Application of Mathematical Modeling in Basic Medical Research

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Abstract: Mathematical modeling, as a bridge connecting mathematical theory with practical problems, lies in its core value of revealing the inherent laws of complex systems through quantitative analysis and logical deduction. Against the backdrop of basic medical research transitioning towards precision, systematization, and intelligence, the concept of mathematical modeling has become an essential tool for deciphering physiological mechanisms, optimizing experimental design, predicting disease progression, and enhancing diagnostic and therapeutic efficiency. This paper elucidates the integration of mathematical modeling with basic medical research, analyzing its specific application scenarios and practical value in basic medicine from three dimensions: physiological process simulation, disease mechanism elucidation, and drug development optimization. It explores issues such as model applicability and data dependency in current applications and proposes targeted optimization pathways. Simultaneously, aligning with the strategic requirements of "Healthy China 2030", it looks ahead to the convergence trends of mathematical modeling with artificial intelligence and big data technologies, providing comprehensive theoretical and practical references to promote the quantitative upgrading of basic medical research and facilitate medical technological innovation.

Keywords: Basic medicine, Mathematical modeling, Physiological simulation, Disease prediction, Drug development.

1. Introduction

Currently, the global medical field is undergoing a profound transformation from "experience-based medicine" to "precision medicine", with increasingly urgent demands for the prevention and treatment of major diseases and public health emergency response. China's "Healthy China 2030" strategy explicitly proposes to strengthen medical science and technology innovation and promote interdisciplinary integration. With the development of medicine and technology, mathematics is widely and deeply applied in the medical field, from disease diagnosis, treatment, and drug development to human physiological system modeling and medical image processing, none of which can do without mathematics [1]. Against this backdrop, this study aims to comprehensively review the integration of mathematical modeling and basic medical research, clarify the application scenarios of mathematical modeling in core research areas of basic medicine, and conduct an in-depth analysis of key issues and constraints in current applications. It also explores the application value and practical pathways of mathematical modeling in basic medical research, providing theoretical and practical support for addressing the complexity of basic medical research and facilitating breakthroughs in medical technology. The methodology of this study primarily involves reviewing relevant research achievements both domestically and internationally, comparing the research priorities, technical advantages, and existing shortcomings of mathematical modeling in basic medical applications. It selects typical application cases in fields such as physiological process simulation, disease mechanism analysis, and drug development optimization. The study conducts an in-depth analysis of the specific implementation processes, technical methods, and application outcomes of mathematical modeling to enhance the practicality and persuasiveness of the research. Core viewpoints are demonstrated through concrete application cases, and future optimization paths and development trends are deduced in accordance with the interdisciplinary integration development patterns.

The significance of this research lies in providing efficient quantitative research tools for basic medical researchers, helping to solve the

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challenges of studying complex physiological and pathological mechanisms; offering precise solutions for practical fields such as drug development, disease prevention and control, and clinical diagnosis and treatment, thereby improving the efficiency and quality of medical research and healthcare services; responding to the strategic needs of "Healthy China 2030", promoting medical technological innovation and interdisciplinary talent cultivation, and injecting new momentum into the high-quality development of China's medical industry.

2. Research Foundation

2.1 Basic Concepts

(1) Basic Medicine

Basic medicine is a branch of medicine that studies the essence of life phenomena and the mechanisms of disease occurrence and development, providing theoretical foundations and technical support for clinical medicine. Its core focus is on exploring "why diseases occur" rather than directly treating diseases. It centers on two major research areas: the normal structure and function of the human body, and the patterns of change under pathological conditions. This discipline encompasses classic fields such as human anatomy, physiology, biochemistry, pathology, and pharmacology, serving as a bridge between life sciences and clinical medicine.

With the advancement of precision medicine and big data technologies, basic medical research has exhibited three major characteristics: First, the research dimensions have expanded from macroscopic to microscopic levels, delving into molecular aspects such as genes, proteins, and metabolites. Second, research data have evolved from single-modal to multimodal integration, encompassing multi-omics data including genomics, transcriptomics, proteomics, and metabolomics. Third, research objectives have shifted from qualitative descriptions to quantitative analysis, aiming for precise characterization and prediction of physiological and pathological processes. These features provide extensive opportunities for the integration of mathematical modeling and impose higher demands on interdisciplinary research.

(2) Mathematical Modeling

Mathematical modeling is a process of transforming real-world problems into mathematical structures that can be expressed by mathematical symbols, formulas, and algorithms through steps of abstraction, simplification, and hypothesis, and then solving and explaining real-world problems. Its core is "using mathematics to solve practical problems".

The general workflow of mathematical modeling comprises four key phases: problem analysis and simplification, model formulation and construction, model solution and validation, and model optimization and application. In basic medical research, the core value of mathematical modeling lies in transforming complex physiological and pathological processes into quantifiable and computable mathematical problems. Through logical deduction and numerical simulation, it reveals underlying patterns. Common mathematical modeling methods include differential equation modeling, statistical modeling, machine learning modeling, and network modeling, each tailored to different types of medical challenges. For instance, differential equation models are often used to describe dynamic physiological processes, statistical models are suitable for disease risk prediction, and machine learning models are applicable for mining large-scale medical data.

(3) The logical integration of the two

The integration of basic medical research and mathematical modeling is essentially a bidirectional process of "mathematizing medical problems" and "medicalizing mathematical models". Its core convergence manifests in three aspects: First, the alignment of research objectives, as both strive to uncover the intrinsic laws of life and disease, thereby providing scientific support for health protection. Second, the complementarity of research methods, where experimental data from basic medical research serve as the empirical basis for mathematical modeling, while the quantitative tools of mathematical modeling offer precise analytical means for basic medical research. Third, the synergy in research development, where complex issues in basic medical research drive innovations in mathematical modeling methods, and breakthroughs in mathematical modeling technology propel basic medical research toward deeper advancements.

This integrative logic enables mathematical modeling to effectively address the limitations of traditional basic medical research. On one hand, mathematical modeling can transform abstract physiological and pathological mechanisms into computable models, resolving issues that are difficult to quantify in conventional research. On

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the other hand, it can integrate multidimensional and massive medical data to uncover hidden correlations within the data, providing novel research perspectives and discovery pathways for basic medical research.

2.2 Domestic and International Research Findings

Scholars both domestically and internationally have conducted extensive in-depth research on the integration of mathematical modeling with basic medicine. Internationally, physiologically based pharmacokinetic (PBPK) models have been continuously iterated, incorporating multidimensional data such as single-cell sequencing and metabolomics to achieve precise customization of dosing regimens in targeted drug development, significantly improving the success rate of clinical trials [2]. Improved SIR models and their derivatives, combined with big data analysis techniques, have played a pivotal role in predicting the transmission trends of infectious diseases such as COVID-19 and monkeypox, as well as evaluating the effectiveness of prevention and control measures [3]. Domestic research has focused on localized medical needs, achieving remarkable results in areas such as chronic disease prevention and treatment, and cancer mechanism studies. Early warning models for chronic diseases, constructed using random forests, support vector machines, and deep learning algorithms, have demonstrated an early prediction accuracy of over 95% for conditions such as hypertension and diabetes. Breakthroughs in multimodal data fusion modeling technology have been made in tumor classification and biomarker screening, providing novel tools for precision diagnosis and treatment of tumors [4]. Additionally, in the study of neurodegenerative diseases, neural network models based on differential equations have successfully simulated neuronal signal transduction mechanisms, offering quantitative evidence for the pathogenesis research of diseases such as Alzheimer's disease.

3. Application of Mathematical Modeling in Basic Medical Research

Traditional basic medical research often relies on experimental observation and qualitative analysis, making it difficult to accurately depict the dynamic changes and interactions of complex biological systems. Mathematical modeling is the core driving force that propels basic medical research from "phenomenon description" to "mechanism analysis" and "precise prediction" [5]. Its core value lies in breaking the limitations of traditional medical research through interdisciplinary integration. Future basic medical research should further strengthen the application of mathematical modeling, focusing on enhancing the interpretability, practicality, and localization adaptability of models, promoting their deep integration with clinical research and public health practices, and providing core support for medical technology innovation and the implementation of the health China strategy [6].

3.1 Solving Physiological Process Simulation Problems Using Mathematical Modeling

Mathematical modeling plays a pivotal role in simulating physiological processes. The human physiological system is a complex network composed of multiple organs and molecules, characterized by nonlinear and coupled dynamic changes, which are difficult to fully analyze through traditional experimental methods. Through mathematical modeling, physiological processes such as blood flow, neural signal transmission, and metabolic network regulation can be abstracted into models like differential equations, enabling quantitative descriptions of physiological mechanisms. For instance, the atrioventricular model can simulate the absorption, distribution, metabolism, and excretion of drugs in vivo, accurately predicting the temporal variation of drug concentrations. By leveraging the geometric significance of definite integrals in single-variable calculus, the area under the drug concentration-time curve can be calculated to estimate the actual effective dose of the drug [1], as illustrated in Figure 1.

3.2 Mathematical Modeling for Disease Mechanism Analysis

Mathematical modeling demonstrates unique advantages in disease mechanism analysis and prediction. The pathogenesis and progression of diseases involve multiple factors, including genetic, environmental, and physiological system interactions, resulting in complex and individualized processes. Mathematical modeling can integrate multidimensional biological data to construct disease risk prediction models and pathological progression models, enabling precise forecasting of disease occurrence probability and developmental trends [7]. Utilizing single-variable differential calculus, tumor growth models can be established to

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quantify the dynamic processes of tumor cell proliferation, invasion, and apoptosis, revealing key drivers of tumor progression and providing theoretical references for the development of targeted therapeutic strategies [1], as illustrated in Figure 2.

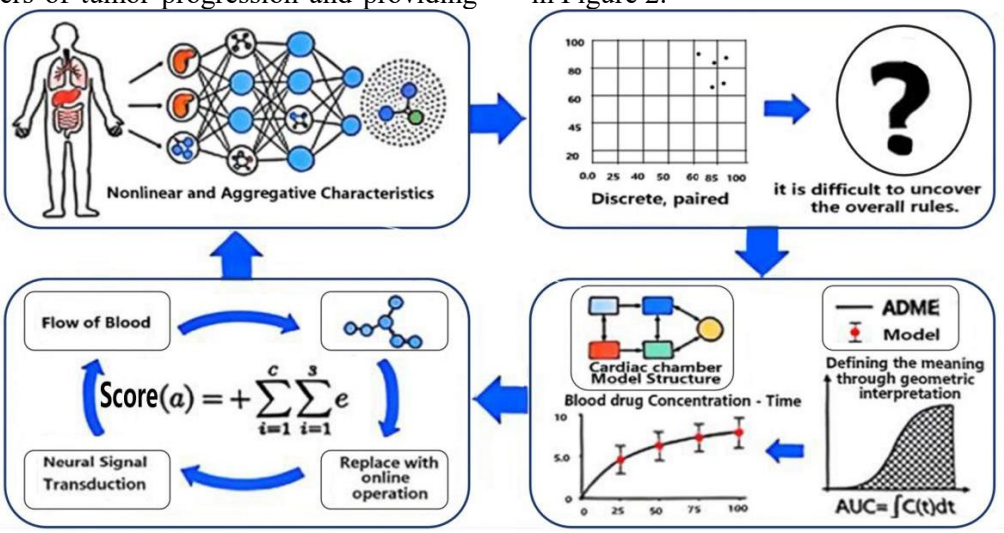

Figure 1. Logical flowchart of mathematical model for physiological process simulation

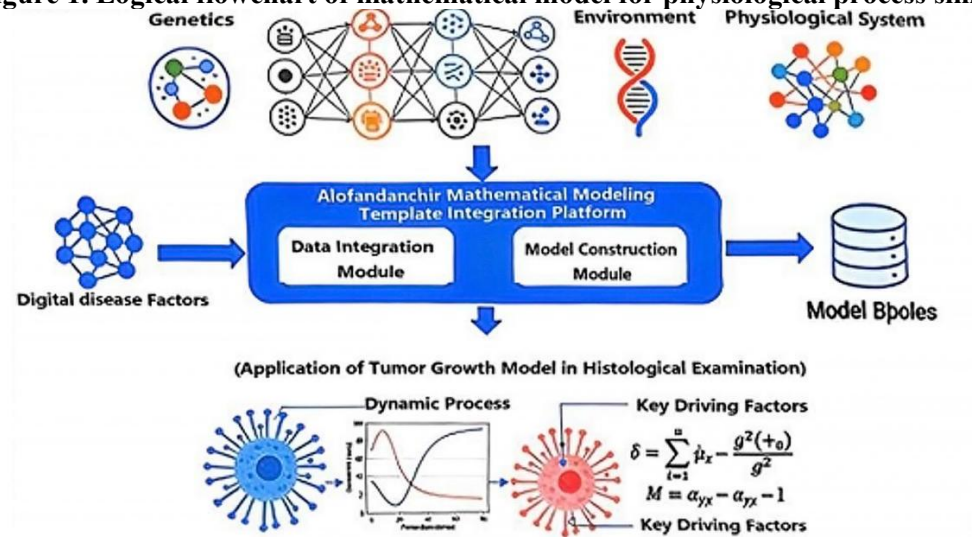

Figure 2. Application of Mathematical Modeling in the Analysis and Prediction of Tumor Disease Mechanisms

3.3 Mathematical Modeling for Optimizing Drug Development Processes

Drug development represents a pivotal application of basic medical research, where the integration of mathematical modeling has significantly enhanced both efficiency and precision. Traditional drug development faces challenges such as prolonged timelines, high costs, and low success rates. Mathematical modeling, however, can be applied throughout the entire drug development process: During the drug screening phase, molecular docking models and pharmacodynamic prediction models enable rapid identification of potential active compounds, reducing experimental costs. In clinical trials, statistical modeling methods optimize trial designs and allocate sample sizes rationally, thereby improving the reliability of trial outcomes. For dosing regimen optimization, population pharmacokinetic models combined with individual patient characteristics allow for personalized dosing, enhancing therapeutic efficacy while minimizing adverse reaction risks. Leveraging digital twin technology, the pathogenesis of diseases can be elucidated, and all relevant molecular, phenotypic, and environmental factors reconstructed. By replicating digital twins and calculating the digital effects of different drugs, the most effective therapeutic agent can be identified [8]. Using pharmacokinetic differential equations, the general solution can be derived through the separation of variables method, providing comprehensive insights into drug metabolism in the human body [9]. This approach enables

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better dosage control and improves drug development [3], as illustrated in Figure 3.

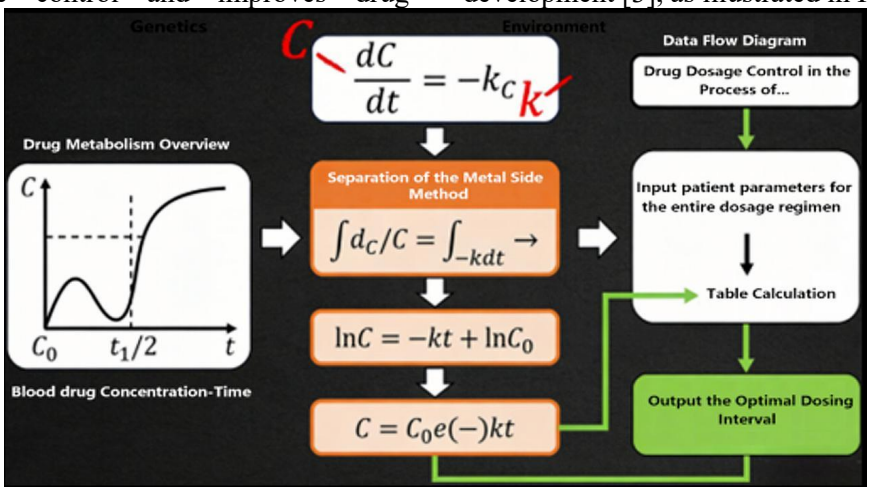

Figure 3. Schematic Diagram of Mathematical Modeling Research in Drug Development

4. Statistical Models for Data Analysis

Statistics is a methodological discipline that collects, organizes, analyzes, and interprets data to draw conclusions and reveal patterns, with extensive applications in scientific research, finance, and other fields. In basic medical research, statistical methods such as statistical testing, survival analysis, and logistic models have been widely adopted in recent years. By leveraging emerging technologies like computer-aided deep thinking, statistical methods enable efficient and accurate processing of complex data. This not only ensures the precision and rigor of experimental data processing but also enhances research efficiency, shortens study timelines, and accelerates the translation of findings into practical applications [10]. In recent years, statistical methods have become an indispensable component of medical research, particularly in areas such as tumor prognosis evaluation, genetic testing interpretation, and disease prediction model construction.

5. Conclusion

In conclusion, the application of mathematical models in medical research can accelerate the advancement of medical studies. Many aspects of medical research are often abstract, and the use of mathematical models for analysis allows for the interpretation of various abstract issues from a mathematical perspective, thereby facilitating the development of diverse medical research endeavors.

However, despite the significant achievements of mathematical modeling in basic medical research, it still faces numerous challenges: Firstly, the biological applicability of models is insufficient, with some models oversimplifying biological processes and deviating from the complex physiological and pathological realities. Secondly, there is a strong dependence on high-quality data, as the heterogeneity and incompleteness of biological data constrain model accuracy. Thirdly, interdisciplinary integration is inadequate, as the communication and collaboration mechanisms between medical researchers and mathematical researchers remain underdeveloped, resulting in models that fail to fully meet research needs.

In this regard, further research is needed in areas such as the biological relevance of mathematical models and the standardization of biological data systems. It is essential to establish interdisciplinary collaboration platforms to facilitate in-depth cooperation among researchers in fields such as medicine, mathematics, and computer science, thereby promoting the deep integration of mathematical modeling with basic medical research.

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