



Article

Diabetic Cardiomyopathy and the Role of Regular Exercise in Preventing the Disease: A Review

Smail, Manal M.A., Singh, Ram, Bidasee, Keshore, Howarth, Frank, Hanoman, Carlin and Singh, Jaipaul

Available at <http://clock.uclan.ac.uk/21864/>

Smail, Manal M.A., Singh, Ram, Bidasee, Keshore, Howarth, Frank, Hanoman, Carlin and Singh, Jaipaul ORCID: 0000-0002-3200-3949 (2018) Diabetic Cardiomyopathy and the Role of Regular Exercise in Preventing the Disease: A Review. World Heart Journal, 9 (4). ISSN 1556-4002

It is advisable to refer to the publisher's version if you intend to cite from the work.

For more information about UCLan's research in this area go to <http://www.uclan.ac.uk/researchgroups/> and search for <name of research Group>.

For information about Research generally at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLoK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the [policies](#) page.

Diabetic Cardiomyopathy and the Role of Regular Exercise in Preventing the Disease: A Review

**Manal M. A. Smail^{1,2}, Ram Singh³,
Keshore Bidasee⁴, Frank C. Howarth¹
, Carlin Hanoman² and Jaipaul Singh^{2,*}**

¹Department of Physiology, College of Medicine and Health Sciences, United Arab Emirates University

²School of Forensic and Applied Sciences, University of Central Lancashire, Preston, PR1 2HE, Lancashire, England, United Kingdom

³The Halberg Hospital and Research Institute, Moradabad, India

⁴Department of Pharmacology and Neuroscience, University of Nebraska Medical Centre, Omaha, NE, USA

Abstract

Diabetes mellitus (DM) is a major global metabolic disorder currently affecting over 450 million people and this number is rising rapidly. Heart failure (HF) is the major cause of death among diabetic patients. The disorder is due to elevated blood glucose level beyond physiological range or hyperglycaemia (HG), which in turn leads to a number of long-term complications, including diabetic cardiomyopathy (DC) over time. Around 80% of all diabetics will eventually die from DC. If left untreated, DC has been shown to be a critical factor in HF, independent of atherosclerosis, hypertension and valvular malfunction. The inability to maintain glucose homeostasis in the myocardium compromises cardiac structure and function in human diabetic subjects and also in animals with experimental diabetes. Daily exercise is known to protect the heart from sudden cardiac death. Exercise training (ET) is a beneficial non-pharmacological intervention for the treatment of cardiovascular diseases (CVDs). ET can induce cardio-protection in normal hearts and also in a partially diseased heart through a range of molecular mechanisms. The cardio-protective effect of ET is associated with the improvement of antioxidant capacity, mitochondrial viability and it can activate physiological cardiac growth, which are all mediated via distinct cellular and molecular mechanisms compared to those in pathological hypertrophy. Beneficial cardiac protection following regular ET in diabetes has been reported in both clinical and experimental animal studies. ET is a cost-effective strategy for prevention and treatment DC. However, the cellular and molecular mechanisms underlying DC and HF in diabetes and how regular exercise can reverse the pathology are not fully clear and further research should be carried out.

Keywords: Diabetes mellitus, heart, cardiomyopathy, hyperglycaemia, exercise, function

Introduction

* Corresponding author: Professor Jaipaul Singh. School of Forensic and Applied Sciences, University of Central Lancashire, Preston, PR1 2HE, Lancashire, England,

United Kingdom. Email: Jsingh3@uclan.ac.uk. Mobile: 00447990575580.

Cardiovascular diseases (CVDs) are directly linked to DM and are responsible for about 80% of mortality in the diabetic population [1]. Diabetic cardiomyopathy (DC) is diabetes-mediated, resulting in pathological cardiac remodelling in the absence of coronary artery disease, hypertension and valvular disease. In fact, diabetes is a multi-factorial disease. Therefore, the mechanism underlying DC is complex. However, an understanding of that mechanism is essential for preventing heart failure (HF) caused by diabetes or reversing the pathological cardiac remodelling [2]. In fact, HF is one of the main causes of mortality in the world despite advances in drug and treatments [3]. Epidemiological data show that macrovascular complications, including coronary artery disease (CAD), hypertension, heart failure, peripheral vascular disease (PVD) and stroke are more common 2-4 times among diabetic patients in comparison with non-diabetic people [4]. Renal failure and CVDs are the two major causes of morbidity and mortality in diabetic patients and hearts of diabetic patients are frequently in a compromised condition [5]. According to the Framingham study, the frequency of CAD is twice more common in diabetic patients of both genders [6]. DM increases the risk for heart failure by progressive weakening of cardiac function. It can also affect cardiac structure and function without causing changes in blood pressure and CAD [7]. This term was introduced in 1972 for the description of 4 patients with DM and HF, but without any signs of either hypertension or CAD [8]. DC represents the major cause of mortality and morbidity among diabetics [9]. It has been defined as ventricular dysfunction which occurs in diabetic patients independent of a recognized cause such as CAD or hypertension. The early stage of DC is a hidden subclinical period in which cellular structural changes lead initially to diastolic dysfunction, later to systolic dysfunction, and eventually to HF. The most common contributors to DC onset and progression are left ventricular hypertrophy, metabolic abnormalities, (mitochondrial dysfunction), extracellular matrix changes (fibrosis), small vessel disease (endothelial dysfunction), cardiac autonomic neuropathy, insulin resistance, oxidative stress, and apoptosis, all leading to cardiac remodelling [10]. DC is also accompanied by comorbidities such as obesity, hypertension and others. These complications

often precede the development of systolic function, CAD and heart failure [11].

Historical Background of Diabetic Cardiomyopathy

DC affects the heart by enhancing fatty acid metabolism, suppressing glucose oxidation and modifying intracellular signalling, all of which lead to alteration in multiple steps of the excitation-contraction coupling (ECC) process, inefficient energy production, increased susceptibility to ischemia and contractile dysfunction [12]. The exact underlying mechanism of DC is still not fully clear, and several causes have been proposed including metabolic disorder, autonomic dysfunction, and interstitial fibrosis [13]. Metabolic disturbances such as altered lipid handling and substrate utilization, decreased mechanical efficiency, mitochondrial dysfunction, disturbances in non-oxidative glucose pathways and increased oxidative stress are all hallmarks of DC. Thus, the pathogenesis of DC is multifactorial and complex, eventually leading to an energetically compromised heart with reduced cardiac working capacity and heart failure [14]. This review highlights the available data about the development of DC, how ET may influence cellular, structural and functional changes in DC, and in particular, to further explore the effect of exercise training (ET) on mitochondrial biogenesis in DC and how ET preserves cardiac function and prevents myocardial apoptosis and fibrosis. Since this review is based on non-pharmacological intervention to treat DC, then much emphasis will be focused on ET as non-pharmacological intervention in the treatment of heart disease.

Historical Background of ET as Medicine

The history of ET as a treatment and prevention measure may be attributed to the ancient Greek Society. Exercise as medicine was first proposed by Greek philosophers during the 4th century B.C. Furthermore, Hippocrates wrote two books on regimen and noted that “eating alone will not keep a man well; he must also take exercise” [15]. The effect of ET in lowering glycosuria has been evident since 600 B.C,

when Shushruta, an Indian Physician, noted the reduction in the sweetness of urine from diabetic patients after ET [16]. Nowadays, it is well established that physical exercise continues to be one of the most valuable and cost-effective forms of non-pharmacological therapy. ET can induce cardio-protection in normal hearts through a range of molecular mechanisms [17]. ET was defined by the American College of Sports Medicine as “Any and all activity involving generation of force by the activated muscle(s) that results in disruption of a homeostatic state” [18]. ET is classified by the type, intensity, and duration of activity. Endurance exercise reflects prolonged and continuous periods of contractile activity (high repetition) against low resistance [19]. In contrast, resistance exercise (strength training) involves short periods of contractile activity (low repetition) against a high opposing resistance, while sprint exercise occurs during short periods of maximal (intense) repetitive contractile activity, where there is a short period of exercise against a low resistance, such as running a 100-m sprint race. However, sprint training can also be performed against high resistance, which results in a combination of resistance and endurance modalities, for example, running with added weights [18]. The beneficial cardiac impact of ET in diabetes management has been reported in clinical medicine [20, 21] and experimental animal studies [22, 23]. ET is a low-cost strategy for the prevention and treatment of DC. ET has a beneficial impact on diabetes-related systemic changes and it may also improve the metabolic disturbances of the diabetic myocardium. These changes are the result of both indirect effects, exercise-mediated systemic changes and direct effect originating from the high contractile activity of the heart during ET [14]. The cardio-protective effect of ET is associated with the improvement of antioxidant capacity and mitochondrial viability and activated physiological cardiac growth which are all mediated via distinct cellular and molecular mechanisms from those patients with pathological hypertrophy [24]. Similarly, in animal models, it has been shown that ET can prevent ventricular remodelling and attenuated derangement of glucose and lipid metabolism, and improve mitochondrial function and antioxidant capacity leading to ameliorated cardiac performance in early stage of DC [24].

Structural and Functional Changes in DC

DC leads to structural and functional changes in the heart. The structural changes are manifested by left ventricular hypertrophy, interstitial fibrosis, increased cell death or apoptosis and oxidative stress [25, 26]. DC also results in functional changes including a derangement in cellular calcium homeostasis, diastolic dysfunction, systolic dysfunction and impaired contractile reserve [27]. In type 2 diabetes (T2DM), left ventricular mass is an independent marker of cardiovascular risk. It often occurs independent of atrial blood pressure. Therefore, diabetes is an independent risk factor leading to left ventricular hypertrophy and myocardial stiffness [28]. DC is also characterized by interstitial fibrosis, mostly composed of collagen and perivascular fibrosis [29]. At the cellular level, prolongation of cardiac action potential duration (CAPD) has been consistently shown in diabetic hearts. Significant alterations in the ionic currents that constitute cardiac action potential (CAP) configuration have been proposed as the main culprit of this prolongation [30, 31]. The intracellular free Ca^{2+} concentration $[Ca^{2+}]_i$ is very essential for the myocardium contraction [32]. DC-induced abnormalities during cardiac contractility have been correlated with the intracellular Ca^{2+} changes. Diabetic cardiac dysfunction most likely arises due to changes in expression and/or activity of cellular mechanisms that regulate Ca^{2+} transport during cardiac cycle [33]. Thus, DC results in changes in biomechanical, contractile and hypertrophic properties changes of cardiac myocytes.

These changes could be a result of altered myocardial glucose and fatty acid metabolism due to DM. Chronic hyperglycaemia leads to non-enzymatic glycation of vascular and membrane proteins, producing advanced glycation end products (AGEs), reactive oxygen species (ROS) and reactive carbonyl species (RCS) [34]. AGEs may play an important role in the pathobiology of heart failure [35]. AGEs are either proteins or lipids that become glycated after exposure to sugars. They are prevalent in the diabetic vasculature contributing to the development of

atherosclerosis. Moreover, they have been shown to be increased in plasma by hyperglycaemia [35]. Accumulation of AGE in collagen was associated with reduced collagen turnover, indicating the possibility that cross-linking of collagen makes collagen resistant to hydrolytic turnover. Such AGE-mediated cross-linking of collagen is thought to be responsible for increased stiffness of arteries and the myocardium. In fact, AGEs are increased in the myocardium during T1DM and T2DM, and there are positive correlations of serum level of AGEs with ventricular isovolumetric relaxation time, arterial stiffness, and carotid intimal thickness all of which have been shown in diabetics [35]. There is a significant increase in the deposition of collagen around the vessel and between the myofibres of heart biopsies from diabetic patients. In addition, deposits of lipofuscin, which are brown pigment granules composed of lipid-containing residues, were found in left ventricular transmural biopsies. Myocardial triglyceride and cholesterol contents in these biopsies were measured and significant increases in these molecules were found in the heart tissue [2].

DC, Insulin, and Metabolic Alteration

Insulin has a vital role in the regulation of various aspects of cardiovascular metabolism and function. In fact, the human heart produces and uses between 3.5 and 5 kg of ATP every day to pump. The energy generation depends on the cardiac environment including coronary flow, blood substrate supply, hormones and nutritional status [36]. Alteration of myocardial substrate and energy metabolism are considered as significant factors for the development of DC [37]. DM is characterized by reduced glucose and lactate metabolism and increased fatty acid (FA) metabolism [38]. In the diabetic heart, the myocardial glucose transport is impaired because of decreased myocardial concentration of GLUT1 and GLUT4 protein and mRNA level [39]. A second mechanism of reduced glucose oxidation is via the inhibitory effect of fatty acid oxidation on pyruvate dehydrogenase complex due to high circulating FFA [40]. Insulin induces glucose uptake in cardiomyocytes by binding to insulin receptor (IR). IR undergoes auto-transphosphorylation which initiates a signalling cascade initiated by tyrosine phosphorylation of insulin

receptor substrates (IRS), followed by phosphorylation of phosphatidylinositol-3 kinase (PI3K), phosphoinositide-dependent kinase 1 (PDK1), Akt, and protein kinase C (PKC). These events lead the glucose transporter type 1 (GLUT1) and type 4 (GLUT4) translocation to the membrane to facilitate glucose uptake into the cell. In the heart, contractile-mediated translocation of GLUT4 represents the major mechanism that regulates glucose entry in the beating heart, with GLUT1 playing a lesser role [41].

Insulin resistance and hyperinsulinemia are recognized as risk factors for DC [42]. In hyperinsulinemia and insulin resistance, a disturbance of insulin-mediated glucose metabolism occurs which can significantly worsen metabolic efficiency of both skeletal and cardiac muscle. Insulin affects the diabetic heart by both systemic metabolism abnormalities and direct effects on insulin signalling pathways that are intrinsic to the cardiac tissue [43]. In the evolution of insulin resistance, the initial change that develops in the hearts of animal models is the impairment in the ability of insulin to increase glucose transport [44]. A recent study revealed that insulin resistance is associated with cardiac contractile dysfunction. The authors of the study generate a new insulin resistant animal rat model on high cholesterol fructose (HCF) diet. HCF diet induced insulin resistance on both metabolic response tissue and the heart as well. These findings illustrate that insulin resistance is associated with metabolic alteration and consequently leading to the development of DC [43]. Circulating FAs and triglycerides (TGs) are increased by enhanced lipolysis in adipose tissue and lipoprotein synthesis in liver, resulting in hyperglycaemia and insulin resistance. When the FAs exceed the oxidative capacity of the heart, the FAs are converted to lipid-like TG or ceramide which can lead to lipo-toxicity and cell apoptosis [45]. Thus, DM leads to increased rates of FA oxidation and decreased rates of glucose oxidation.

DC and Fibrosis

Interstitial and perivascular fibrosis is a histological symptom of DC [8]. The extent of fibrosis correlates with heart weight. The pathogenesis of fibrosis in the diabetic heart is proposed to be due to diabetic micro-angiopathy. When the diabetic heart is

affected by hypertension or CAD, there may be additive micro-angiopathy and large vessel-induced ischaemia leading to diffuse myocardial scarring. The generalized fibrosis can result in increased wall stiffness and diastolic dysfunction [46]. Activation of the renin-angiotensin system (RAS) is known to have a role in the development of DC [40]. In the diabetic heart, Angiotensin II (Ang-II) receptor density and mRNA expression are elevated [47]. The activation of RAS in DM is associated with increased oxidative damage, fibrosis and cell apoptosis [48]. Inhibition of the RAS was shown to reduce reactive oxygen species (ROS) production in streptozotocin-induced type 1 diabetic rats, similar to the effect observed with antioxidant treatment [49]. Ang-II, given exogenously to rodents, has been shown to cause cellular changes within myocardium leading to hypertrophy and fibrosis [50].

Mitochondrial Dysfunction

Mitochondria play a significant role in energy production in cells. They are also involved in other phenomena such as ion homeostasis, free radical production, and ultimately cell death [51]. Mitochondria are the center of fatty acid and glucose metabolism. Diabetes can lead to impaired metabolism associated with mitochondrial dysfunction. Recent studies have shown ultrastructural and functional changes of diabetic cardiac mitochondria. DM affects the protein composition of diabetic mitochondria [52]. In a model of chronic type 1 diabetic mice, damage to mitochondria was indicated by impaired function and ultrastructure abnormalities. Damage was accompanied by indicators of mitochondrial biogenesis, including increases in 11 specific mitochondrial proteins, elevation of mRNA for the mitochondrial regulatory protein and increased total mitochondrial DNA area and number. These findings showed that mitochondria are a major focus of diabetes-induced damage to the heart [53]. Along with those findings, DM also leads to a decrease in mitochondrial efficiency for ATP production. A recent study demonstrated the relationship between impaired insulin signaling and altered mitochondrial energetics by using mice with a cardiac-specific deletion of the insulin receptor. In the study, the

authors found that impaired myocardial insulin signaling promotes oxidative stress and mitochondrial uncoupling, which, were accompanied with reduced fatty acid oxidative capacity and impaired mitochondrial energetics [54]. Diabetic mitochondria also produce more ROS than normal mitochondria [55]. According to the molecular theory of DC, hyperglycemia (HG) is the main pathogenic factor [56]. HG stimulates the overproduction or pathophysiological levels of ROS and reactive carbonyl species (RCS). ROS and RCS are significant contributors to structural and functional abnormalities of the myocardium [56]. Mitochondria are the major source of ROS and RAC productions and depletion of antioxidants as depicted in the flow diagram of Figure 1.

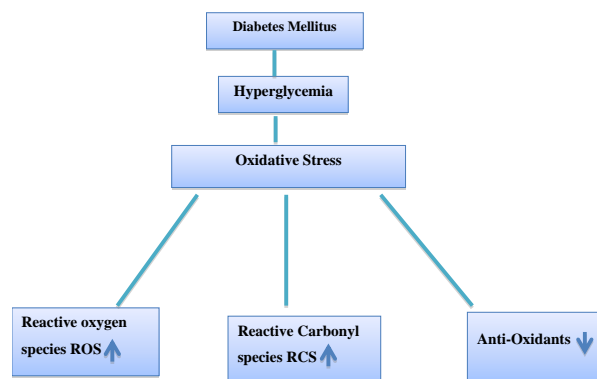


Figure 1. Flow diagram showing how DM can lead to hyperglycaemia and oxidative stress which in turn induced the production of ROS and RCS and a decrease in anti-oxidant capacity of the myocardium during diabetic cardiomyopathy.

Cellular sources of ROS generation within the heart include cardiac myocytes, endothelial cells and neutrophils. ROS induces cellular damage through many mechanisms including oxidation, interference with nitric oxide and modulation of detrimental intracellular signaling pathways. Thus, increased ROS leads to cardiac dysfunction by direct damage to proteins and DNA resulting in apoptosis [57]. RCS are diverse in chemical structures generated in different cell types including vascular smooth muscle cells of the body. They are derived from multiple sources, including auto-oxidation of glucose and lipids, triose pathway fluxes and from enzymes such as semicarbazide-sensitive amine oxidases and methylglyoxal synthase. In contrast, RCS also have

unique characteristic compared to ROS in that their half-lives are longer (minutes vs millisecond), and they are uncharged molecules, allowing them to migrate far distance from their site of production [58].

Impaired Ca^{2+} Homeostasis

Ca^{2+} is a major trigger, initiator, modulator, second messenger and regulator (signaling mechanism) of cardiac contractility. Most of the Ca^{2+} that activates contraction is released from sarcoplasmic reticulum (SR) through ryanodine receptors (RyRs). RyRs are themselves activated by the inducing Ca^{2+} through activation of voltage-dependent L-type Ca^{2+} channels and this mechanism is known as Ca^{2+} -induced Ca^{2+} release (CICR) [59]. The cytosolic Ca^{2+} ions in turn interact with contractile proteins. By binding to troponin C, the Ca^{2+} triggers the sliding of thin and thick filaments resulting in cardiac muscle contraction. Ca^{2+} then returns to diastolic levels mainly by activation of the SR Ca^{2+} pump (SERCA2a), the sarcolemma Na^+ - Ca^{2+} exchanger (NCX), and the sarcolemma Ca^{2+} ATPase [7]. DM leads to mitochondrial dysfunction which contributes to the development of DC by altering ATP generation and Ca^{2+} movement as illustrated in Figure 2 [60]. Furthermore, it has been suggested that HG is associated with the alteration of the expression and function of RyRs and SERCA and this alteration may lead to impair myocardial systolic and diastolic function [27]. Thus, Ca^{2+} homeostasis is altered in DC by affecting the ability of SR to take up Ca^{2+} and the Na^+ - Ca^{2+} exchanger, and the sarcolemma Ca^{2+} ATPase to pump Ca^{2+} out of the cell [61, 62], all leading to elevated diastolic Ca^{2+} . In streptozotocin (STZ)-induced type 1 diabetic rats, a depression in contraction and relaxation in myocytes was found in parallel with depression in the rise and decline of intracellular free Ca^{2+} concentration. The SR Ca^{2+} store and rates of Ca^{2+} release and reuptake into SR were depressed and the rate of Ca^{2+} efflux via sarcolemma Na^+ - Ca^{2+} exchanger was also depressed. The depression in SR function was associated with decreased SR Ca^{2+} -ATPase and ryanodine receptor proteins and increased total and non-phosphorylated phospholamban proteins [63]. In DC, prolongation of cardiac action potential duration

(CAPD) and slower decay of Ca^{2+} transient are consistently observed in DC. As for prolongation of CAPD, reduction in transient outward K^+ (Ito) current has been shown in animal models of diabetes [64]. There is also a reduced expression of L-type Ca^{2+} channel activity which is also an additional abnormality in the heart [65]. The prolongation of APD is potentially a compensatory mechanism for preserving Ca^{2+} influx in cardiomyocytes with down-regulated L-type Ca^{2+} channel [66].

ET Effects on Glucose Transport

In 1982, the increase in sensitivity of glucose transport process in skeletal muscle after ET was discovered. It was reported that ET could increase insulin sensitivity and moreover, it was shown that a session of swimming could lead to an increase in muscle glucose uptake in the absence of added insulin that could be measured in perfused rat muscle after cessation of ET [67]. These results were confirmed by Garetto et al. [68] in a study in which they showed that enhanced glucose uptake after ET occurred in two phases. The first phase is independent of added insulin and, as this increase in glucose transport was reversed, it was replaced by an increase in insulin sensitivity [68-70]. Subsequent studies have established that contractions can stimulate glucose transport in the complete absence of insulin [71-73] and that the maximal effects of contractions and insulin are additive in nature. Moreover, both contractions and insulin can stimulate glucose transport by separate signaling pathways. The initial steps in the signaling pathways by which contractions stimulate glucose transport have been identified in the heart [69]. One of these is the release of Ca^{2+} from the SR resulting in activation of Ca^{2+} /calmodulin-dependent protein kinase (CaMK) II, which is the isoform of CaMK found in skeletal muscle [74]. This process can be studied using sub-concentrations of agents such as caffeine, that release Ca^{2+} from the SR. Studies using this approach have shown that either the inhibition of Ca^{2+} release from the SR, or inhibition of CaMKII can prevent the increase in glucose transport induced by Ca^{2+} [69, 74].

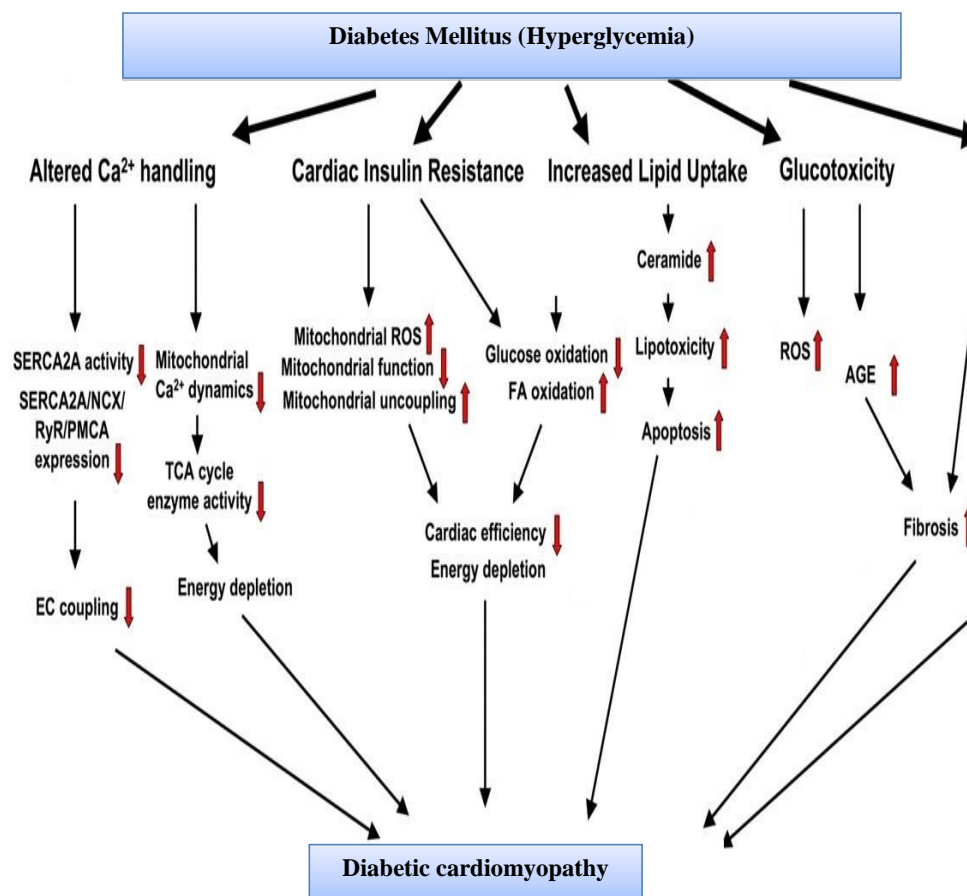


Figure 2. Flow diagram showing changes occurring in the heart during diabetic cardiomyopathy. DC can lead to structural, functional and biochemical changes at cellular and subcellular levels.

Athlete's Heart

In clinically healthy individuals, regular high-intensity physical activity for 5 to 6 hours per week may lead to cardiac adaptation known as an athlete's heart resulting in compensatory myocardial hypertrophy [75]. Acute responses to endurance ET include significant increases in maximum oxygen consumption, cardiac output, stroke volume and systolic blood pressure, all of which are associated with decreased peripheral vascular resistance. However, long-term cardiovascular adaptation to dynamic training results in increased maximal oxygen uptake due to increased cardiac output and arteriovenous oxygen difference. Strength exercise results in little or no increase in oxygen uptake. Thus, endurance exercise predominantly produces volume load on the left ventricle (LV), and strength exercise causes largely

a pressure load [76]. LV physiological hypertrophy is caused by a proportional increase in myocardial cell length and width without evidence of myocardial hyperplasia in the majority of cases and this is mediated via increased cardiac insulin-like growth factor-1 (IGF-1) expression and activation of phosphoinositide-3 kinase (PI3K) [77].

Physiological and pathological cardiac hypertrophies are caused by different stimuli and functionally distinguishable as illustrated in Table 1. A pathological stimulus causing pressure overload like aortic stenosis or hypertension produces an increase in systolic wall stress which results in concentric hypertrophy (heart with thick wall relatively small cavities) [75]. However, pathological stimulus can cause volume overload resulting in aortic regurgitation or arteriovenous fistula. This produces an increase in diastolic wall stress resulting in eccentric hypertrophy

(heart with large dilated cavities and relatively thin wall). For the physiological hypertrophy, isotonic exercises such as walking, running and cycling involve movements of large muscles resulting in an increase in venous return and the increased volume will lead to eccentric hypertrophy. Generally, physiological concentric hypertrophy is caused by isometric or static exercise such as weight lifting which involves muscular tension against resistance with little movement. Reflex and mechanical changes rather than volume can cause a pressure load on the heart [78]. Function of the pathological hypertrophied heart may eventually decompensate leading to left ventricle dilation and heart failure, while in physiological hypertrophy, it does not decompensate compared to dilated cardiomyopathy of heart failure [75]. Thus, ET can result in a beneficial physiological, rather than an abnormal pathological growth.

ET-induced adaptation of the coronary circulation can be divided into two main processes. The first

process is angiogenesis leading to an expansion of the capillary network by the formation of new blood vessels. This occurs at the level of capillaries and resistance arterioles, but not in large arteries. The second process involves arteriogenesis which can result in the enlargement of existing blood vessels [79].

The molecular mechanisms underlying angiogenesis induced by exercise training are not fully understood. It has been suggested that growth factors such as vascular endothelial growth factor (VEGF), fibroblast growth factor (FGF) and angiopoietins (AQP), as well as their corresponding receptors, are involved in the process. In addition, proteases necessary for the degradation of the capillary basement membrane such as matrix metalloproteinases (MMPs), urokinase, tissue plasminogen activator and plasminogen, are also likely to contribute to the mechanism of sprouting angiogenesis [80].

Table 1: Table showing the changes which occur in the heart during ET and DC

Heart remodeling	Exercise Training	Diabetic Cardiomyopathy
Hypertrophy	Physiological hypertrophy does not decompensate to dilated cardiomyopathy of heart failure [75].	Pathological hypertrophy eventually decompensates leading to left ventricle dilation and heart failure [75].
Metabolism	Fatty acids and lactate are the major substrates for the heart during exercise [81]. Also increased rates of glucose oxidation and glycolysis [82]	Associated with reduced glucose and lactate metabolism, as well as increased fatty acid metabolism [38].
Oxidative stress	Decreasing reactive oxygen species (ROS) by dampening the activators of ROS producing enzymes [83].	Overproduction of reactive oxygen species (ROS) and reactive carbonyl species (RCS) [56].
Cellular Ca ²⁺ homeostasis	Effectively restoring myocardial expression and activity of sarcoplasmic reticulum Ca ²⁺ ATPase- pump (SERCA) [84].	Altering Ca ²⁺ movement [60] by affecting the ability of SR to take up Ca ²⁺ , and the Na ⁺ -Ca ²⁺ exchanger and the sarcolemma Ca ²⁺ ATPase to extrude Ca ²⁺ from the cell [61]

Non-Pharmacological Intervention for DC Treatment

The first recognition of ET as a non-pharmacological option to prevent and treat CVDs was in 1890s by Robert Babcock [85]. He stated that “Improved arterial circulation is so manifest a result of

these exercises that lessen the frequency, nay, even the severity of attacks of angina pectoris in individuals with arteriosclerosis who had been unable to indulge in even very moderate physical exercise taken in the ordinary ways of walking.” Currently, regular ET is a valuable therapeutic method/tool, and evidence from the scientific and medical communities strongly

supports the need to integrate the practice of regular ET in the therapeutic management of the disease and to limit diabetic-related long-term complications [86]. In fact, ET improves metabolic control and cardiovascular fitness. Many clinical studies have found that ET decreases cardiovascular risk factors [87, 88]. Similarly, several scientific reports have shown the advantages of ET on cardiac function and structure of diabetic patients, as well as in experimental models of DM, including reduced fibrosis, hypertrophy and apoptosis of the myocardium [89, 90]. Regular exercise is very important for maintenance of LV mass and function. As studied in bed-rest trials, prolonged physical inactivity leads to significant reductions in LV mass and impaired cardiac compliance, resulting in reduced upright stroke volume and orthostatic intolerance [91]. Since DC is associated cardiac remodeling (CR) which is characterized by myocardial hypertrophy, fibrosis and apoptosis, physiological hypertrophy in response to ET may differ in its structure and molecular profile to pathological hypertrophy [78].

The beneficial effect of exercise on coronary artery function has been demonstrated in diabetic rodent models [92, 93]. Since cardiac tissue has an extremely high metabolic demand, consequently, cardiac function is highly dependent on adequate coronary blood flow. Thus, coronary artery dysfunction directly impacts on optimal myocardial function. An eight-week moderate-intensity exercise regime in individuals with T2DM significantly improved endothelial cell function in the brachial artery as indicated by the improved flow-mediated dilation [94]. In another study, a 14-month moderate-intensity resistant training in adults with T2DM improved endothelial cell function-dependent and -independent vasodilation in response to acetylcholine and sodium nitroprusside, respectively [95]. Repeated exercise sessions may stimulate other adaptive changes which can contribute to both improved insulin sensitivity and metabolic health. Increased oxidative capacity and capillary density were observed in skeletal muscle in response to aerobic exercise [96]. In addition, increased adipose tissue insulin sensitivity has been observed 72-hours after completion of a 6-week exercise intervention [97].

ET Impact on Cardiac Metabolism in Health and During DC

Metabolic flexibility is the ability of the heart to ensure sufficient ATP production rate under diverse physiological and dietary conditions. The lack of this flexibility has been regarded as fundamental in the development of heart failure, including DC [98]. ET has an impact on cardiac metabolism. An acute exercise session can result in alteration of metabolic state by high level of plasma lactate from glycolysis in exercising muscle and non-esterified FAs. FAs and lactate are the major substrates for the heart during exercise [81]. In STZ diabetic rats, ET results in increased rates of glucose oxidation and glycolysis [82], while FA oxidation was unaltered [99].

ET and Oxidative Stress

It is now well established that increased ROS and RCS productions can lead to cardiac dysfunction by direct damage to regulatory proteins and DNA and induced apoptosis. Moreover, ROS producing enzymes are influenced by long-term endurance exercise training, through very different mechanisms. ET leads to improvement of insulin signaling, reduced inflammatory status, alteration of plasma lipids, and reduced RAS. Most likely, ET participates in decreasing ROS in the diabetic cardiomyocyte by dampening the activators of ROS-producing enzymes. It was reported that the exercise-induced elevation of mitochondrial ROS production was attenuated in cardiac mitochondria from endurance trained rats [83]. Theoretically, tissues with fewer cell divisions are more susceptible to cumulative damage by ROS compared to tissues with high replication rates [100]. One of the most frequently used bio-markers that provides an indication of the overall lipid peroxidation level is the plasma concentration of malondialdehyde (P-MDA), one of several byproducts of lipid peroxidation processes [78]. In animal models of ageing, increased malondialdehyde levels were observed in sedentary old rats. Although the expression of anti-oxidative enzymes such as superoxide dismutase (SOD) was unchanged, its enzymatic activity was reduced resulting in a net decline of anti-oxidative protection. Regular ET seems to delay the

accumulation of ROS-mediated cell damage by improving the anti-oxidative protection in the myocardium [100].

ET and Ca²⁺ Homeostasis

Calcium homeostasis has a major role in the process of contraction and relaxation (ECC) of the heart. ET has been shown to improve cardiac myocytes contractility in diabetic models and this improvement was associated with improvement of Ca²⁺ homeostasis. ET also prevents the development of DC and the dysregulation of SR protein content in an inducible animal model of T2DM [22]. Regular ET can effectively lead to restoring myocardial expression and activity of SERCA and L-type Ca²⁺ channel activity [84]. The release of Ca²⁺ from the internal SR via type 2 ryanodine receptor (RyR2) is an integral step in the cascade of events leading to cardiac muscle contraction [101, 102]. Recent studies showed that ventricular myocytes isolated from streptozotocin (STZ)-induced type 1 diabetic rat hearts exhibited increased frequency of spontaneous Ca²⁺ sparks. In longer term or more severe experimental diabetes, reduction in steady-state levels of RyR2 and other Ca²⁺ cycling proteins also contribute to the process [63, 103]. RyR2 becomes leaky during diabetes and this defect may be responsible for the reduced SR Ca²⁺ load. Diastolic Ca²⁺ release could also serve as a substrate for delayed after-depolarizations, contributing to the increased incidence of arrhythmias and sudden cardiac death in T1DM [102]. Alterations in the sensitivity of RyR2 to Ca²⁺ activation could result of oxidation in the RyR2 by either ROS or RCS [104]. Time to peak myocyte Ca²⁺ transient was prolonged by light and moderate exercise initiated 2 months after the onset of diabetes [105]. To date, the effect of ET during diabetes on myocyte intracellular Ca²⁺ cycling and the function of SR proteins remain poorly understood.

Psychological Intervention to Enhance ET Adherence

ET should be considered an essential therapeutic tool which has a beneficial effect on DC. In fact, the beneficial effects of ET have been observed to wane

within 3 to 10 days or even longer following exercise. Therefore, effective ET therapy programs are associated with high ET adherence, as this would ensure long-term glycemic control [106].

Several factors create obstacles to ET, for example low motivational status, self-efficacy, negative learning history with exercising, lack of coping skills and aversive environmental characteristics such as reduced access to physical activity facilities, high costs of training programs, low social and cultural support and time barriers. Improving adherence to ET is a critical challenge. In order to promote adherence to ET, combined supplementary psychological intervention is extremely effective in encouraging the attendance to the exercise program [107]. In addition, national health services throughout the world should prescribe regular daily exercise to patients suffering from DC and other related diseases.

Conclusion

DM is a major metabolic disorder which can lead to damage and subsequent failure to a number of organs in the body including the heart where hemodynamic disturbances frequently occur. Figure 2 summarizes the processes and mechanism(s) whereby DM can lead to DCM subsequently and heart failure. Initially, these are induced at sub-cellular, cellular, molecular and interstitial levels in the heart, including changes in size, shape and function of the myocardium. Diabetes, if left untreated, can result in hyperglycemia-induced generation of ROS and RCS, endothelial and mitochondrial dysfunctions, structural changes to cardiomyocytes, infiltration of fibrosis, apoptosis or death of some cardiomyocytes, followed by hypertrophy, disturbances in cellular calcium homeostasis, myofilaments insensitivity to calcium and subsequently delayed contraction and prolonged relaxation all leading to remodeling of the myocardium. Most of these changes in the heart can either be delayed or prevented by regular ET, which is a valuable non-pharmacological therapeutic tool. It is now highly recommended by scientific and medical communities, which strongly support the need to integrate the practice of regular ET in the therapeutic management of the disease and to limit diabetic-related complications. Of particular importance, ET can also

improve metabolic control and cardiovascular fitness. Many clinical studies have found that ET decreases cardiovascular risk factors. However, the cellular and molecular mechanisms underlying DC and heart failure in diabetes are not fully clear and further studies should be done to unravel the process.

References

- [1] Voulgari C, Papadogiannis D, Tentolouris N. Diabetic cardiomyopathy: from the pathophysiology of the cardiac myocytes to current diagnosis and management strategies. *Vasc Health Risk Manag* 2010; 21 (6): 883-903.
- [2] Boudina S, Abel ED. Diabetic cardiomyopathy, causes and effects. *Rev Endocr Metab Disord* 2010; 11 (1): 31-39.
- [3] Roger VL. The heart failure epidemic. *Int J Environ Res Public Health* 2010; 7 (4): 1807-1830.
- [4] Zimmet P, Alberti KG, Shaw J. Global and societal implications of the diabetes epidemic. *Nature* 2001; 414 (6865): 782-787.
- [5] Wright J, Hutchison AK. Cardiovascular disease in patients with chronic kidney disease. *Vasc Health Risk Manag* 2009; 5: 713-722.
- [6] Kannel WB, McGee DL. Diabetes and cardiovascular disease: the Framingham Study. *JAMA* 1979; 241 (19): 2035-2038.
- [7] Boudina S, Abel ED. Diabetic cardiomyopathy revisited. *Circulation* 2007; 115 (25): 3213-3223.
- [8] Rubler S, Dlugash J, Yuceoglu YZ, Kumral T, Branwood AW, Grishman A. New type of cardiomyopathy associated with diabetic glomerulosclerosis. *Am J Cardiol* 1972; 30 (6): 595-602.
- [9] Abe T, Ohga Y, Tabayashi N, Kobayashi S, Sakata S, Misawa H, Tsuji T, Kohzuki H, Suga H, Taniguchi S, Takaki M. Left ventricular diastolic dysfunction in type 2 diabetes mellitus model rats. *Am J Physiol Heart Circ Physiol* 2002; 282 (1): 138-148.
- [10] Falcao-Pires I, Leite-Moreira AF. Diabetic cardiomyopathy: understanding the molecular and cellular basis to progress in diagnosis and treatment. *Heart Fail Rev* 2012; 17 (3): 325-344.
- [11] Todd Cade W. Diabetes-related microvascular and macrovascular disease in the physical therapy setting. *Physical Therapy* 2008; 88 (11): 1322-1335.
- [12] Miki T, Yuda S, Kouzu H, Miura T. Diabetic cardiomyopathy: pathophysiology and clinical features. *Heart Fail Rev* 2013; 12 (2): 149-166.
- [13] Spector KS. Diabetic cardiomyopathy. *Clin Cardiol* 1998; 21 (12): 885-887.
- [14] Hafstad AD, Boardman N, Aasum E. Exercise training represents nowadays a useful nonpharmacological strategy for the treatment of cardiovascular diseases. *Antioxid Redox Signal* 2015; 22 (17): 1587-1605.
- [15] Chales MT. The history of "Exercise Is Medicine" in ancient civilizations. *Adv Physiol Educ* 2013; 38 (2): 109-117.
- [16] Berryman JW, Park RJ. Sport and Exercise Science: Essays in the History of Sports Medicine. Chicago: University of Illinois Press 1992; 1-10.
- [17] Golbidi S, Laher I. Molecular mechanisms in exercise-induced cardioprotection. *Cardiol Res Pract* 2011; 2011: 1-15.
- [18] Ghosh S, Golbidi S, Werner I, Verchere BC, Laher I. Selecting exercise regimens and strains to modify obesity and diabetes in rodents: an overview. *Clin Sci* 2010; 119 (2): 57-74.
- [19] Heo M, Kim E. Effects of endurance training on lipid metabolism and glycosylated hemoglobin levels in streptozotocin-induced type 2 diabetic rats on a high-fat diet. *J Phys Ther Sci* 2013; 25 (8): 989-992.
- [20] Hollekim-Strand S, Bjorgaa M, Albrektsen G, Tjonna A, Wisloff U, Ingul C. High-intensity interval exercise effectively improves cardiac function in patients with type 2 diabetes mellitus and diastolic dysfunction: a randomized controlled trial. *J Am Coll Cardiol* 2014; 64 (16): 1758-1760.
- [21] Riehle C, Wende A, Zhu Y, Oliveira K, Pereira R, Jaishy BP, Bevins J, Valdez S, Noh J, Kim BJ, Moreira AB, Weatherford ET, Manivel R, Rawlings TA, Rech M, White MF, Abel ED. Insulin receptor substrates (IRS) are essential for the bioenergetic and hypertrophic response of the heart to exercise training. *Mol Cell Biol* 2014; 34 (18): 3450-3460.
- [22] Epp R, Susser S, Morissette M, Kehler D, Jassal DS, Duhamel T. Exercise training prevents the development of cardiac dysfunction in the low-dose streptozotocin diabetic rats fed a high-fat diet. *Can J Physiol Pharmacol* 2016; 91 (1): 80-89.
- [23] Shao CH, Wehrens XH, Wyatt TA, Parbhu S, Rozanski GJ, Patel KP, Bidasee KR. Exercise training during diabetes attenuates cardiac ryanodine receptor dysregulation. *J Appl Physiol* (1985) 2009; 106 (4): 1280-1292.
- [24] Wang A, Bei Y, Lu Y, Sun W, Liu Q, Wang Y, Cao Y, Chen P, Xiao J, Kong X. Exercise prevents cardiac injury and improves mitochondrial biogenesis in advanced diabetic cardiomyopathy with PGC-1 α and Akt activation. *Cell Physiol Biochem* 2015; 35: 2159-2168.
- [25] Aragno M, Mastrocola R, Medana C, Catalano MG, Vercellinato I, Danni O, Bocuzzi G. Oxidative stress-dependent impairment of cardiac-specific transcription factors in experimental diabetes. *Endocrinology* 2006; 147 (12): 5967-5974.
- [26] Asbun J, Villarreal FJ. The pathogenesis of myocardial fibrosis in the setting of diabetic cardiomyopathy. *J Am Coll Cardiol* 2006; 47 (4): 693-700.

- [27] Poornima IG, Parikh P, Shannon RP. Diabetic cardiomyopathy: the search for a unifying hypothesis. *Circ Res* 2006; 98 (5): 596-605.
- [28] Jia G, Demarco VG, Sowers JR. Insulin resistance and hyperinsulinaemia in diabetic cardiomyopathy. *Nat Rev Endocrinol* 2016; 12 (3): 144-153.
- [29] Adeghate E. Molecular and cellular basis of the aetiology and management of diabetic cardiomyopathy: a short review. *Mol Cell Biochem* 2004; 261 (1-2): 187-191.
- [30] Ozturk N, Olgar Y, Ozdemir S. Trace elements in diabetic cardiomyopathy: An electrophysiological overview. *World J Diabetes* 2013; 4 (4): 92-100.
- [31] Stones R, Calaghan SC, Billeter R, Harrison SM, White E. Transmural variations in gene expression of stretch-modulated proteins in the rat left ventricle. *Pflugers Arch* 2007; 454 (4): 545-549.
- [32] Shimoni Y, Severson D, Giles W. Thyroid status and diabetes modulate regional differences in potassium currents in rat ventricle. *J Physiol* 1995; 488 (Pt 3): 673-688.
- [33] Lindsey ML, Borg TK. Understanding the role of the extracellular matrix in cardiovascular development and disease: Where do we go from here? *J Mol Cell Cardiol* 2009; 48 (3): 431-432.
- [34] Poirier P, Bogaty P, Philippon F, Garneau C, Fortin C. Diastolic dysfunction in normotensive men with well-controlled type 2 diabetes: importance of manoeuvres in echocardiographic screening for preclinical diabetic cardiomyopathy. *Diabetes Care* 2001; 24: 5-10.
- [35] Berg TJ, Snorgaard O, Faber J, Torjensen PA, Hildebrandt P, Mehlsen J, Hanssen KF. Serum levels of advanced glycation end products are associated with left ventricular diastolic function in patients with type 1 diabetes. *Diabetes Care* 1999; 22 (7): 1186-1190.
- [36] Bertrand L, Horman S, Beauloye C, Vanoverschelde JL. Insulin signalling in the heart. *Cardiovasc Res* 2008; 79 (2): 238-248.
- [37] Lopaschuk GD. Metabolic abnormalities in the diabetic heart. *Heart Fail Rev* 2002; 7 (2): 149-159.
- [38] Stanley WC, Lopaschuk GD, McCormack JG. Regulation of energy substrate metabolism in the diabetic heart. *Cardiovasc Res* 1997; 34 (1): 25-33.
- [39] Camps M, Castello A, Munoz P, Monfar M, Testar X, Palacin M, Zorzano A. Effect of diabetes and fasting on GLUT-4 (muscle/fat) glucose-transporter expression in insulin-sensitive tissues. Heterogeneous response in heart, red and white muscle. *Biochem J* 1992; 282 (Pt 3): 765-772.
- [40] Fang ZY, Prins JB, Marwick TH. Diabetic cardiomyopathy: evidence, mechanisms, and therapeutic implications. *Endocr Rev* 2004; 25 (4): 543-567.
- [41] Dale Abel E, O'Shea KM, Ramasamy R. Insulin Resistance: Metabolic mechanisms and consequences in the heart. *Arterioscler Thromb Vasc Biol* 2012; 32 (9): 2068-2076.
- [42] Despres JP, Lamarche B, Mauriege P, Cantin B, Dagenais GR, Moorjani S, Lupien PJ. Hyperinsulinemia as an independent risk factor for ischemic heart disease [see comments]. *N Engl J Med* 1996; 334 (15): 952-957.
- [43] Huang JP, Hung LM. Insulin resistance and cardiomyopathy. In: Veselka J, ed. *Cardiomyopathies -- From Basic Research to Clinical Management*. Intechweb.org 2012.
- [44] Wright JJ, Kim J, Buchanan J, Boudina S, Sena S, Bakirtzi K, Ilkun O, Theobald HA, Cooksey RC, Kandror KV, Abel ED. Mechanisms for increased myocardial fatty acid utilization following short-term high-fat feeding. *Cardiovasc Res* 2009; 82 (2): 351-360.
- [45] Zhou YT, Grayburn P, Karim A, Shimabukuro M, Higa M, Baetens D, Orci L, Unger RH. Lipotoxic heart disease in obese rats: implications for human obesity. *Proc Natl Acad Sci USA* 2000; 97 (4): 1784-1789.
- [46] van Hoesven KH, Factor SM. A comparison of the pathological spectrum of hypertensive, diabetic, and hypertensive-diabetic heart disease [see comments]. *Circulation* 1990; 82 (3): 848-855.
- [47] Fiordaliso F, Li B, Latini R, Sonnenblick EH, Anversa P, Leri A, Kajstura J. Myocyte death in streptozotocin-induced diabetes in rats is angiotensin II-dependent. *Lab Invest* 2000; 80 (4): 513-527.
- [48] Frustaci A, Kajstura J, Chimenti C, Jakoniuk I, Leri A, Maseri A, Nadal-Ginard B, Anversa P. Myocardial cell death in human diabetes. *Circ Res* 2000; 87 (12): 1123-1132.
- [49] Cai L, Wang Y, Zhou G, Chen T, Song Y, Li X, Kang YJ. Attenuation by metallothionein of early cardiac cell death via suppression of mitochondrial oxidative stress results in a prevention of diabetic cardiomyopathy. *J Am Coll Cardiol* 2006; 48 (8): 1688-1697.
- [50] Billet S, Aguilar F, Baudry C, Clauser E. Role of angiotensin II AT1 receptor activation in cardiovascular diseases. *Kidney Int* 2008; 74 (11): 1379-1384.
- [51] Piquereau J, Caffin F, Novotova M, Lemaire C, Veksler V, Garnier A, Ventura-Clapier R, Joubert F. Mitochondrial dynamics in the adult cardiomyocytes: which roles for a highly specialized cell? *Front Physiol* 2013; 4 (102): 1-12.
- [52] Duncan JG. Mitochondrial dysfunction in diabetic cardiomyopathy. *Biochim Biophys Acta* 2011; 1813 (7): 1351-1359.
- [53] Shen X, Zheng S, Thongboonkerd V, Xu M, Pierce Jr WM, Klein JB, Epstein PN. Cardiac mitochondrial damage and biogenesis in a chronic model of type I diabetes. *Am J Physiol Endocrinol Metab* 2004; 287 (5): 896-905.
- [54] Boudina S, Bugger H, Sena S, O'Neill BT, Zaha VG, Ilkun O, Wright JJ, Mazumder PK, Palfreyman E, Tidwell TJ, Theobald H, Khalimonchuk O, Wayment B, Sheng X, Rodnick KJ, Centini R, Chen D, Litwin SE, Weimer BE, Abel ED. Contribution of impaired myocardial insulin signaling to mitochondrial

- dysfunction and oxidative stress in the heart. *Circulation* 2009; 119 (9): 1272-1283.
- [55] Ye G, Metreveli NS, Donthi RV, Xia S, Xu M, Carlson EC, Epstein PN. Catalase protects cardiomyocyte function in models of type 1 and type 2 diabetes. *Diabetes* 2004; 53 (5): 1336-1343.
- [56] Tarquini R, Lazzeri C, Pala L, Rotella C, Gensini GF. The diabetic cardiomyopathy. *Acta Diabetol* 2016; 48 (3): 173-181.
- [57] Rodrigues B, Cam MC, McNeill JH. Metabolic disturbances in diabetic cardiomyopathy. *Mol Cell Biochem* 1998; 180 (1-2): 53-57.
- [58] Tian C, Alomar F, Moore CJ, Shao CH, Kutty S, Singh J, Bidasee KR. Reactive carbonyl species and their roles in sarcoplasmic reticulum Ca²⁺ cycling defect in the diabetic heart. *Heart Fail Rev* 2014; 19 (1): 101-112.
- [59] Wier WG, Balke W. Ca²⁺ release mechanisms, Ca²⁺ sparks, and local control of excitation-contraction coupling in normal heart muscle. *Circ Res* 1999; 85: 770-776.
- [60] Sivitz WI, Yorek MA. Mitochondrial dysfunction in diabetes: from molecular mechanisms to functional significance and therapeutic opportunities. *Antioxid Redox Signal* 2010; 12 (4): 537-577.
- [61] Lopaschuk GD, Tahiliani AG, Vadlamudi RV, Katz S, McNeill JH. Cardiac sarcoplasmic reticulum function in insulin- or carnitine-treated diabetic rats. *Am J Physiol* 1983; 245 (6): 969-976.
- [62] Pierce GN, Dhalla NS. Cardiac myofibrillar ATPase activity in diabetic rats. *J Mol Cell Cardiol* 1981; 13 (12): 1063-1069.
- [63] Choi KM, Zhong Y, Hoit BD, Grupp IL, Hahn H, Dilly KW, Guatimosim S, Lederer WJ, Matlib MA. Defective intracellular Ca²⁺ signaling contributes to cardiomyopathy in Type 1 diabetic rats. *Am J Physiol Heart Circ Physiol* 2002; 283 (4): 1398-1408.
- [64] Lacombe VA, Viatchenko-Karpinski S, Terentyev D, Sridhar A, Emani S, Bonagura JD, Feldman DS, Györke S, Carnes CA. Mechanisms of impaired calcium handling underlying subclinical diastolic dysfunction in diabetes. *Am J Physiol Regul Integr Comp Physiol* 2007; 293: 1787-1797.
- [65] Pereira L, Matthes J, Schuster I, Valdivia HH, Herzig S, Richard S, Gómez AM. Mechanisms of [Ca²⁺]_i transient decrease in cardiomyopathy of db/db type 2 diabetic mice. *Diabetes* 2006; 55 (3): 608-615.
- [66] Sah R, Oudit GY, Nguyen TT, Lim HW, Wickenden AD, Wilson GJ, Molkentin JD, Backx PH. Inhibition of calcineurin and sarcolemmal Ca²⁺ influx protects cardiac morphology and ventricular function in Kv4.2N transgenic mice. *Circulation* 2002; 105: 1850-1856.
- [67] Richter EA, Garetto LP, Goodman MN, Ruderman NB. Muscular glucose metabolism following exercise in the Rat. Increased sensitivity to insulin. *J Clin Invest* 1982; 69: 785-793.
- [68] Garetto LP, Richter EA, Goodman MN, Ruderman NB. Enhanced muscle glucose metabolism after exercise in the rat: the two phases. *Am J Physiol* 1984; 246 (6 Pt 1): E471-5.
- [69] Holloszy JO. Exercise-induced increase in muscle insulin sensitivity. *J Appl Physiol* 2005; 99 (1): 338-343.
- [70] Wallberg-Henriksson H, Constable SH, Young DA, Holloszy JO. Glucose transport into rat skeletal muscle: interaction between exercise and insulin. *J Appl Physiol* 1989; 65: 909-913.
- [71] Nashold R, Karl IE, Kipnis DM. Dissociation of effect of insulin and contraction on glucose transport in rat epitrochlearis muscle. *Am J Physiol Cell Physiol* 1985; 249: 226-232.
- [72] Ploug T, Galbo H, Richter EA. Increased muscle glucose uptake during contraction: no need for insulin. *Am J Physiol* 1984; 247: 726-731.
- [73] Wallberg-Henriksson H, Holloszy JO. Contractile activity increases glucose uptake by muscle in severely diabetic rats. *J Appl Physiol* 1984; 57: 1045-1049.
- [74] Wright DC, Hucker KA, Holloszy JO, Han DH. Ca²⁺ and AMPK both mediate stimulation of glucose transport by muscle contraction. *Diabetes* 2005; 53: 330-335.
- [75] Pluim BM, Zwinderman AH, Van der Laarse, van der Laarse A, van der Wall EE. The athlete's heart. A meta-analysis of cardiac structure and function. *Circulation* 2000; 101: 336-344.
- [76] Maron BJ, Pelliccia A. The heart of trained athletes: cardiac remodeling and the risks of sports, including sudden death. *Circulation* 2006; 114 (15): 1633-1644.
- [77] Galanti G. Increased cardiac sympathetic activity and insulin-like growth factor-I formation are associated with physiological hypertrophy in athletes. *Circ Res* 2001; 89: 977-982.
- [78] Nielsen F, Mikkelsen BB, Nielsen JB, Andersen HR, Grandjean P. Plasma malondialdehyde as biomarker for oxidative stress: reference interval and effects of lifestyle factors. *Clinical Chemistry* 1997; 43 (7): 1209-1214.
- [79] Leung FP, Yung LM, Laher I, Yao X, Chen ZY, Huang Y. Exercise, vascular wall and cardiovascular diseases: an update (part 1). *Sports Medicine* 2008; 38 (12): 1009-1024.
- [80] Rehman J, Li J, Parvathaneni L, Karlsson G, Panchal VR, Temm CJ, Mahenthiran J, March KL. Exercise acutely increases circulating endothelial progenitor cells and monocyte/macrophage-derived angiogenic cells. *J Am Coll Cardiol* 2004; 43 (12): 2314-2318.
- [81] Gertz EW, Wisneski JA, Stanley WC, Neese RA. Myocardial substrate utilization during exercise in humans. Dual carbon-labeled carbohydrate isotope experiments. *J Clin Invest* 1988; 82 (6): 2017-2025.
- [82] Broderick TL, Poirier P, Gillis M. Exercise training restores abnormal myocardial glucose utilization and

- cardiac function in diabetes. *Diabetes Metab Res Rev* 2005; 21 (1): 44-50.
- [83] Bo H, Jiang N, Ma G, Qu J, Zhang G, Cao D, Wen L, Liu S, Ji LL, Zhang Y. Regulation of mitochondrial uncoupling respiration during exercise in rat heart: role of reactive oxygen species (ROS) and uncoupling protein 2. *Free Radic Biol Med* 2008; 44 (7): 1373-1381.
- [84] Bennett CE, Johnsen VL, Shearer J, Belke DD. Exercise training mitigates aberrant cardiac protein O-GlcNAcylation in streptozotocin-induced diabetic mice. *Life Sci* 2013; 92: 657-663.
- [85] Babcock RH. Report of cases of chronic heart disease treated by the Schott method of baths and gymnastics. *Trans Am Climatol Assoc* 1895; 10: 298-314.
- [86] Lahaye SD, Bekono FR, Broderick TL. Physical activity and diabetic cardiomyopathy: myocardial adaptation depending on exercise load. *Current Diabetes Reviews* 2014; 10 (6): 1-20.
- [87] Iscoe KE, Campbell JE, Jamnik V, Perkins BM, Riddell MC. Efficacy of continuous real-time blood glucose monitoring during and after prolonged high-intensity cycling exercise: spinning with a continuous glucose monitoring system. *Diabetes Technology & Therapeutics* 2006; 8 (6): 627-635.
- [88] Heyman E, Toutain C, Delamarche P, Berthon P, Briard D. Exercise training and cardiovascular risk factors in type 1 diabetic adolescent girls. *Pediatric Exercise Science* 2007; 19 (4): 408-419.
- [89] Graham C, Lasko-McCarthy P. Exercise options for persons with diabetic complications. *The Diabetes Educator* 1990; 16 (3): 212-220.
- [90] Marwick TH. Diabetic heart disease. *Heart* 2006; 92: 296-300.
- [91] Perhonen MA, Franco F, Lane LD, Buckey JC, Blomqvist CG, Zerwekh JE, Peshock RM, Weatherall PT, Levine BD. Cardiac atrophy after bed rest and spaceflight. *J Appl Physiol* 2001; 91: 645-653.
- [92] Lee S, Park Y, Dellsperger KC, Zhang C. Exercise training improves endothelial function via adiponectin-dependent and independent pathways in type 2 diabetic mice. *Am J Physiol Heart Circ Physiol* 2011; 301 (1): 306-314.
- [93] Moien-Afshari F, Ghosh S, Elmi S, Rahman MM, Sallam N, Khazaei M, Kieffer TJ, Brownsey RW, Laher I. Exercise restores endothelial function independently of weight loss or hyperglycaemic status in db/db mice. *Diabetologia* 2008; 51 (7): 1327-1337.
- [94] Okada S, Hiuge A, Makino H, Nagumo A, Takaki H, Konishi H, Goto Y, Yoshimasa Y, Miyamoto Y. Effect of exercise intervention on endothelial function and incidence of cardiovascular disease in patients with type 2 diabetes. *J Atheroscler Thromb* 2010; 17 (8): 828-833.
- [95] Cohen ND, Dunstan DW, Robinson C, Vulikh E, Zimet PZ, Shaw JE. Improved endothelial function following a 14-month resistance exercise training program in adults with type 2 diabetes. *Diabetes Res Clin Pract* 2008; 79 (3): 405-411.
- [96] Dubé JJ, Fleishman KMS, Rousson V, Goodpaster BH, Amati F. Exercise dose and insulin sensitivity: relevance for diabetes prevention. *Med Sci Sports Exerc* 2012; 44 (5): 793-799.
- [97] Dario A, Gutierrez BS, Michael J, Hasty AH. Impact of Increased Adipose Tissue Mass on Inflammation, Insulin Resistance, and Dyslipidemia. *Curr Diab Rep* 2009; 9 (1): 26-32.
- [98] Hafstad AD, Boardman N, Aasum E. How exercise may amend metabolic disturbances in diabetic cardiomyopathy. *Antioxid Redox Signal* 2015; 22 (17): 1587-1605.
- [99] Paulson DJ, Mathews R, Bowman J, Zhao J. Metabolic effects of treadmill exercise training on the diabetic heart. *J Appl Physiol* 1992; 73 (1): 265-271.
- [100] Gielen S, Schuler G, Adams V. Cardiovascular effects of exercise training. *Circulation* 2010; 122: 1221-1238.
- [101] Bers DM. Cardiac excitation-contraction coupling. *Nature* 2002; 415: 198-205.
- [102] Shao CH, Rozanski GJ, Patel KP, Bidasee KR. Dyssynchronous (non-uniform) Ca²⁺ release in myocytes from streptozotocin-induced diabetic rats. *J Mol Cell Cardiol* 2007; 42 (1): 234-246.
- [103] Bidasee KR, Nallani K, Yu Y, Cocklin RR, Zhang Y, Wang M, Dincer UD, Besch HR Jr. Chronic diabetes increases advanced-glycation end products on cardiac ryanodine receptors (RyR2). *Diabetes* 2003; 52: 1825-1836.
- [104] Xu L, Eu JP, Meissner G, Stamler JS. Activation of the cardiac calcium release channel (ryanodine receptor) by poly-S-nitrosylation. *Science* 1989; 279: 234-237.
- [105] Howarth FC, Almagaddum FA, Qureshi MA, Ljubisavijevic M. Effects of varying intensity exercise on shortening and intracellular calcium in ventricular myocytes from streptozotocin (STZ)-induced diabetic rats. *Mol Cell Biochem* 2008; 317 (1-2): 161-167.
- [106] Martinus R, Corban R, Wackerhage H, Atkins S, Singh J. Effect of psychological intervention on exercise adherence in type 2 diabetic subjects. *New York Academy of Sciences* 2006; 1084: 350-360.
- [107] Grave RD, Calugi S, Centis E, Ghoch ME, Marchesini E. Cognitive-behavioral strategies to increase the adherence to exercise in the management of obesity. *Journal of Obesity* 2011; 2011: 1-11.