

2024 International Conference on Science and Technology, Modern Education and Management (TMEM 2024)

Investigating the Impact of Different Diets on Metabolism and Related Diseases Based on Gut Microbiota

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Abstract

The gut microbiota, as a critical regulator of host metabolism, is significantly influenced by dietary patterns. This study explores the effects of different diets on gut microbiota and their relationship with metabolism and related diseases. First, the composition of gut microbiota and its role in metabolism are reviewed. Next, the impacts of high-fat diets, low-carbohydrate diets, and high-fiber diets on the structure and function of gut microbiota are analyzed, and how these changes affect the onset and progression of metabolic syndrome, diabetes, and obesity is discussed. Finally, theoretical models based on existing research are proposed to explain the interactions between gut microbiota, diet, and metabolic diseases, with a discussion on future research directions. This study aims to provide theoretical foundations and practical guidance for dietary interventions and the prevention of metabolic diseases.

Keywords

Gut microbiota, Dietary patterns, Metabolic syndrome, Obesity

1. Introduction

In recent years, the gut microbiota, as a crucial microbial community within the human body, has garnered extensive attention for its role in maintaining host health and metabolic balance. The gut microbiota not only participates in food digestion and nutrient absorption but also influences overall health through the production of metabolites and the regulation of the immune system. Increasing evidence suggests that the composition and function of the gut microbiota are regulated by various factors, with dietary patterns being a key determinant. Different dietary patterns, such as high-fat diets, low-carbohydrate diets, and high-fiber diets, can significantly alter the structure and function of gut microbiota. These changes not only affect the metabolic activities of the gut microbiota but may also have profound implications for the host's metabolic processes and overall health.

2. Overview of Gut Microbiota

2.1 Composition and Function of Gut Microbiota

The gut microbiota refers to the community of microorganisms residing in the human gut, including bacteria, fungi, viruses, and protozoa. The composition of the gut microbiota is complex and diverse, primarily consisting of bacteria from phyla such as Firmicutes, Bacteroidetes, Actinobacteria, and Proteobacteria. These microorganisms coexist in high numbers and diversity within the gut and play a crucial role in maintaining host health. Firstly, the gut microbiota plays a significant role in nutrient metabolism. It helps break down dietary fibers and complex carbohydrates to produce short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These metabolites not only provide energy but also contribute to regulating gut health and immune function. For example, butyrate is known to protect gut epithelial cells and promote the maintenance of gut barrier function. Secondly, the gut microbiota plays a key role in the regulation of the immune system. Microbes in the gut interact with the host's immune system, influencing immune tolerance and immune responses. These microorganisms stimulate the development of the immune system and maintain gut immune balance by secreting antimicrobial peptides and regulating inflammatory responses. Additionally, the gut microbiota is closely related to the host's metabolic state. Research indicates that imbalances in the gut microbiota are associated with various metabolic diseases such as obesity, diabetes, and metabolic syndrome. Dysbiosis may lead to abnormal secretion of metabolic products, which in turn affects the host's energy metabolism and insulin sensitivity. In summary, the diversity and complexity of the gut microbiota make it a crucial research area for understanding human health and disease. Studying the composition and function of the gut microbiota is essential for revealing its role in metabolism and disease mechanisms (Beam, Elizabeth & Lei, 2021).

2.2 Relationship Between Gut Microbiota and Metabolism

The gut microbiota plays a critical role in host metabolism through various mechanisms that affect energy balance and metabolic status. Gut microbiota not only participate in the digestion and metabolism of nutrients but also influence overall health by regulating the production of metabolic products and host physiological functions. Firstly, the role of gut microbiota in energy metabolism is significant. Gut microorganisms ferment undigested dietary fibers and complex carbohydrates to produce short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These SCFAs are not only important energy sources but also regulate body weight by affecting fat storage and energy expenditure. Research has shown that SCFAs have significant effects on gut fat cells, gut epithelial cells, and overall metabolism. Secondly, gut microbiota participate in the regulation of glucose metabolism by modulating insulin sensitivity and blood glucose levels. Dysbiosis in gut microbiota can lead to increased inflammation, affecting insulin signaling pathways and insulin sensitivity. This process is closely related to the development of type 2 diabetes. Imbalances in specific gut microbiota, such as the ratio of Firmicutes to Bacteroidetes, are associated with insulin resistance and diabetes development. Furthermore, gut microbiota affect lipid metabolism by influencing fat storage and body

weight. Gut microbiota can synthesize and secrete various metabolic products that affect fat cell function and potentially alter fat storage by modulating fatty acid absorption and metabolism. For example, certain microbiota can enhance fatty acid transport and utilization, impacting lipid metabolism in the host. The relationship between gut microbiota and the host's energy balance and metabolic status is also evident in its effect on systemic inflammation levels. Gut microorganisms interact with the host's immune system to regulate inflammatory responses. Chronic low-grade inflammation is closely related to the occurrence of various metabolic diseases, including obesity, diabetes, and cardiovascular diseases. In conclusion, the gut microbiota plays a crucial role in host metabolism by affecting SCFA production, glucose metabolism, lipid metabolism, and inflammatory responses. Understanding these mechanisms helps reveal the role of gut microbiota in metabolic diseases and provides new insights for the prevention and treatment of related conditions (Fan & Oluf, 2021).

3. Impact of Diet on Gut Microbiota

3.1 Overview of Dietary Patterns

Dietary patterns have a significant impact on the composition and function of gut microbiota. Different dietary patterns influence the types and quantities of microbes in the gut by altering environmental conditions, thus having profound effects on host health. The main dietary patterns include high-fat diets, low-carbohydrate diets, and high-fiber diets, each affecting the gut microbiota differently. High-fat diets involve consuming a large amount of fat while relatively reducing other nutrients. This dietary pattern is common in modern eating habits, particularly with the increased consumption of fast food and high-fat products. Research indicates that high-fat diets significantly alter the structure of gut microbiota, reducing beneficial bacteria such as Bifidobacteria and Lactobacilli while promoting the proliferation of potentially pathogenic bacteria. High-fat diets may also decrease the diversity of gut microbiota, which is closely linked to an increased risk of metabolic syndrome, obesity, and type 2 diabetes. Low-carbohydrate diets, such as ketogenic diets, emphasize reducing carbohydrate intake while increasing fat and protein consumption (Myhrstad et al., 2020). The impact of low-carbohydrate diets on gut microbiota typically manifests as a reduction in microbes that utilize carbohydrates and an increase in microbes that utilize fats and proteins. This dietary pattern can lead to significant changes in the composition of gut microbiota, affecting gut health and metabolic state. High-fiber diets focus on consuming large amounts of dietary fiber from sources like whole grains, vegetables, and fruits. Dietary fiber is a crucial nutrient for gut microbiota, promoting the growth of beneficial bacteria and the production of metabolic products. High-fiber diets are generally associated with increased diversity of gut microbiota, which helps maintain gut health, reduce inflammation, and may lower the risk of metabolic diseases. In summary, different dietary patterns influence the structure and function of gut microbiota in various ways, impacting host metabolism and health. Understanding how these dietary patterns alter gut microbiota can aid in developing effective dietary interventions to improve gut health.

and prevent metabolic diseases.

3.2 Impact of Diet on Gut Microbiota Structure

Diet significantly affects the structure of gut microbiota, with different dietary patterns leading to notable changes in microbial communities. These changes not only influence the composition of gut microbiota but also can have broad implications for host health. The following are the impacts of several major dietary patterns on gut microbiota structure:

(1) Impact of High-Fat Diets

High-fat diets typically lead to decreased diversity in gut microbiota and promote the proliferation of certain potentially pathogenic bacteria. Studies have found that high-fat diets reduce the numbers of beneficial bacteria such as Bifidobacteria and Lactobacilli while increasing the proportion of Gram-negative bacteria like Escherichia coli. These changes can lead to an imbalance in gut microbiota, increasing inflammation and the risk of metabolic diseases. High-fat diets may also result in the overgrowth of specific microbial groups associated with obesity and diabetes.

(2) Impact of Low-Carbohydrate Diets

Low-carbohydrate diets (e.g., ketogenic diets) alter the metabolic environment of gut microbiota by significantly reducing carbohydrate intake. This dietary pattern leads to a decrease in carbohydrate-utilizing microbiota while increasing those that utilize fats and proteins. For example, low-carbohydrate diets may increase bacteria associated with protein fermentation while reducing those related to carbohydrate fermentation. These changes can impact the production of metabolic products and overall gut health.

(3) Impact of High-Fiber Diets

High-fiber diets positively affect the function of gut microbiota. Dietary fiber, an important nutrient, promotes the growth and metabolic activity of beneficial bacteria. This dietary pattern increases the production of short-chain fatty acids (SCFAs), including acetate, propionate, and butyrate, which not only provide energy but also have anti-inflammatory and gut barrier-improving effects. High-fiber diets are usually associated with increased diversity of gut microbiota, which helps maintain gut barrier function, reduce inflammation, and lower the risk of metabolic diseases. High-fiber diets also promote the growth of beneficial microbial populations while inhibiting pathogenic and potentially harmful bacteria.

(4) Impact of Other Dietary Patterns

In addition to the aforementioned major dietary patterns, other dietary habits such as high-protein and high-salt diets also impact gut microbiota. High-protein diets may increase the production of protein metabolism products, such as amino acid metabolites, which can affect the composition and function of gut microbiota. High-salt diets may alter the structure of gut microbiota and influence gut immunity and health.

In summary, diet significantly impacts the structure of gut microbiota, with different dietary patterns altering microbial diversity and function. These changes can have important implications for host

metabolism and health. Understanding how diet affects gut microbiota structure can aid in developing dietary interventions to optimize gut and overall health.

4. Gut Microbiota and Metabolic-Related Diseases

4.1 Metabolic Syndrome

Metabolic syndrome is a clinical condition characterized by multiple metabolic abnormalities, including abdominal obesity, hyperglycemia, dyslipidemia, and hypertension. Recent studies have highlighted the significant role of gut microbiota in the onset and progression of metabolic syndrome. Dysbiosis, which involves a reduction in beneficial bacteria and an increase in pathogenic bacteria, is closely associated with the development of metabolic syndrome. Specifically, the gut microbiota of individuals with metabolic syndrome often shows reduced diversity, with decreased levels of beneficial bacteria such as Bifidobacteria and Lactobacilli, and an increased proportion of bacteria associated with obesity and inflammation. This dysbiosis may promote the development of metabolic syndrome through various mechanisms, including increased inflammatory responses and altered energy metabolism (Croci et al., 2021). Dysbiosis can lead to chronic low-grade inflammation, which is closely related to the symptoms of metabolic syndrome. Pathogenic bacteria can produce endotoxins (such as lipopolysaccharides) that enter the bloodstream, triggering systemic inflammation. Chronic low-grade inflammation affects insulin action, leading to insulin resistance and subsequently high blood sugar and diabetes. Additionally, this inflammation can interfere with lipid metabolism, resulting in dyslipidemia and abdominal obesity. Furthermore, gut microbiota also regulates host energy metabolism by affecting the production of short-chain fatty acids (SCFAs). SCFAs such as acetate, propionate, and butyrate not only serve as energy sources but also improve insulin sensitivity, inhibit fat synthesis, and promote fat oxidation. However, a high-fat diet and dysbiosis may reduce SCFA production, thereby affecting energy metabolism and promoting obesity and metabolic syndrome. The metabolic products of gut microbiota, such as SCFAs and bile acids, also play a crucial role in metabolic syndrome. SCFAs regulate inflammation and metabolism by activating G protein-coupled receptors (such as GPR41 and GPR43), while bile acids modulate lipid metabolism and energy expenditure through interaction with intestinal receptors. Dysbiosis can lead to abnormalities in these metabolic products, negatively impacting metabolic syndrome. Based on the relationship between gut microbiota and metabolic syndrome, improving the structure and function of gut microbiota may offer an effective intervention strategy. For instance, supplementation with probiotics and prebiotics has been studied for its potential to correct dysbiosis, reduce inflammation, and improve metabolic status. Additionally, dietary adjustments, such as increasing fiber intake and reducing fat and sugar consumption, are also considered helpful in optimizing gut microbiota and alleviating symptoms of metabolic syndrome. In summary, the relationship between gut microbiota and metabolic syndrome is complex and significant. Understanding the role of gut microbiota in metabolic syndrome can provide new insights and strategies for disease prevention and treatment.

4.2 Diabetes and Obesity

Diabetes and obesity are prevalent metabolic diseases in modern society, and they are closely linked. Gut microbiota plays an important role in the onset and development of both conditions. Research indicates that the composition and function of gut microbiota are closely related to the pathological mechanisms of diabetes and obesity, and understanding these relationships can aid in developing new prevention and treatment strategies. Firstly, dysbiosis is considered an important factor in the development of diabetes and obesity. In obese individuals, gut microbiota typically shows reduced diversity, with decreased levels of beneficial bacteria (such as Bifidobacteria and Lactobacilli) and increased proportions of pathogenic bacteria (such as Klebsiella and Escherichia coli). This dysbiosis may promote the development of obesity and diabetes through various mechanisms. For example, changes in gut microbiota can lead to chronic low-grade inflammation, which is closely related to insulin resistance. Chronic low-grade inflammation induces systemic inflammatory responses through the production of endotoxins (such as lipopolysaccharides), affecting insulin function and leading to diabetes. Secondly, gut microbiota's regulation of energy metabolism and fat storage is also related to the mechanisms of obesity and diabetes. Gut microbiota ferments dietary fibers to produce short-chain fatty acids (SCFAs), which serve as energy sources and play a role in regulating fat metabolism and insulin sensitivity. However, dysbiosis may reduce SCFA production, affecting energy balance and promoting obesity. Moreover, certain metabolites from gut microbiota may impact host lipid metabolism and appetite regulation, further exacerbating obesity. Diabetes, particularly type 2 diabetes, is closely related to gut microbiota dysfunction. Studies have shown that the gut microbiota of diabetes patients undergoes changes in both metabolic function and structure. Dysbiosis may lead to impaired gut barrier function, increasing intestinal permeability and allowing endotoxins to enter the bloodstream, which triggers inflammation and insulin resistance. Imbalances in gut microbiota can also affect insulin secretion and function, worsening diabetes. Obesity also has a complex relationship with gut microbiota. Obesity not only alters the composition of gut microbiota but also affects metabolic function to promote fat accumulation. The gut microbiota of obese individuals often has higher energy extraction efficiency, leading to more food energy being converted into fat storage. Additionally, obesity-related dysbiosis may further exacerbate obesity and related metabolic diseases through its effects on inflammation, lipid metabolism, and insulin sensitivity. In summary, gut microbiota plays a critical role in the onset and development of diabetes and obesity. Understanding how gut microbiota affects the pathological mechanisms of these diseases can help in developing new intervention strategies, including dietary adjustments and the use of probiotics or prebiotics to improve gut health and, consequently, prevent and treat diabetes and obesity (Wilson et al., 2020).

5. Mechanisms and Theoretical Models

5.1 Specific Mechanisms of Gut Microbiota in Metabolism

The impact of gut microbiota on metabolism is mediated through various mechanisms, including

microbial metabolites, inflammatory responses, and energy balance. First, gut microbiota generates short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate through the fermentation of dietary fibers and other indigestible carbohydrates. SCFAs not only serve as an energy source but also regulate inflammation and insulin sensitivity by activating G-protein-coupled receptors (such as GPR41 and GPR43). For instance, butyrate, a primary energy source for colonocytes, has significant anti-inflammatory effects, helps maintain the integrity of the intestinal barrier, and reduces systemic inflammation levels. Additionally, SCFAs impact lipid metabolism by promoting fatty acid oxidation and inhibiting fat synthesis, thus playing a crucial role in weight management and metabolic balance. Secondly, an imbalance in gut microbiota can lead to the disruption of the intestinal barrier function, increasing the translocation of endotoxins (such as lipopolysaccharides, LPS) into the bloodstream. These endotoxins trigger systemic inflammation, causing chronic low-grade inflammation that is closely associated with insulin resistance, metabolic syndrome, and diabetes. Improving gut microbiota can enhance intestinal barrier function, reduce endotoxin release, and lower systemic inflammation levels, thus improving metabolic health. Moreover, gut microbiota also regulates the host's energy metabolism. Studies have found that the composition of gut microbiota is closely related to the host's energy balance. Specific microbiota can increase energy extraction efficiency, leading to more food energy being converted into fat storage. Additionally, gut microbiota affects the digestion and absorption of dietary components; for example, certain microbiota can enhance dietary fat absorption, leading to increased fat storage, which impacts body weight and metabolic status. The regulation of insulin sensitivity by gut microbiota is also significant. Microbial imbalance may trigger inflammatory responses that affect insulin function. Gut microbiota influences insulin secretion and action by regulating the secretion of gut hormones, such as GLP-1 (glucagon-like peptide-1) and GIP (gastric inhibitory polypeptide). Additionally, SCFAs improve insulin sensitivity by affecting insulin signaling pathways, thereby having a positive impact on metabolic health. Finally, the metabolic products of gut microbiota, such as SCFAs, bile acids, and gases (e.g., hydrogen and methane), significantly affect the host's metabolism. Bile acids not only participate in lipid digestion but also regulate lipid and glucose metabolism by activating nuclear receptors (such as FXR and TGR5). The production of gases is also related to gut microbiota functionality and may impact gastrointestinal motility and metabolic processes. These metabolic products interact with the host's metabolic system, affecting energy balance, lipid metabolism, and overall health. In summary, gut microbiota profoundly influences the host's metabolism through various mechanisms, including the generation of short-chain fatty acids, endotoxin-induced inflammatory responses, energy metabolism regulation, insulin sensitivity improvement, and systemic effects of metabolic products. Understanding these mechanisms not only reveals the specific impacts of gut microbiota on metabolism but also provides a scientific basis for developing relevant intervention strategies (Catalkaya et al., 2020).

5.2 Proposals and Discussion of Theoretical Models

To gain a deeper understanding of how gut microbiota affects metabolic health, several theoretical models have been proposed to explain this complex biological process. These models help systematically integrate the relationships between gut microbiota, metabolic pathways, and host health. First, the Microbiota-Host Interaction Model emphasizes the bidirectional interaction between gut microbiota and the host. According to this model, gut microbiota directly affects the host's metabolic processes through the production of short-chain fatty acids (SCFAs) and other metabolites, while the host's diet and lifestyle also influence the composition and function of gut microbiota. This bidirectional interaction mechanism reveals how gut microbiota impacts metabolic health by regulating inflammation responses, insulin sensitivity, and energy metabolism. Next, the Inflammation-Metabolism Interaction Model focuses on the impact of chronic low-grade inflammation caused by gut microbiota imbalance on metabolic health. This model suggests that gut microbiota imbalance disrupts intestinal barrier function, allowing endotoxins (such as lipopolysaccharides) to enter the bloodstream and trigger systemic inflammation. Chronic inflammation promotes the occurrence of metabolic syndrome, diabetes, and obesity by interfering with insulin signaling pathways and lipid metabolism. This model provides a framework for understanding how gut microbiota regulates the host's metabolic processes through inflammatory mechanisms. The Energy Balance Regulation Model explores how gut microbiota regulates body weight and metabolic status by affecting energy intake, digestion, and storage. This model emphasizes that the production of short-chain fatty acids, digestion and absorption of dietary components, and gut microbiota's regulation of host energy metabolism are key mechanisms through which gut microbiota impacts weight and metabolic balance. Changes in microbiota can influence the efficiency of energy utilization, thereby affecting weight management and metabolic balance. Additionally, the Hormonal Regulation Model addresses how gut microbiota influences metabolic health by regulating the secretion of gut hormones. This model points out that gut microbiota can modulate the secretion of hormones such as glucagon-like peptide-1 (GLP-1) and gastric inhibitory polypeptide (GIP), which play important roles in regulating appetite, insulin secretion, and lipid metabolism. The model suggests that changes in gut microbiota may further affect the host's metabolic state by influencing these hormone levels. Finally, the Metabolite Interaction Model investigates how metabolic products produced by gut microbiota (such as short-chain fatty acids and bile acids) interact with the host's metabolic system. This model highlights that these metabolic products not only participate in lipid digestion but also regulate lipid and glucose metabolism by activating nuclear receptors. For instance, bile acids aid in lipid digestion and also regulate overall metabolism through nuclear receptors. This model provides an in-depth understanding of how gut microbiota's metabolic products influence host metabolic health. In summary, these theoretical models offer different perspectives and explanatory frameworks for understanding the impact of gut microbiota on metabolism. Each model reveals distinct mechanisms through which gut microbiota affects metabolic health. Future research can further integrate these models, combine high-throughput omics

technologies with clinical data, and explore gut microbiota's specific roles in metabolism across different populations and disease states to develop personalized health management strategies.

6. Conclusion

This study reviews the impact of gut microbiota on metabolism and related diseases, and examines the effects of different diets on gut microbiota. The research indicates that gut microbiota affects the host's metabolism through various mechanisms, including the production of short-chain fatty acids, regulation of inflammatory responses, modulation of energy balance, and hormone secretion. Different dietary patterns can significantly alter the composition and function of gut microbiota, thereby affecting metabolic health and disease risk. The theoretical models constructed provide a deep understanding of these complex mechanisms and offer a theoretical foundation for future research and intervention strategies. Future studies should further explore the specific connections between gut microbiota and metabolism, especially across different populations and disease states, to develop personalized health management plans.

References

- Beam, A., Elizabeth, C., & Lei, H. (2021). Effect of diet and dietary components on the composition of the gut microbiota. *Nutrients*, 13(8), 2795.
- Catalkaya, G. et al. (2020). Interaction of dietary polyphenols and gut microbiota: Microbial metabolism of polyphenols, influence on the gut microbiota, and implications on host health. *Food Frontiers*, 1(2), 109-133.
- Croci, S. et al. (2021). Dietary strategies for management of metabolic syndrome: Role of gut microbiota metabolites. *Nutrients*, 13(5), 1389.
- Fan, Y., & Oluf, P. (2021). Gut microbiota in human metabolic health and disease. *Nature Reviews Microbiology*, 19(1), 55-71.
- Myhrstad, M. C. W. et al. (2020). Dietary fiber, gut microbiota, and metabolic regulation—Current status in human randomized trials. *Nutrients*, 12(3), 859.
- Wilson, A. S. et al. (2020). Diet and the human gut microbiome: an international review. *Digestive diseases and sciences*, 65, 723-740.