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Review

Targeting mitochondrial phenotypes for non-communicable diseases

Zhengtang Qi [a,b,*], Shuzhe Ding [a,b,*]

[a] *The Key Laboratory of Adolescent Health Assessment and Exercise Intervention (East China Normal University), Ministry of Education, Shanghai 200241, China*

[b] *School of Physical Education and Health, East China Normal University, Shanghai 200241, China*

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Abstract

The concept that "Exercise is Medicine" has been challenged by the rising prevalence of non-communicable chronic diseases (NCDs). This is partly due to the fact that the underlying mechanisms of how exercise influences energy homeostasis and counteracts high-fat diets and physical inactivity is complex and remains relatively poorly understood on a molecular level. In addition to genetic polymorphisms in humans that lead to gross variations in responsiveness to exercise, adaptation in mitochondrial networks is central to physical activity, inactivity, and diet. To harness the benefits of exercise for NCDs, much work still needs to be done to improve health effectively on a societal level such as developing personalized exercise interventions aided by advances in high-throughput genomics, proteomics, and metabolomics. We propose that understanding the mitochondrial phenotype according to the molecular information of genotypes, lifestyles, and exercise responsiveness in individuals will optimize exercise effects for prevention of NCDs.

Keywords: Energy metabolism; Exercise; Mitochondrial; Non-communicable chronic diseases; Physical activity; Precision medicine

1. Introduction

The slogan of "Exercise is Medicine" promotes a global movement to reduce sedentary lifestyles. "Exercise is Medicine" attempts to raise physical activity (PA) levels to a standard medicine for clinical practice, because the benefits of exercise are purported to reduce the risk of non-communicable chronic diseases (NCDs), such as cardiovascular disease, type 2 diabetes and certain cancers. However, in the past decades, the global morbidity and mortality of NCDs is increasing regardless of the efforts of World Health Organization and national governments to promote physically more active lifestyle.[1]

The number of U.S. adults doing sufficient PA increased from 22% in 1996 to 51.6% in 2014.[2] In China, the number of adults attending PA also increased from 15.5% in 1996, to 28.2% in 2008, and to 33.9% in 2014.[3] There are remarkable achievements in promoting PA over the past decade in different countries. Nonetheless, it is discouraging that the mortality between ages 30 and 70 years due to NCDs increased in the US in 2000–2012 with NCDs accounting for 88% of total deaths in 2014. In China, NCDs also increased in males after 2004 and in females during 2000–2012; NCDs account for 87% of total deaths in 2014.[4] The metabolic risk factors for development of NCDs such as body mass index (BMI) and fasting blood glucose showed a less optimistic trend during 1980–2008.[5] These statistics might indicate that there is no an apparent relationship between PA and NCDs risks. Nonetheless, if increases in BMI are reciprocal to increases in PA, it is possible that any benefits of moderate exercise are offset by increased food consumption. In this review, we look into those confounding factors and the possible underlying mechanisms, which may have shaded the outcomes of health benefit of exercise from "Exercise is Medicine". The precision medicine initiative launched by the US claims that detailed genetic and other molecular information about a patient's disease will be routinely used to deploy effective, patient-specific remedies in future.[6] It is urgent to promote personalized exercise intervention linking curative exercise effects to specific health outcomes in different populations. Nonetheless, the weighting of genetic and environmental factors contributing to exercise for health is poorly understood.

2. Energy balance challenged by unhealthy lifestyles

NCDs are often attributed to unhealthy diet and physical inactivity. Meanwhile, life expectancy is increasing with the

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* Corresponding authors.

E-mail addresses: szding@tyxx.ecnu.edu.cn (S. Ding), qzht79@163.com (Z. Qi)

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ability of modern societies to provide high-quality medical and social facilities, regardless of these unhealthy lifestyles. To better evaluate the extent to which PA prevents NCDs, the mechanisms involving unhealthy lifestyles need to be explored at an evolutionary and physiological level. Energy balance is critical for the survival of all mammals. Current findings suggest that NCDs are mostly associated with metabolic disorder and its complications. Metabolic syndrome is often characterized by higher BMI, hyperglycemia, hyperlipidemia, insulin resistance, ectopic lipid accumulation, and mitochondrial dysfunction, for example, in type 2 diabetes and cardiovascular diseases.[7,8] With these considerations, it is necessary to focus our attention on those lifestyles that probably impair energy balance. High-fat diets are a major contributor to metabolic syndrome. Physiologically, high-fat diet leads to the impairment of fuel metabolism, increases in ectopic lipid accumulation in non-fat tissues (i.e., muscle and liver) and consequent adiposity. Evolutionarily, humans have undergone a dramatic shift in the composition of diet and motivation to eat.[9] Currently people have more reasons to eat something compared to our ancestors, because diet is an expression of culture and lifestyle, other than simply hunger. Unnecessary food intake overshoots the demand for energy and thereby impacts energy homeostasis. If excessive food consumption is the main reason for obesity, weight loss should be achieved by reducing food intake and increasing energy expenditure with PA. However, a cohort study that took place from 2004 to 2014 showed that PA and diet control might be not as effective as expected in obesity treatment. The authors reveal that the annual probability of attaining normal weight was 1/210 for men and 1/124 for women after obesity treatments.[10] Such a low probability is not encouraging for counteracting obesity through these means. It is noteworthy that the individual propensity to be physically active is determined by both genetic and environmental factors.[11] The individual propensity to be obesity-prone or obesity-resistant in response to high-fat diet is, for example, associated with the acyl chain length of phosphocholine species,[12] hypothalamic-pituitary-thyroid axis function,[13] proteomic profile of adipose tissues and liver.[14,15] This indicates that the individual propensity for PA and diet needs to be taken into consideration in obesity treatment frameworks.

In direct contrast to PA, physical inactivity leads to the development of insulin resistance.[16] Bed rest reduced expression of *PGC-1α* and other genes involved in mitochondrial biogenesis, contributing to the development of insulin resistance.[17] Evolutionarily, humans were selected to avoid extraneous PA because energy from food was limited and exercise increases unnecessary energy expenditure. Consequently, physical inactivity (except for necessary physical work) was the best strategy for survival when availability of food was limited.[18] Nonetheless, physical work in hunting for food coupled to lower energy intakes might have provided sufficient amount of PA to retain such a level of metabolic activity that our ancestors were resistant to NCDs. The advent of modern technology has now relegated PA from a necessity of human existence to lifestyle choice. Since physical inactivity poses a challenge to public health, exercise remains a most efficacious treatment for metabolic diseases, such as diabetes and cardiovascular diseases. Exercise provokes widespread perturbations in cells, tissues, and organs and challenges whole-body homeostasis by increasing metabolic activity of contracting skeletal muscles.[19] In doing so, exercise promotes "metabolic flexibility"—the ability to maintain metabolic health even in the face of excessive energy consumption.

Together, the metabolic syndrome appears to be at the intersection of endocrinology, oncology, and cardiology, such that maintaining energy balance has emerged as a major target for treating NCDs. Evolutionarily, the changes in food consumption and physical inactivity pose a great challenge to energy system in humans who have been evolutionally selected for food shortage and necessary physical work. Pathologically, long-term exposure to high-energy diet and physical inactivity induces obesity, insulin resistance and decreased energy expenditure. Although the synergistic interaction between unhealthy lifestyles and exercise remains elusive, PA is known as the best way to tame metabolic disorders and restore energy balance.

3. Mitochondria and metabolic health

Many NCDs involve mitochondrial dysfucntion.[20] While high-fat diets paradoxically result in an increase in mitochondrial biomass, they have also been associated with impaired mitochondrial respiratory capacity, mitochondrial biogenesis, insulin resistance, and metabolic inflexibility.[21] These same effects are related to physical inactivity.[22] By contrast, calorie restriction strengthens mitochondrial network and extends lifespan.[23] Exercise-induced mitochondrial biogenesis has been well documented, for example, in brain and skeletal muscle.[24,25] In these tissues mitochondrial plasticity follows the principle of "use it or lose it"; increased mitochondrial networks and mitochondrial function resulting from exercise are considered essential for health, while physical inactivity and sedentary behaviors are associated with mitochondrial dispansion (Fig. 1). It is now evident that mitochondria function as important signaling organelles; for example, via releasing metabolites, reactive oxygen species, and peptides and ions.[26] The quantity of mitochondria in cells is controlled by the master regulator of mitochondrial biogenesis, *PGC-1α* signaling, and mitophagy pathways (mitochondrial breakdown). We speculate that physical inactivity undermines the endo-symbiotic relationship between mitochondria and host eukaryotic cells. Here, we provide a framework by which mitochondria are provoked to drive the formation of the whole-cell phenotype (Fig. 1). Mechanistically, exercise has been proved to improve energy metabolism and mitochondrial adaptability. Thus, PA is a hopeful means to hold back the prevalence of NCDs. However, there is a great gulf between the bench and the bedside. A leading review indicates that a person's predisposition to engage in exercise is highly variable and simultaneously influenced by the environment, complex genomics, and their interactions.[27] In short, exercise is not always effective for everyone at any time. The development of individualized exercise prescription for the control of NCDs is an appealing concept. Unhealthy lifestyles impair energy balance, mitochondrial adaptability, and mitochondrial-coupled cell signaling implicated in the pathogenesis of NCDs. Why is target-

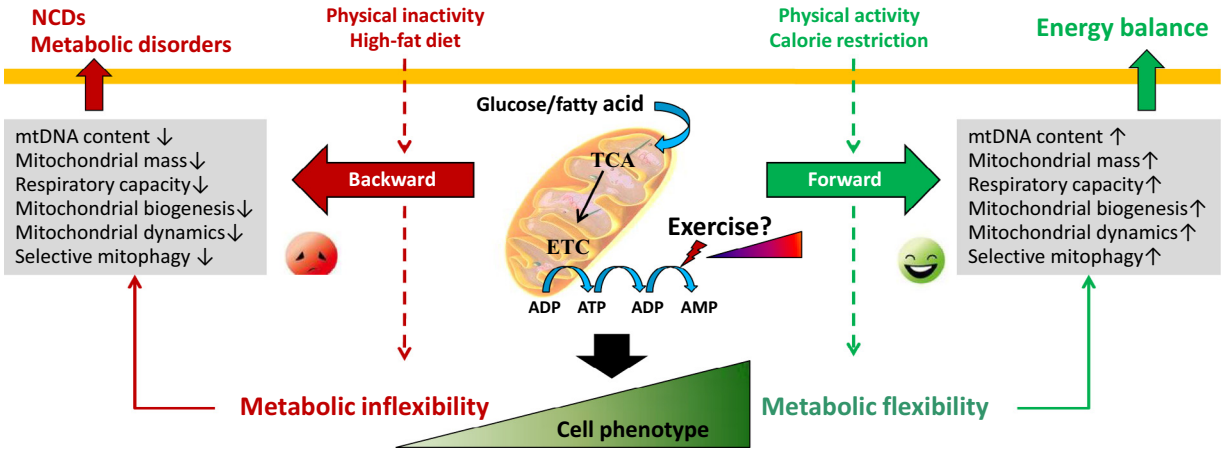

Fig. 1. The 2-way adaptations of mitochondria and mitochondrial-coupled cell phenotype. Mitochondria are highly self-organized to adapt via up- or down-regulation in response to energy intake and expenditure, such as high-fat diets, calorie restriction, physical activity and inactivity. The mechanisms underlying mitochondrial adaptability involve the regulations in mitochondrial DNA (mtDNA) content, mitochondrial mass, mitochondrial respiratory capacity, mitochondrial biogenesis, mitochondrial dynamics, and selective elimination of damaged mitochondria (i.e., mitophagy). By these mechanisms, mitochondrial activity could be turned up or down and mitochondrial network could be stronger or weaker. Furthermore, mitochondria are centered to switch energy metabolic signals to cell signaling responsible for the whole-cell phenotype, which represents a phenotypic feature with metabolic flexibility or inflexibility. In contrast to the role of mitochondrial abnormality in non-communicable chronic diseases (NCDs) and metabolic disorders, mitochondrial-centered cell signaling may be well adapted to exercise and capable of inducing a phenotype with greater metabolic flexibility.

ing mitochondrial phenotype required for NCDs? In brief, the benefits of exercise to a person with NCDs are contingent on individual-level factors, such as lifestyles, environment, genotype, and so on. These factors, to a large extent, lead to the variability of mitochondrial phenotypes and affect a person's responsiveness to exercise. Herein, we propose that targeting mitochondrial phenotypes will be a key necessity for treating NCDs (Fig. 1).

A great challenge to this is diversity of the human nuclear-mitochondrial genotype and the influence of environmental factors. For example, the mitochondrial phenotype is dynamically regulated by diet.[28] Moreover, humans and other primates have acquired hundreds of active "foreign" genes concerned with metabolism through horizontal gene transfer (HGT).[29] HGT is an important driving force to induce mitochondrial intron diversity, promote intron mobility and consequently shape mitochondrial genome architecture.[30] Mitochondrial DNA (mtDNA) polymorphism modulates the effects of coffee or alcohol consumption on the risk of hypertension, dyslipidemia, glucose intolerance, and hyperuricemia.[31,32] In addition, endurance performance and trainability in humans were associated with the polymorphism of mtDNA, intron *MYL1*, angiotensin I-converting enzyme (*ACE*), and manganese superoxide dismutase (*MnSOD*).[33–35] The *ACE* polymorphism alters mitochondrial metabolism and muscle energy supply in response to exercise through a novel expression pathway, which contributes to the varying trainability in endurance performance.[36] For metabolic disease, exercise is a powerful stimulus capable of restoring the metabolic flexibility of fuel selection in genetically-susceptible individuals.[37] Thus, mitochondrial phenotype is potentially determined by the combination of diet, muscle activity, and genotype. A recent report indicates that standard pharmacological methods are not sufficient to thoroughly predict a patient's phenotype in response to drug treatment, because the cytochrome P450 (CYP) enzymes responsible for drug clearance have more than 6000 single nucleotide variants distributed across 57 human *CYP* genes.[38] Similarly, inter-individual variability in mitochondrial phenotype persists as a major problem for exercise as a medicine for NCDs. We need to re-evaluate the role of exercise in preventing NCDs and key to this will be understanding variability in mitochondrial phenotypes for optimizing therapeutic effects of exercise.

4. Conclusion

The global promotion of PA has not been effective at controlling the prevalence of NCDs. Evolutionarily and mechanistically, energy balance is being challenged by unhealthy diets and physical inactivity, which are known as the contributors to metabolic disorders and NCDs. PA is, for example, of great value in suppressing various metabolic disorders. In our opinion, the underlying mechanisms for exercise are far from consistent and reliable enough to raise PA up to be a standard medicine for NCDs. To further improve the curative and preventive effects of exercise, we have proposed that targeting the mitochondrial phenotype will be central to delivering on tailored exercise intervention (responses to which depend on lifestyle, genetic, and other molecular information about a person). A major step toward this goal will be to better understand individual exercise "responsomics" that will identify the responses of key molecules in exercise responsive tissues, thus informing us what exercise is the best for a person.

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Authors' contributions

Both authors were involved in the development of this review article. SD proposed the outline of the paper and offered the main opinion. ZQ performed the writing of the paper. Both authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

Competing interests

Neither of the authors declare competing financial interests.

References

1. Sacco RL, Smith SC, Holmes D, Shurin S. Accelerating progress on non-communicable diseases. *Lancet* 2013;**382**:e4–5.
2. McGuire S. *Centers for disease control and prevention. state indicator report on physical activity*. Atlanta, GA: U.S. Department of Health and Human Services; 2014.p.762–3.
3. General Administration of Sport of China. The official bulletin of public physical activity survey in 2014. *China Sports Daily*. Available at: http://read.sportspress.cn/zgtyb/page/1/2015-11-17/01/41061447721264251.pdf; 2015 [accessed 20.01.016].
4. World Health Organization. Noncommunicable diseases country profiles. Available at: http://apps.who.int/iris/bitstream/10665/128038/1/9789241507509_eng.pdf?ua=1; 2014 [accessed 20.01.2016].
5. World Health Organization. Noncommunicable diseases country profiles. Available at: http://www.who.int/nmh/countries/chn_en.pdf?ua=1; 2011 [accessed 20.01.2016].
6. Jaffe S. Planning for US Precision Medicine Initiative underway. *Lancet* 2015;**385**:2448–9.
7. Lowell BB, Shulman GI. Mitochondrial dysfunction and type 2 diabetes. *Science* 2005;**307**:384–7.
8. Heusch G, Libby P, Gersh B, Yellon D. Cardiovascular remodelling in coronary artery disease and heart failure. *Lancet* 2014;**383**:1933–43.
9. Tattersall I. Diet as driver and constraint in human evolution. *J Hum Evol* 2014;**77**:141–2.
10. Fildes A, Charlton J, Rudisill C, Littlejohns P. Probability of an obese person attaining normal body weight: cohort study using electronic health records. *Am J Public Health* 2015;**105**:e54–9.
11. Bauman AE, Reis RS, Sallis JF, Wells JC. Correlates of physical activity: why are some people physically active and others not? *Lancet* 2012;**380**:258–71.
12. Nam M, Choi MS, Jung S, Jung Y. Lipidomic profiling of liver tissue from obesity-prone and obesity-resistant mice fed a high fat diet. *Sci Rep* 2015;**5**:16984. doi:10.1038/srep16984
13. Xia SF, Duan XM, Hao LY, Li LT. Role of thyroid hormone homeostasis in obesity-prone and obesity-resistant mice fed a high-fat diet. *Metabolism* 2015;**64**:566–79.
14. Joo JI, Oh TS, Kim DH, Choi DK. Differential expression of adipose tissue proteins between obesity-susceptible and -resistant rats fed a high-fat diet. *Proteomics* 2011;**11**:1429–48.
15. Wang X, Choi JW, Joo JI, Kim DH. Differential expression of liver proteins between obesity-prone and obesity-resistant rats in response to a high-fat diet. *Br J Nutr* 2011;**106**:612–26.
16. Bergouignan A, Rudwill F, Simon C, Blanc S. Physical inactivity as the culprit of metabolic inflexibility: evidence from bed-rest studies. *J Appl Physiol* 2011;**111**:1201–10.
17. Alibegovic AC, Sonne MP, Hojbjerre L, Bork-Jensen J. Insulin resistance induced by physical inactivity is associated with multiple transcriptional changes in skeletal muscle in young men. *Am J Physiol Endocrinol Metab* 2010;**299**:E752–63.
18. Lieberman DE. Is exercise really medicine? An evolutionary perspective. *Curr Sports Med Rep* 2015;**14**:313–9.
19. Hawley JA, Hargreaves M, Joyner MJ, Zierath JR. Integrative biology of exercise. *Cell* 2014;**159**:738–49.
20. Raimundo N. Mitochondrial pathology: stress signals from the energy factory. *Trends Mol Med* 2014;**20**:282–92.
21. Morris EM, Jackman MR, Meers GM, Johnson GC. Reduced hepatic mitochondrial respiration following acute high-fat diet is prevented by PGC-1α overexpression. *Am J Physiol Gastrointest Liver Physiol* 2013;**305**:G868–80.
22. Wagatsuma A, Kotake N, Kawachi T Shiozuka M. Mitochondrial adaptations in skeletal muscle to hindlimb unloading. *Mol Cell Biochem* 2011;**350**:1–11.
23. Michan S. Calorie restriction and NAD(+)/sirtuin counteract the hallmarks of aging. *Front Biosci (Landmark Ed)* 2014;**19**:1300–19.
24. Steiner JL, Murphy EA, McClellan JL, Carmichael MD. Exercise training increases mitochondrial biogenesis in the brain. *J Appl Physiol* 2011;**111**:1066–71.
25. Hood DA, Saleem A. Exercise-induced mitochondrial biogenesis in skeletal muscle. *Nutr Metab Cardiovasc Dis* 2007;**17**:332–7.
26. Chandel NS. Evolution of mitochondria as signaling organelles. *Cell Metab* 2015;**22**:204–6.
27. Kelly SA, Villena FP, Pomp D. The 'omics' of voluntary exercise: systems approaches to a complex phenotype. *Trends Endocrinol Metab* 2015;**26**:673–5.
28. Zlotorynski E. Organelle dynamics: regulation of mitochondrial function by diet. *Nat Rev Mol Cell Biol* 2015;**16**:515. doi: 10.1038/nrm4049
29. Crisp A, Boschetti C, Perry M, Tunnacliffe A. Expression of multiple horizontally acquired genes is a hallmark of both vertebrate and invertebrate genomes. *Genome Biol* 2015;**16**:50. doi: 10.1186/s13059-015-0607-3
30. Wu B, Hao W. Horizontal transfer and gene conversion as an important driving force in shaping the landscape of mitochondrial introns. *G3 (Bethesda)* 2014;**4**:605–12.
31. Kokaze A, Ishikawa M, Matsunaga N, Karita K. Combined effect of longevity-associated mitochondrial DNA 5178 C/A polymorphism and coffee consumption on the risk of hyper-LDL cholesterolemia in middle-aged Japanese men. *J Hum Genet* 2010;**55**:577–81.
32. Kawamoto T, Kokaze A, Ishikawa M, Matsunaga N. Joint effect of longevity-associated mitochondrial DNA 5178 C/A polymorphism and alcohol consumption on risk of hyper-LDL cholesterolemia in middle-aged Japanese men. *Lipids Health Dis* 2011;**10**:105. doi:10.1186/1476-511X-10-105
33. Kritchevsky SB, Nicklas BJ, Visser M, Simonsick EM. Angiotensin-converting enzyme insertion/deletion genotype, exercise, and physical decline. *JAMA* 2005;**294**:691–8.
34. Dionne FT, Turcotte L, Thibault MC, Boulay MR. Mitochondrial DNA sequence polymorphism, VO_{2max}, and response to endurance training. *Med Sci Sports Exerc* 1993;**25**:766–74.
35. Ben-Zaken S, Eliakim A, Nemet D, Kassem E. Increased prevalence of MnSOD genetic polymorphism in endurance and power athletes. *Free Radic Res* 2013;**47**:1002–8.
36. Vaughan D, Huber-Abel FA, Graber F, Hoppeler H. The angiotensin converting enzyme insertion/deletion polymorphism alters the response of muscle energy supply lines to exercise. *Eur J Appl Physiol* 2013;**113**:1719–29.
37. Stephenson EJ, Hawley JA. Mitochondrial function in metabolic health: a genetic and environmental tug of war. *Biochim Biophys Acta* 2014;**1840**:1285–94.
38. Lauschke VM, Ingelman-Sundberg M. Precision medicine and rare genetic variants. *Trends Pharmacol Sci* 2016;**37**:85–6.