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Global Advances in Biomolecular and Applications in Human Health

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Abstract:

Biomolecular science studies molecules responsible for life activities (e.g. proteins, nucleic acids, and metabolites). It has been the primary engine fueling responses to worldwide health issues. In this methodbased review, we comprehensively recapitulate the recent advancements in global biomolecular science, and their potential to benefit human health.This section first provides the fundamental research areas and technical systems of biomolecular science, next evaluates the scientific technological frontier and foreign scientific technology layout of key technological achievements, and finally summarizes typical application of molecular mechanism research cases in the disease diagnosis and disease treatment.Through combing the frontier progress and the clinical practice, this review emphasizes the important position of biomolecular science in the advance for disease recognition, drug therapy and public health improvement, as well as offering a reference for further research and application. This comprehensive overview aims to bridge the gap between fundamental biomolecular research and practical healthcare applications, offering a roadmap for future interdisciplinary research.

Keywords: Biomolecular Technology; Technology Evolution; Disease Process; Medical; International Research Front.

1. Introduction

Biomolecular science explores the structure, function, and interaction of biological molecules (including proteins, DNA, RNA, lipids, and metabolites) that constitute life [1]. It is like a "molecular microscope" helping humans uncover the mysteries of life activities—from how cells "communicate" to why diseases occur. As a rapidly evolving interdisciplinary field, biomolecular science integrates biology, chemistry, physics, computer science, and engineering to decode life at the molecular level.

The significance of biomolecular science in human health is irreplaceable and foundational. In disease mechanism research, it reveals the molecular root cause of diseases: abnormal protein folding is the origin of Alzheimer's disease, and gene mutation could lead to cancer. In drug discovery, it accelerates finding the drugs targets: the COVID-19 vaccine developed by targeting the spike protein of the virus is

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a prototypical example [2]. Public health: it facilitates the prevention and control of disease: tracking variations of disease viruses' genes helps experts predict the infection situation and develop countermeasures.

Recently, along with developments of technologies such as multi-omics (analyzing multiple types of biomolecules simultaneously, e.g. genomics, proteomics, etc.), artificial intelligence (AI), and single-cell sequencing, biomolecular science has been arrived at "big data era", in which researchers could evaluate information of thousands of molecules at one time to solve previously insolvable issues in health.

At global level, research on biomolecular science has achieved unprecedented progress in recent decades. The classical research concentrated on single molecules: For instance, in 1953 the authors identified the double helix structure of the DNA molecule paving the way for molecular genetics, which flourished in the last century. Genomics was nurtured by the success of Human Genome Project, which led to large scale sequencing of the genes. As a rapidly evolving interdisciplinary field, biomolecular science integrates biology, chemistry, physics, computer science, and engineering to decode life at the molecular level.

In recent years, breakthroughs have emerged continuously. In 2021, the AI system AlphaFold developed by DeepMind achieved a breakthrough in protein structure prediction, solving the 50-year-old problem of "how proteins fold into functional shapes" and greatly promoting research in structural biology [3]. The CRISPR-Cas9 gene-editing technology, known as "molecular scissors", allows precise modification of genes, providing new ideas for curing genetic diseases [4]. In addition, multi-omics technologies have been widely used in disease research: for example, analyzing tumor multi-omics data can identify personalized treatment targets for cancer patients.

The reviews of existing biomolecular science in the current literature mostly are restricted to a specific discipline (e.g., proteomics only, gene editing only), or in other cases, they kept basic research apart from the use thereof.Nevertheless, this is a special review writing "dual side" of "progress of frontier" and "application on clinic/health", i. e. try to: (1) clarify the key technical system of global biotechnology; (2) link the frontier technologies with certain applications on the clinic/health with typical example; (3) give a big view to the relationship among basic research and health application.Wethink such combination of theory and practice will assist readers, particularly students and young researchers, to understand the general scenery of biomolecular science and its current practicality. It also emphasizes the importance of global collaboration, data sharing, and open science frameworks for accelerating biomolecular innovation

2. Current Status and Technical Platforms of Global biomolecular Science

2.1 Core Research Areas and Technical Systems

Biomolecular science covers multiple interdisciplinary research fields, supported by a diverse range of technical platforms: Omics Sciences: proteomics (protein of cell all molecule analysis), metabolomics (small molecule metabolite all molecule analysis), transcriptomics (gene expression product of gene RNA detection), epigenetics (regulation of gene without changing gene DNA). These technologies study with the application of mass spectrometry, high throughput sequence.

Structural Biology: Describing 3D structure of molecules in biology to understand how they work. Representative methods: cryo-electron microscopy (frozen molecules under microscope, imaging at high resolution); x-ray crystallography (X-ray spectroscopy on crystal structure of molecules) and nuclear magnetic resonance (NMR, for a small protein/ nucleic-acids) Recent advances include CRISPR-based gene circuits, cell-free systems, and programmable molecular devices, expanding biomolecular science applications.

HTP Screening and Molecular Imaging: A high-throughput screening uses automation tools to screen many, thousands, of molecules at one time, thereby, speeding the process of drug discovery. Molecular imaging methods (fluorescent labeling and confocal microscopy, etc.) enable the observation of the activities of molecules in living cells in real time. Synthetic Biology and Molecular Engineering: Designing and reconstructing biological molecules to generate novel biological function, for instance engineering bacteria to produce insulin and engineering antibodies with improved ability to target tumor.

2.2 Key Technical Breakthroughs and International Research Layout

Among the top biomolecular science research institutes in the world, we can see that U.S.A. dominates in genomics and gene editing research; Germany in structural biology; Japan in synthetic biology at the University of Tokyo. AlphaFold: As mentioned earlier, it can predict protein structures with atomic-level accuracy, which has been applied to research on malaria and Parkinson's disease [3].

Single-Cell Sequencing: This technology allows researchers to explore gene expression profiles of a single cell, which unveils cell heterogeneity of tumors (i.e., cells from the same tumor possess distinct molecular signatures), and

is important for personalized cancer therapy. This technology has reshaped our understanding of developmental biology, immune cell diversity, and tumor evolution
Spatial Transcriptomics: Maps expression of RNA across tissue space, enabling studies into the arrangement and communication among cell types in organs and has been applied to characterization of tumor microenvironment46. Coupled with AI and imaging, spatial omics provides unprecedented insights into tissue organization and disease progression.

2.3 Visual Analysis of Global Research Trends

Based on literature analysis of Web of Science and PubMed databases:
Hot Topics: In the past five years, high-cited papers mainly focus on AI in biomolecular research (e.g., protein prediction), COVID-19 molecular mechanisms, and single-cell multi-omics. These trends reflect a paradigm shift toward AI-driven molecular modeling, integrative omics, and translational precision medicin
International Collaboration: Cross-country collaborative research in the world have grown at 40% over the past ten years. For instance, over 2,000 scientists from more than 70 countries are involved in Human Cell Atlas project to help map all the types of cells in our human body with a better data sharing and standards [5].

3. Cutting-Edge Molecular Mechanisms and Health Application Cases

3.1 Molecular Mechanism New Discoveries

Recent discoveries on regulating signal transduction pathways further helped identify disease pathology: e.g. a novel phosphatase is discovered to control the MAPK pathway by dephosphorylating ERK1/2 to hinder abnormal cell proliferation resulting from pathway over-activation [6].Moreover, in the study of DNA/RNA modification, it has been verified by research that methyltransferase METTL3 catalyzes the m6A modification on oncogene MYC mRNA, making it more stable, and the demethylase FTO does the opposite-mimicking a loop and is closely related to tumor development.To research the proteins' protein interaction network (PPI), compared to the conventional SVM and single machine learning model, RF-PSSM algorithm integrates the evolutionary characteristics of PSSM and extract features from 2DPCA, and effectively predicts 9 possible interacting proteins between HCV E1 protein and human hepatocytes, where the previously unrecognized cyclophilin D is also found [6].

3.2 Typical Disease Mechanisms and Molecular Target Research

One oncologic example is voltage-dependent anion channel 1 (VDAC1), the importance of which as a target has been amply demonstrated because, on the one hand, its binding to hexokinase promotes glycolysis of lung cancer cells [7], whereas, on the other hand, the tubulin antagonist erastin induces VDAC1/2 opening so to induce ferroptosis [8]; and the preclinical evidence further shows VBIT-4 (a VDAC inhibitor) to decrease tumor volume by \$62\%\$ in xenograft models [9].Regarding neurodegenerative diseases, it has been found that AD related GPR120 activation increases matrix metalloproteinase-9 (MMP-9) expression to facilitate degradation of amyloid-β (Aβ) peptides, and docosahexaenoic acid (DHA) treatment of AD model mice reduces the brain Aβ by 38% and also eases brain dysfunction [10]. Regarding infectious diseases, besides rational classification of protein variant in spike protein of SARS-CoV-2 using the PSAC-PDB framework, the major amino acid sites are also been found (e.g., those lying along the interface across multiple protein structures such as ligand-gated ion channel (LGIC) of Homo sapiens [11, 12].This tool predicts for both COVID-19 and influenza variants, among which SARS-COV-2 and D614G represent an example of a variant identified to increase the protein receptor affinity [13]; for influenza, the tool elucidates the hemagglutinin (HA)-sialic acid receptor relationship to illuminate the mechanisms of seasonality induced changes in transmissibility through the evolutionary history of HA [7].

3.3 Case Analysis Supported by Public Databases

Translational research relies heavily on the data from public biological database: TCGA (The Cancer Genome Atlas) provides an integrative analysis of the mutational profiling of the lung adenocarcinoma to uncover the most significant driver genes of lung adenocarcinoma including EGFR and KRAS with mutually exclusive mutated genes as guide to determine targeted drugs [8].The GTEx (Genotype-Tissue Expression) data have demonstrated that the metabolic gene PPARα is liver-specific over-expressed, and its down regulation in the obese patients are associated with insulin resistance-verify its use in type 2 diabetes [13]. PDB (Protein Data Bank) combines AlphaFold-predicted structure, cryo-EM experimental data like the resolved structure of the Aβ fibril, that supply a template design aggregation inhibitor [14].From Drugbank we retrieve interactions between anti-seizure drugs and their targets and we verify that topiramate, binding to KCNJ10 (Kir4.1 channels), has affinity 1.2 μM and levetiracetam

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does not interact with KCNJ10 (these results explain why therapeutic response of EAST/SeSAME syndrome differs in these two patients [15].

4. Conclusion

Biomolecular science bridging basic science and healthcare has transformed prevention and treatment of diseases. As a review reveals, multi-omics, structural biology, and AI-based tools elucidate oncogenesis, neurodegeneration and infection, while data bases facilitate personalisation. Finally, international collaboration enhances developments and demonstrates its significance in pharma and public health.But we think it is lacking in terms of integration of data and interdisciplinary cooperation, thus in the future more efforts are needed to promote interdisciplinary synergy and artificial intelligence for personalized medicine. Another important direction is the translation of these discoveries into scalable and equitable healthcare solutions. While breakthroughs in biomolecular science and personalized medicine often emerge from highly specialized laboratories, their impact depends on integration into health systems that can deliver benefits to diverse populations. This requires not only advances in clinical trial design and regulatory frameworks but also infrastructure for data sharing and harmonization across countries. Building interoperable platforms will allow genomic, proteomic, metabolomic, and imaging data to be compared and validated across different cohorts, thereby improving reproducibility and accelerating clinical uptake. Ethical considerations are becoming increasingly prominent. The ability to generate detailed molecular and clinical profiles raises questions about privacy, ownership, and the potential for inequities in access. If left unaddressed, these challenges may widen the gap between high-income and resource-limited settings. Thus, the next phase of biomolecular innovation must involve bioethicists, policy makers, and patient communities to establish governance models that safeguard rights while fostering scientific progress. Furthermore, biomolecular science is increasingly tied to environmental and societal factors. For example, the study of exposomics—how pollutants, diet, and lifestyle interact with genetic predispositions—illustrates the importance of contextualizing molecular data within broader ecological and social systems. Integrating these dimensions will not only refine disease prediction but also inform public health interventions targeting prevention at the population level. Finally, education and workforce development will be crucial. To fully leverage the potential of biomolecular advances, new generations of scientists, clinicians, and data specialists must be trained to operate across disciplinary boundaries. Programs that combine biology, computer science, engineering, and clinical medicine can foster the skill sets needed to translate complex datasets into actionable healthcare strategies. Such investments will ensure that biomolecular science continues to bridge basic discoveries with meaningful healthcare outcomes, advancing both precision medicine and global health equity.

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