 h and dropped after 14 h. However, no significant difference was observed in hsTnI before and after training.

By analyzing the CDG morphology, remarkable differences in shapes of CDG were found between pre-training (regular shapes) and post-training (irregular shapes). As shown in Figure 1, the CDG of a healthy male athlete aged 19 before training was negative with a regular shape. However, the CDG of 2 h after training was positive with an irregular shape. The CDG of 14 h after training returned to negative, but the shape remained slightly irregular when compared with the CDG obtained before the training. Only one participant was found positive in CDG test before training. CDG tests were positive in seven athletes after training for 2 h, accounting for 41.2% of the athletes. After training for 14 h, the CDG test was positive in five athletes, accounting for 29.4%.

The CDG test result was unsatisfactory when the CK test results were used as standard. The accuracy and specificity were 76.5% and 90.6%, respectively, but the sensitivity was only 52.6% (Table 3). However, the CDG test result was acceptable when using the CK-MB test result as the standard (Table 4). The accuracy, sensitivity, and specificity were approximately 80%. As shown in Table 5, using the hsTnI result as the standard, the accuracy of the CDG test was 80.4%, the sensitivity of 71.5%, and the specificity of 81.8%, which is also acceptable as an early screening instrument.



(a) before training

(b) 2 h after training

(c) 14 h after training

Figure 1. CDG of an athlete before training and 2 and 14 h after training.

Table 3. Comparison of the results of CDG and CK tests.

	CK test		
CDG test	Positive (+)	Negative (-)	total
Positive (+)	10 (52.6%)	3 (9.4%)	13
Negative (-)	9 (47.4%)	29 (90.6%)	38
Total	19	32	51

Accuracy = 76.5%; sensitivity = 52.6%; specificity = 90.6%; kappa = 0.462.

Table 4. Comparison of the results of CDG and CK-MB tests.

	CK-MB test		
CDG test	Positive (+)	Negative (-)	total
Positive (+)	4 (80.0%)	9 (19.6%)	13
Negative (-)	1 (20.0%)	37 (80.4%)	38
Total	5	46	51

Accuracy = 80.4%; sensitivity = 80.0%; specificity = 80.4%; kappa = 0.353.

Table 5. Comparison of the results of CDG and hsTnI tests.

	hsTnI test		
CDG test	Positive (+)	Negative (-)	total
Positive (+)	5(71.4%)	8(18.2%)	13
Negative (-)	2(28.6%)	36(81.8%)	38
Total	7	44	51

Accuracy = 80.4%; sensitivity = 71.4%; specificity = 81.8%; kappa = 0.391.

Discussion

When proposing a sports training program for athletes and ordinary people, one of the key intentions is to determine individualized exercise intensity according to their physiological characteristics and post-exercise responses. When physiological function and health status of athlete is monitored accurately and timely, the sports training plan can be reasonably arranged and adjusted, thus avoiding excessive fatigue, reducing sports injury, and improving the efficacy and safety of the training. Biomarkers including CK, CK-MB, and hsTnI are widely applied as instruments for sports training monitoring in long-term practice. However, the disadvantages of the traditional method include (1) blood sampling, which is an invasive test and unwelcome by athletes; (2) time delay – usually takes several hours to several days to draw the conclusion –, thus resulting in the irreversible mistakes; and (3) relatively complex and quite expensive test procedures. As such, many sports teams cannot use the traditional method for long term.

Recent research suggested that microvolt change of ST-T in electrocardiosignal may be an important marker to detect heart function and cardiac damage (Verrier et al., 2011), which also provides an excellent, promising new indicator for sports training monitoring. An ordinary ECG instrument can hardly detect tiny electrocardiosignal changes. The deterministic learning theory applied in the CDG is utilized to detect small oscillation faults generated from nonlinear dynamical system (Wang et al., 2016). It was reported that the microvolt ST-T change can be captured by CDG, and the technology could be used as an early noninvasive diagnostic tool for coronary artery disease (Deng et al., 2017). The results of the current study suggested that CDG not only could be used as an early screening tool for myocardial ischemia but may also be utilized to monitor exercise training.

The current study showed that hsTnI and CK-MB of athletes increased after high-intensity training, which suggested that attention should be paid to the negative effects of high-intensity sports training on the heart. It was reported that high-intensity, long-term exercise can lead to the increase of myocardial injury serum biomarkers including cTn, CK-MB, and B-type natriuretic peptide (Banfi et al., 2012; Neumayr et al., 2001; Scherr et al., 2011). Another review summarized 45 studies from 1997 to 2014 and found that the cTn level exceeded the normal value in more than half of the participants after high-intensity sports training (Sedaghat-Hamedani et al., 2015). Moreover, another study reported that the elevated cTn existed in most athletes after training and is more common among young athletes (Tian, Nie, Huang, & George, 2012). However, the question whether the elevated serum biomarkers of myocardial injury or pathological myocardial injury after exercise are normal physiological responses remains controversial. Mainstream studies still regard exercise-induced cTn and CK-MB release as physiological response rather than a pathological change (Shave et al., 2010). Moreover, imaging studies have not found the evidence that high-intensity, prolonged exercise can cause myocardial damage (Shave et al., 2010). However, high-intensity prolonged exercise can undeniably increase the relative risk of sudden exercise death (Siegel, 2012). Some studies suggested that the risk of SCD caused by vigorous exercise was 2.38–16.9 times than that of sedentary lifestyle (Albert et al., 2000; Whang et al., 2006). In this study, remarkable differences in shapes of CDG are found between pre-training and post-training, and CDG test was found to be positive in about 40% of athletes after a high-intensity, long-term sports training. The results indicated that CDG is a sensitive test for vigorous sports training.

In the current study, using CK-MB and hsTnI as the "gold standard," the CDG test performed well, with an accuracy of about 80.4% and specificity of 80.4% and 81.8%. By contrast, the sensitivity was relatively lower, which might be related to the relatively low positive rate in the participants in the current study. CK, a commonly used biomarker in detecting the microscopic injury of the muscle including both cardiac and skeletal muscles, has a distinct difference from CK-MB and hsTnI. Therefore, CDG and CK test results are less consistent when CK-MB and hsTnI were compared.

The small sample size is the main limitation of the current study. The participants in this study needed to complete a prolonged, high-intensity sports training, and blood sampling is also required for three times. Recruiting many participants who could meet the requirements was not easy. Nevertheless, this study including a small sample simple initially demonstrated the feasibility of CDG for sports training monitoring. The noninvasive, simple, and economical tool may be beneficial to the scientific sports training, which still needs further studies.

Conclusion

The accuracy of CDG test was approximately 80% when CK-MB and hsTnI were used as standards. Given that the CDG test was noninvasive, simple, and economical, this approach is expected to be a new method to monitor the cardiac function of athletes and exercisers during exercise training. Nevertheless, the applicability of CDG still needs further research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Zhejiang Provincial Natural Science Foundation of China [LY18C110001]; key research grant for national fitness from General Administration of Sport of China [2015B043]; research grant for key laboratory of physical fitness and exercise technology in Zhejiang Province (grant no. 2011F10052-10(2016)) and the fundamental research funds for the central universities

References

Albert, C. M., Mittleman, M. A., Chae, C. U., Lee, I. M., Hennekens, C. H., & Manson, J. E. (2000). Triggering of sudden death from cardiac causes by vigorous exertion. *The New England Journal of Medicine*, *343*(19), 1355–1361.

Baird, M. F., Graham, S. M., Baker, J. S., & Bickerstaff, G. F. (2012). Creatine-kinase- and exercise-related muscle damage implications for muscle performance and recovery. *Journal of Nutrition and Metabolism*, *2012*(4), 960363.

Banfi, G., Colombini, A., Lombardi, G., & Lubkowska, A. (2012). Metabolic markers in sports medicine. *Advances in Clinal Chemistry*, *56*, 1–54.

Deng, M., Tang, M., Wang, C., Shan, L., Zhang, L., Zhang, J., … Xia, L. (2017). Cardiodynamicsgram as a new diagnostic tool in coronary artery disease patients with nondiagnostic electrocardiograms. *American Journal of Cardiology*, *119*(5), 698–704.

Feng, L. S., & Zhang, L. (2007). *A practical guide to physiological and biochemical monitoring in elite athletes' training*. Beijing: People's Sports Press.

Giri, S., Thompson, P. D., Kiernan, F. J., Clive, J., Fram, D. B., Mitchel, J. F., … Waters, D. D. (1999). Clinical and angiographic characteristics of exertion-related acute myocardial infarction. *Journal of American Medical Association*, *282*(18), 1731–1736.

Keller, T., Zeller, T., Ojeda, F., Tzikas, S., Lillpopp, L., Sinning, C., … Blankenberg, S. (2011). Serial changes in highly sensitive troponin I assay and early diagnosis of myocardial infarction. *Journal of American Medical Association*, *306*(24), 2684–2693.

Lee, I. M., Rexrode, K. M., Cook, N. R., Manson, J. E., & Buring, J. E. (2001). Physical activity and coronary heart disease in women: Is "no pain, no gain" passe? *Journal of American Medical Association*, *285*(11), 1447–1454.

Merghani, A., Malhotra, A., & Sharma, S. (2015). The U-shaped relationship between exercise and cardiac morbidity. *Trends in Cardiovascular Medicine*, *26*(3), 232–240.

Mittleman, M. A., Maclure, M., Tofler, G. H., Sherwood, J. B., Goldberg, R. J., & Muller, J. E. (1993). Triggering of acute myocardial infarction by heavy physical exertion. Protection against triggering by regular exertion. Determinants of myocardial infarction onset study investigators. *The New England Journal of Medicine*, *329*(23), 1677–1683.

Morris, J. N., Heady, J. A., Raffle, P. A., Roberts, C. G., & Parks, J. W. (1953). Coronary heart-disease and physical activity of work. *Lancet*, *265*, 1111–1120.

Neumayr, G., Gaenzer, H., Pfister, R., Sturm, W., Schwarzacher, S. P., Eibl, G., … Hoertnagl, H. (2001). Plasma levels of cardiac troponin I after prolonged strenuous endurance exercise. *American Journal of Cardiology*, *87*(3), 369–371.

Scherr, J., Braun, S., Schuster, T., Hartmann, C., Moehlenkamp, S., Wolfarth, B., … Halle, M. (2011). 72-h kinetics of high-sensitive troponin T and inflammatory markers after marathon. *Medicine & Science in Sports & Exercise*, *43*(10), 1819–1827.

Schneider, C. M., Dennehy, C. A., Rodearmel, S. J., & Hayward, J. R. (1995). Effects of physical activity on creatine phosphokinase and the isoenzyme creatine kinase-MB. *Annals of Emergency Medicine*, *25*(4), 520–524.

Sedaghat-Hamedani, F., Kayvanpour, E., Frankenstein, L., Mereles, D., Amr, A., Buss, S., et al. (2015). Biomarker changes after strenuous exercise can mimic pulmonary embolism and cardiac injury–A meta-analysis of 45 studies. *Clinical Chemistry*, *61*(10), 1246–1255.

Sharma, S., Merghani, A., & Mont, L. (2015). Exercise and the heart: The good, the bad, and the ugly. *European Heart Journal*, *36*(23), 1445–1453.

Shave, R., Baggish, A., George, K., Wood, M., Scharhag, J., Whyte, G., … Thompson, P. D. (2010). Exercise-induced cardiac troponin elevation: Evidence, mechanisms, and implications. *The New England Journal of Medicine*, *56*(3), 169–176.

Shave, R., George, K. P., Atkinson, G., Hart, E., Middleton, N., Whyte, G., … Collinson, P. O. (2007). Exercise-induced cardiac troponin T release: A meta-analysis. *Medicine & Science in Sports & Exercise*, *39*(12), 2099–2106.

Siegel, A. J. (2012). Pheidippides redux: Reducing risk for acute cardiac events during marathon running. *The American Journal of Medicine*, *125* (7), 630–635.

Sullivan, A. M., Xia, H., Mcbride, J. C., & Zhao, X. (2010). Reconstruction of missing physiological signals using artificial neural networks. *Computers in Cardiology*, *37*(7), 317–320.

Swift, D. L., Lavie, C. J., Johannsen, N. M., Arena, R., Earnest, C. P., O'Keefe, J. H., et al. (2013). Physical activity, cardiorespiratory fitness, and exercise training in primary and secondary coronary prevention. *Circulation Journal*, *77*(2), 281–292.

Tanasescu, M., Leitzmann, M. F., Rimm, E. B., Willett, W. C., Stampfer, M. J., & Hu, F. B. (2002). Exercise type and intensity in relation to coronary heart disease in men. *Journal of American Medical Association*, *288*(16), 1994–2000.

Thompson, P. D., Franklin, B. A., Balady, G. J., Blair, S. N., Corrado, D., Estes, N. A. M., et al. (2007). Exercise and acute cardiovascular events: Placing the risks into perspective: A scientific statement from the American Heart Association Council on nutrition, physical activity, and metabolism and the council on clinical cardiology. *Circulation*, *115*(17), 2358–2368.

Thygesen, K., Alpert, J. S., Jaffe, A. S., Simoons, M. L., & Chaitman, B. R. (2012). Third universal definition of myocardial infarction. *European Heart Journal*, *9*(20), 2173–2195.

Tian, Y., Nie, J., Huang, C., & George, K. P. (2012). The kinetics of highly sensitive cardiac troponin T release after prolonged treadmill exercise in adolescent and adult athletes. *Journal of Applied Physiology*, *113*(3), 418–425.

Verrier, R. L., Klingenheben, T., Malik, M., El-Sherif, N., Exner, D. V., Hohnloser, S. H., … Rosenbaum, D. S. (2011). Microvolt t-wave alternans physiological basis, methods of measurement, and clinical utility–Consensus guideline by international society for holter and noninvasive electrocardiology. *Journal of the American College of Cardiology*, *58*(13), 1309–1324.

Wang, C., Dong, X., Ou, S., Wang, W., Hu, J., & Yang, F. (2016). A new method for early detection of myocardial ischemia: Cardiodynamicsgram (CDG). *Science China Information Sciences*, *59*(1), 1–11.

Whang, W., Manson, J. E., Hu, F. B., Chae, C. U., Rexrode, K. M., Willett, W. C., … Albert, C. M. (2006). Physical exertion, exercise, and sudden cardiac death in women. *Journal of American Medical Association*, *295*(12), 1399–1403.

Xia, H., Garcia, G. A., Bains, J., Wortham, D. C., & Zhao, X. (2012). Matrix of regularity for improving the quality of ecgs. *Physiological Measurement*, *33*(9), 1535–1548.