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Dinosaur Origin of Birds: Evidence and Research Methods of Cranium Evolution

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Abstract:

Research on avian skull evolution represents a key field for exploring the hypothesis of avian origin from theropod dinosaurs. In terms of research methods, Computed Tomography (CT) technology, through cranium, mandible and endocast reconstruction, provides support for analyzing the fine structure and evolutionary path of the cranium; the combination of fossil records and gene expression has made breakthroughs in the research on the gene regulation of embryonic teeth and the molecular mechanism of the origin of bird beaks and palates. Current research is limited by incomplete fossil preservation, insufficient data volume, large differences in data structures among institutions, and the lack of a sharing mechanism. In response, artificial intelligence technology can improve the accuracy of CT model reconstruction and the efficiency of data processing, helping to deduce incomplete fossils; establishing a shared database (e.g., learning from the experience of existing mineral and fossil databases, building a bio-environment database and promoting data linkage between genes and phenotypes) can solve the problem of data sharing. In the future, introducing AI technology and constructing a standardized sharing platform will be the core development directions of this field, which are expected to fill research gaps and promote the exploration of the evolutionary mechanism of bird craniums. This paper focuses on the research of bird cranium evolution and systematically sorts out the core research methods, progress, limitations and solutions in this field around the theropod dinosaur origin hypothesis of birds.

Keywords: Bird Cranium Evolution; Computed Tomography Technology; Fossil Records; Gene Expression; Artificial Intelligence.

1. Introduction

The highly evolved, light and toothless cranium of birds is another major innovation in evolutionary history after the evolution of feathers. It provides important evidence for the theropod dinosaur origin hypothesis of birds, and also offers a new perspective for the study of bird flight evolution [1]. It is of key significance in deducing paleoecology and paleogeography. The continuous development and improvement of technology have brought new methods and ideas to the study of bird cranium evolution. Recent studies noted clade-specific differences in bird embryonic chondrocranial features and chondrification sequences [2]. In present, research in this field mainly extracts fossil information and combines it with digital reconstruction technology for restoration. This is to restore the cranium shape and reconstruct muscle tissue for analysis [3]. Researchers also build intracranial models through digitalization to realize intracranial cavity visualization. This helps to reconstruct fossil endocasts and analyze the evolution process of bird beaks efficiently [4]. Besides, researchers modify genes to reconstruct the expression of ancestral genes. They compare this with existing fossil information to explore the potential developmental mechanisms of bird mandible and beaks [3].

Although the above new technologies have provided new technical paths for the study of bird cranium evolution, current research is still limited by the preservation status and scarcity of fossils [1]. It is also limited by insufficient data and the lack of a complete management system. At present, well-preserved early bird fossils are extremely scarce, and cranium fossil information is seriously lacking. Research mainly relies on data reconstruction technology for restoration, and a complete database has not yet been formed. This leaves many gaps in research field [1]. It is worth noting that the data structures used by different research institutions vary greatly now. This makes information exchange difficult and leads to the lack of a data exchange and sharing mechanism, which further limits the full use of existing specimens [3]. Against the background of the rapid development of artificial intelligence technology, the quality and efficiency of data calculation and processing have much room for improvement. The current situation where network systems are widely used in management means that data resources need to be upgraded to the network level to achieve standardized management. So, the introduction of artificial intelligence technology and the construction of a standardized resource sharing platform are urgent needs.

This paper will summarize the main methods in the study of bird cranium evolution. It will evaluate the application methods, key progress and shortcomings of these technologies in the field. It will also discuss the feasibility of introducing AI and establishing a database to fill research gaps, as well as future research directions, under the background of the rapid development of network, artificial intelligence and data.

2. Computed Tomography Technology

Computed tomography technology uses physical methods such as X-rays or near-infrared light combined with computer processing. It reconstructs 2D tomographic images into 3D structures to realize non-invasive analysis of the fine internal structures of fossils. Its core advantage is that it can reconstruct the shape and deduce the function without damaging the fossil. At present, this technology has been widely used in the study of bird cranium evolution. It is mainly reflected in three aspects: cranium reconstruction, mandible reconstruction and endocast reconstruction. It provides strong support for in-depth understanding of the fine structure and evolution process of the cranium.

2.1 Cranium Reconstruction

Computed tomography technology provides a non-invasive and high-precision analysis method for paleontological cranium reconstruction. Based on this, new breakthroughs have been made in the study of samples such as juvenile enantiornithine birds from the early Cretaceous in China. Wang et al. used Computed Tomography Imaging to scan the cranium and craniocervical vertebrae of a juvenile enantiornithine bird sample (IVPP V12707) from the early Cretaceous in China [1]. At the same time, the team scanned the cranium fossils of Linheraptor exquisitus (Dromaeosauridae), Dromaius novaehollandiae and Tragopan caboti (two main representatives of crown birds) and conducted phylogenetic analysis. The phylogenetic position of IVPP V12707 was determined using the latest character matrix of the Mesozoic Avian Phylogeny (MAP) project, which is actively maintained and expanded by the avian evolution research team of the IVPP. To enhance scanning resolution, IVPP V12707 was scanned three times, with each scan focusing on distinct body parts: the skull and cranial cervical vertebrae, the dorsal vertebrae and legs, and the tail, respectively.The research results show that: the cranium, jaw, temporal region, specialized rostrum and cranial roof of this bird highlight the specialized evolution process of bird craniums.

Wang et al. found through CT scanning of fossils that two theropod dinosaurs (small oviraptorids and Archaeopteryx, an early Cretaceous bird) had ontogenetic degeneration of tooth sockets [5]. These are transitional phenotypes in the evolution process of beaks. Finally, the team summarized the macro-evolutionary model of edentulism in

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vertebrates.

So, computed tomography technology is not only crucial for the restoration and simulation of various cranium shapes and lays a foundation for simulating the role of muscle tissue. It also plays a core role in clarifying the evolutionary path of the cranium.

2.2 Mandible Reconstruction

The mandible is an important functional structure of the cranium. Its reconstruction research is a key link in evolutionary analysis. Based on the study of cranium shape, computed tomography technology has been further extended to the analysis of the mandible and its functions. Stephan et al. built a digital model of the fossil part of the mandible and carried out appropriate reconstruction to highly restore its shape [3]. At the same time, they reconstructed the adductor muscle tissue to estimate the values of muscle and bite force.

For the skull and lower jaw of E. andrewsi, researchers conducted functional analysis via detailed simulations of cranial hard-tissue and soft-tissue structures. They applied 3D finite-element analysis (FEA):a computational technique for predicting stress and strain distribution in complex geometric objects:to compare and assess the biomechanical performance of different morphological configurations. Convergence and sensitivity tests were done to measure accuracy and variation across different model sizes and element types. Besides the restored morphology, various hypothetical models based on alternative interpretations of osteological correlates were also tested.To obtain reliable and roughly accurate muscle and bite force data, the adductor musculature of E. andrewsi was digitally reconstructed in Avizo. 3D models of each muscle were created using osteological correlates from the original specimen, the restored skull model, as well as topological and neurovascular criteria.

So, computed tomography technology has promoted the development of mandible research, greatly improved the research accuracy and efficiency, and provided a new perspective for the construction of the evolution model of beaks.

2.3 Endocast Reconstruction

In addition to the skeletal level, computed tomography technology also makes the reconstruction of endocasts possible. A standard endocast forms at the boundary between the skeleton (usually bone or cartilage) and the soft tissue (or fluid) directly beneath it. By nature, an endocast has a defined shape and volume but lacks internal structure. Nearly all endocasts provide valuable morphological insights,even if the only takeaway is that the brain did not fully occupy the intracranial cavity. When there is uncertainty in analysis, a phylogenetic viewpoint can offer helpful context [4].

The digital construction of intracranial models can be used to show fine morphological information and help understand the bird brain structure and fossil structure [4]. Researchers pointed out that digital tomography data realized the visualization of the intracranial cavity of vertebrates, which is of great significance for the study of fossil endocasts. The researchers explained some practical guidelines in the paper to improve research efficiency and function. They put forward that the ultimate goal of this field is to fully understand the neuroanatomical structures, functions and evolution of vertebrates.

At present, CT imaging has become a standard practice in paleontology. With the emergence of new technologies, endocast research continues to develop and expand. Computed tomography technology is indispensable.

3. Combination of Fossil Records and Gene Expression

When fossil evidence is limited, relying solely on morphological research is often difficult to reveal the underlying mechanisms of bird cranium evolution. To make up for this deficiency, researchers have begun to combine fossil records with gene expression experiments. They manipulate the expression of related genes to recreate ancient developmental pathways. They compare this with existing fossil research and data to explore the molecular mechanisms of bird craniums and beaks. This technology integrates comparative anatomy, comparative developmental gene expression, fossil records and experimental methods. It promotes the research on teeth, beaks and palate and provides a powerful methodological template for exploring major evolutionary transitions.

3.1 Gene Regulation of Embryonic Teeth

The combination of fossil records and gene expression experiments has promoted the in-depth development of research on teeth and toothless beaks, and promoted the generation and extended application of key conclusions. Yang et al. integrated the conventional hypothesis on the origin of toothless beaks (that is, all characteristics of bird beaks come from ecological adaptation) [6]. They pointed out that the research of Bright et al. on bird morphological characteristics has proved the close correlation between bird beak shape and body size. Fossil evidence can infer that the edentulism of Limusaurus evolved from the early termination of tooth replacement. This phenomenon can be explained by heterochrony. Other studies on caenagnathids and Sapeornis also support this explanation. In terms of experimental developmental biology, studies have shown that bird genes still retain some pathways for tooth formation. The absence of the Bmp4 gene will lead to edentulism in chickens. Wang et al. proposed that in the theropod dinosaur lineage with beaks, the excessive expansion of keratinized epithelium mediated by BMP4 is related to the truncation of neoteny in tooth development [3]. This leads to the repeated evolution of beaks in non-avian and avian dinosaurs.

The combination of fossil records and gene expression experiments helps researchers explore the molecular mechanism of edentulism formation. It complements and improves the results of fossil records and data analysis, and lays a foundation for further research on edentulism.

3.2 Molecular Mechanism of the Origin of Bird Beaks and palate

The combination of fossil records and gene expression experiments has provided new ideas for the study of the evolution of mandibles and beaks. Bhart-Anjan et al. examined the candidate gene expression domains in the embryonic face of embryos of several non-model reptiles and birds [3]. They used inhibitors of two pathways to replicate the gene expression of ancestral amniotes in chickens. They inferred the ancestral craniofacial expression pattern and studied the evolution process of the dynamic beak formation in birds. In addition, the researchers found that the premaxilla and palatal region of the specimens are similar to the ancestral phenotype. This is consistent with the fossil records and the research on the dynamic beak formation of birds.

The method of combining fossil data with gene expression research has enriched the research on mandible evolution and promoted the in-depth development of research on beak formation.

4. Research Limitations and Future Prospects

4.1 Limitations of CT Technology and Application of AI Technology

Current research is mainly limited by the completeness and scarcity of fossil preservation. Digital reconstruction models are still in the initial stage, which also hinders the promotion of research in various fields and the comparison and supplement of results. At present, AI large models are developing rapidly and have been widely used in various scientific research fields. They have gradually become irreplaceable in many fields such as data processing and model construction. Against this background, combining AI large models to improve the efficiency and quality of data processing and analysis. This is to supplement and infer missing fossil structures, which is very important for the future development of the field. Based on the fact that many scholars have suggested introducing AI large models to assist experimental data processing, this paper will cite multiple literatures to provide supporting logic for AI to solve technical bottlenecks in the field of bird cranium evolution.

AI has played an important role in the field of CT model reconstruction. With the help of AI-assisted motion correction algorithm, CCTA exam reconstruction could be performed with minimum radiologist involvement and still meet image quality requirement [7]. Yu et al. developed an AI-based CT-MRI fusion/segmentation tech for ACLR planning, which boosts accuracy—a reference for AI-aided fossil CT reconstruction [8-9]. Guo et al. suggested that the AI-based 3D reconstruction technology can optimize the surgical workflow, promote postoperative recovery, enhance prosthesis performance, and demonstrate relatively high safety [3]. AI also has obvious technical advantages in data integration and optimization. Sun et al. proposed an AI-based data integration scheme that improves processing efficiency and accuracy via deep learning parallel processing, which can support efficient fossil data sorting [10].

So, the current advancement and functional scope of artificial intelligence technology can undertake the tasks of learning, analyzing and constructing scanning data in the scientific research field. It can also greatly improve data accuracy and efficiency, and enhance the repeatability and comparability of experiments. This is exactly the core demand of the current field.

4.2 Data Scarcity and Establishment of a Shared Database

At present, the field is affected by the lack of complete fossil samples. It also lacks a data exchange and sharing mechanism, which leads to the inability to make full use of existing specimens. The data information structures designed by different research institutions vary greatly, which further increases the difficulty of information exchange. Against the background that network systems have been widely used in specimen management, data resources need to be upgraded to the network level. A sharable database should be established and standardized management should be realized.

The National Network of Mineral and Fossil Specimen Resources, a national-level database, sets a model by digitizing and classifying specimens for efficient retrieval—

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this can guide the building of a specialized database for bird cranium evolution. The Hebei Provincial Mineral and Fossil Database, with dynamic inventory management and high compatibility, also provides references for standardizing data structures in our target field.

Regarding the specific directions of data sharing, the following points are of practical significance for filling the current gaps in the field. Current researches mainly focus on the research and reconstruction of scattered individual fossils, which lack data reconstruction of external conditions such as habitat environment and diet, as well as comparative research on data of similar fossils. In the future, a bio-environment database can be established to realize data linkage and improve research efficiency.

At present, genetic research and phenotypic research are independent of each other. If data linkage between the two can be realized, it can increase research perspectives and provide more data support for conclusions.

5. Conclusion

This paper summarizes the core methods, research progress, research limitations and solutions in the study of bird cranium evolution.

First, in terms of research methods: computed tomography technology has become a standard practice in the field. Through cranium, mandible and endocast reconstruction, it clarifies the evolutionary path of the cranium, expands the research perspective on beak evolution, and helps analyze the brain and fossil structures. The combination of fossil records and gene expression has made breakthroughs in the gene regulation of embryonic teeth and the molecular mechanism of bird beak and palate origin, providing support for the study of evolutionary transitions.

Second, current research has obvious limitations. Poor fossil preservation and scarcity lead to information shortage. In addition, insufficient data, large differences in data structures among different institutions, and the lack of a sharing mechanism restrict the utilization of specimens and results comparison.

In view of the limitations, AI technology can improve the accuracy of CT model reconstruction and the efficiency of data processing, helping to deduce incomplete fossils. For the shared database, we can learn from the practice of existing mineral and fossil databases. In the future, it is necessary to establish a bio-environment database and promote data linkage between genes and phenotypes to solve the problem of data sharing.

In summary, the study of bird cranium evolution has made important progress, but the limitations need to be addressed. Introducing AI technology and building a standardized sharing platform will be the core directions of this field in the future. This is expected to fill research gaps and promote the exploration of evolutionary mechanisms.

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