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The supporting principle of microtubule cytoskeleton dynamic assembly for cell polarity establishment

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Abstract:

This article aims to elaborate on the supporting principles of microtubule cytoskeleton dynamic assembly for the establishment of cell polarity. Cell polarity is a crucial concept in cell biology, referring to the spatial asymmetry of intracellular molecules and structures, which is essential for cell differentiation and functional implementation. As an important component of the cytoskeleton, microtubules undergo a dynamic assembly process that includes nucleation, polymerization, and stabilization phases, regulated by various factors and exhibiting significant dynamic instability. The microtubule cytoskeleton provides critical support for the establishment of cell polarity by influencing intracellular transport, organelle localization, and signal transduction, playing an indispensable role in cellular physiological activities and developmental processes.

Keywords:

Microtubule cytoskeleton
Dynamic assembly
Cell polarity

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1. Introduction

Cells are the basic units of life activities, and their normal functioning relies on the precise organization and coordination of various intracellular structures and molecules. Cell polarity, as an important spatial organization form within cells, plays a key role in numerous physiological processes such as cell differentiation, morphogenesis, material transport, and signal transduction. The microtubule cytoskeleton, as a vital component of the cytoskeletal system, exerts an indispensable supporting function in the establishment and maintenance of cell polarity due to its unique dynamic assembly characteristics. Deeper investigation into the supporting principles of microtubule cytoskeleton dynamic assembly for cell polarity establishment is of great significance for revealing the basic laws of cellular life activities and the pathogenesis of related diseases.

2. Structure and Dynamic Assembly of the Microtubule Cytoskeleton

The microtubule cytoskeleton, as a critical component of cell structure, profoundly influences cellular life activities through its structural and dynamic assembly properties. In this section, we will delve into the construction of microtubules from molecular composition to complete structure, providing a detailed analysis of the various stages involved in their dynamic assembly. Additionally, we will precisely dissect the multiple key factors and precise regulatory mechanisms that affect this process, laying a solid foundation for understanding how the microtubule cytoskeleton supports the establishment of cell polarity.

2.1 Structural Composition of Microtubules

Microtubules are the primary structural components of the neuronal cytoskeleton and serve as essential tracks for intracellular transport, crucial for maintaining neuronal survival and function. Microtubules exhibit dynamic properties of growth and shrinkage due to their ability to undergo continuous depolymerization and polymerization. The structure and function of microtubules are coordinated by various microtubule-associated proteins and regulatory proteins[1]. Microtubules are hollow tubular structures with an outer diameter of approximately 24-26 nm and an inner diameter of approximately 12 nm. They are primarily composed of α-tubulin and β-tubulin proteins. These two tubulin proteins first form heterodimers, and multiple heterodimers further assemble into microtubule protofilaments. Typically, 13 protofilaments are arranged longitudinally to form the wall of a microtubule.

2.2 Dynamic assembly process of microtubules

The dynamic assembly of microtubules is divided into three phases: delay phase (nucleation phase), polymerisation phase (extension phase) and stabilisation phase. In the delayed phase, α and β microtubule proteins first polymerize into short oligomeric structures to form the core, then dimers at the ends and sides of a large number of increased and expanded into sheet-like bands, to be sheet-like bands widened to 13 protofibrils after the curl, together to form the original microtubule, this stage as the beginning of microtubule polymerization, the speed is slow and is the rate-limiting process of polymerization [2]; polymerization phase, due to the high concentration of free microtubule proteins in the cell, the polymerization of microtubules During the polymerisation phase, due to the high concentration of free microtubule proteins in the cell, microtubule polymerisation speed exceeds the depolymerisation speed, and the new dimer continues to be added to the positive end of the original microtubule to promote its prolongation; during the stabilisation phase, the free microtubule proteins in the cytoplasm reaches a critical concentration, the microtubule assembly and de-assembly speeds are at the same level, and the length of the microtubule is in a relatively stable state.

2.3 Influencing factors and regulatory mechanisms of dynamic microtubule assembly

Dynamic assembly of microtubules is regulated by a variety of factors, including GTP and αβ heterodimer binding will be activated, so that the microtubule protein molecule is linear, which in turn triggers the heterodimer polymerisation to form microtubules, at the same time GTP hydrolysed to GDP and phosphoric acid, microtubule growth at the end of the GTP cap intact to prevent depolymerisation, the cap decreases or disappears easy to depolymerisation; microtubule protein concentration also has an impact on the concentration, the concentration of high-polymerization, and the low is the depolymerization The concentration of microtubule proteins also has an effect, with high concentrations facilitating polymerisation and low concentrations increasing the relative rate of depolymerisation [3]; microtubule-binding proteins, such as stathmin and αβ-heterodimer pair-binding, can impede assembly, and when phosphorylated, microtubule proteins have a higher effective concentration, increased rate of assembly, and reduced dynamic instability, while dephosphorylation decreases the rate of assembly and increases the dynamic instability; in addition, pH, temperature, Mg^{2+} and Ca^{2+} concentrations can also affect the rate of assembly, and the concentration of microtubule proteins can also increase. $^{+}$ concentration, for example, a pH of 6.9, a temperature of 37°C and the presence of Mg^{2+} are required, whereas an excess of Ca^{2+} can cause microtubule depolymerisation.

3. Concept and mechanism of cell polarity formation

Cell polarity is one of the core concepts in cell biology and plays a decisive role in the normal physiological function and development of cells. In this chapter, the precise definition and diversified manifestations of cell polarity will be clarified, and then the complex mechanisms behind its formation will be deeply excavated, from the fine transport and directional distribution of intracellular molecules, to the key role of cytoskeletal system, to the regulation of extracellular signalling molecules and inter-cellular interactions, to comprehensively reveal the mysteries of the establishment of cell polarity.

3.1 Definition and expression of cell polarity

Cell polarity refers to the spatial asymmetry of molecules and structures inside the cell, which is manifested by the obvious differences in morphology, structure, function and biochemical composition of the cell. For example, epithelial cells have obvious polarity, one side of which faces the surface of the body or the luminal surface of luminal organs, called the free surface, which usually has a special structure such as microvilli to increase the surface area of the cell, facilitating the absorption of substances and other functions [4]; the other side opposite to the free surface faces the connective tissues in deeper parts, called the basolateral surface, which is connected to the basement membrane and participates in the interactions between the cells and the extracellular matrix.

3.2 Mechanism of cell polarity formation

The mechanism of cell polarity formation involves several aspects. In terms of intracellular molecular transport and directional distribution, the material transport system (like vesicle transport) can transport specific proteins, lipids and other molecules to specific areas of the cell, resulting in asymmetric distribution of molecules within the cell, laying the foundation for the establishment of cell polarity. The cytoskeletal system (including microtubules, microfilaments and intermediate filaments) influences the positioning and movement of other intracellular components by virtue of its own organisation and distribution, and participates in the formation of cell polarity, in which the microtubule skeleton plays a prominent role in providing a trajectory for intracellular transport of substances, and also directly influencing organelle positioning and cellular morphology [5]. Extracellular signaling molecules (e.g. growth factors, hormones, etc.) interact with cells at the level of interaction, and these signaling molecules and cell surface receptors bind to activate intracellular signaling pathways, regulate cytoskeletal reorganization as well as intracellular molecule transport, and guide the formation of cell polarity, and the mutual behaviours of the cells, such as adhesion, have an impact on the establishment and maintenance of cell polarity.

4.The role of dynamic assembly of the microtubule skeleton in supporting the establishment of cell polarity

An in-depth understanding of the close connection between the dynamic assembly of the microtubule skeleton and the establishment of cell polarity is crucial for revealing the intrinsic laws of cellular life activities. In this chapter, we will focus on the key supporting role of dynamic microtubule skeleton assembly in the establishment of cell polarity. From building a precise track for intracellular substance transport, to influencing the positioning of organelles, to participating in the transduction and regulation of cell signals, we will show its indispensable importance and mechanism of action in an all-round way.

4.1 Providing tracks for intracellular substance transport

Microtubules provide an important track for the directional transport of intracellular substances, and various intracellular vesicles, protein complexes and other substances can be transported along the microtubules. During the establishment of cell polarity, specific substances need to be transported to specific regions of the cell to form and maintain cell polarity [6]. For example, in nerve cells, substances such as neurotransmitters need to be transported from the cell body to the axon terminals for nerve signalling. The dynamic assembly of microtubules can adjust their distribution and polarity according to the needs of the cell, thus guiding the direction of substance transport, ensuring the asymmetric

distribution of substances within the cell, and providing a material basis for the establishment of cell polarity. According to the study, during the axonal growth of neurons, the positive end of microtubules continuously extends towards the axon end, providing a directional track for the transport of substances within the axon, and promoting the polar growth and development of the axon.

4.2 Influence on organelle localisation and distribution

The dynamic assembly of the microtubule skeleton has an important influence on the localisation and distribution of organelles, which in turn is involved in the establishment of cell polarity. Different organelles have specific distribution positions within the cell, and the asymmetry of this distribution is one of the important manifestations of cell polarity. For example, the location of the centrosome, the centre of microtubule organization, is crucial for the establishment of cell polarity. During pre-cell division, the dynamic assembly of microtubules causes the centrosomes to move towards the cell poles, thus determining the polarity of cell division [7]. In addition, the positioning of organelles such as the Golgi apparatus is also dependent on the microtubule skeleton. The Golgi apparatus is usually located in the central region of the cell or near the side of the nucleus, and its interaction with microtubules enables it to maintain a relatively stable position within the cell, participate in the processing of intracellular substances and secretion processes, and play an important role in the maintenance of cell polarity.

4.3 Participate in cellular signal transduction and regulation

The microtubule skeleton is not only a support structure for intracellular substance transport and organelle positioning, but also participates in the cell signal transduction process and regulates the establishment and maintenance of cell polarity. Microtubule proteins and related binding proteins on microtubules can interact with a variety of signalling molecules and regulate the activity of signalling pathways. For example, some signal transduction proteins can be transported and localised along microtubules, thereby activating or inhibiting relevant signalling pathways in specific regions of the cell and affecting cell polarity [8]. It has been found that the dynamic assembly of the microtubule skeleton changes accordingly when the cell is stimulated by external signals, and such changes can affect the distribution and activity of intracellular signalling molecules, which in turn regulate the polarity response of the cell.

5.Diseases related to abnormal dynamic assembly of microtubule skeleton and cell polarity

The normal functioning of the dynamic assembly of the microtubule skeleton is crucial for the maintenance of stable cell polarity, and once this process is abnormal, it will trigger a series of chain reactions, which are closely related to the emergence of a variety of diseases. In this chapter, we focus on the root causes of abnormal microtubule skeleton dynamics, elaborate its various triggering factors and external manifestations, and explore the inextricable links between such abnormalities and cell polarity-related diseases, so as to reveal its potential mechanisms and important impacts in the process of disease development.

5.1 Causes and manifestations of abnormal dynamic assembly of microtubule skeleton

A variety of factors can lead to abnormal dynamic assembly of microtubule skeleton, such as gene mutation, environmental factors, drug effects and so on. Genetic mutations may lead to changes in the structure or function of microtubule proteins, which may affect the normal assembly of microtubules; changes in temperature, acidity and alkalinity in environmental factors may also interfere with microtubule stability and the dynamic assembly process; certain drugs, such as colchicine, periwinkle alkaloids, etc., are able to bind with microtubule proteins and inhibit microtubule polymerisation, whereas paclitaxel can promote microtubule polymerisation and stabilise the formed microtubules [9]. Abnormal dynamic assembly of the microtubule skeleton is mainly manifested in the destruction of microtubule structure, abnormal aggregation or dispersion of microtubule proteins, and imbalance of microtubule growth and depolymerisation, which then affects the normal physiological function of cells.

5.2 Relationship with cell polarity-related diseases

Abnormal dynamic assembly of microtubule skeleton is closely related to the development of many cell polarity-related diseases. For example, in tumour cells, the structure and function of the microtubule skeleton are often altered, leading to loss of cell polarity and abnormal cell morphology and function, which is associated with enhanced invasion and metastasis of tumour cells [10]. Studies have shown that the expression level of microtubule proteins, the stability of microtubules, and the number and distribution of microtubule organisation centres in tumour cells may undergo aberrant changes, affecting intracellular substance transport and signal transduction, and disrupting cell polarity, thereby promoting malignant proliferation and metastasis of tumour cells. In addition, neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease are also associated with abnormalities in the microtubule skeleton. Damage to the microtubule structure of neurons in these diseases affects intracellular transport of substances and signal transduction in nerve cells, leading to a loss of neuron polarity, which in turn affects neurological function.

6.Conclusion

In conclusion, the dynamic assembly of the microtubule skeleton plays an important supporting role in the establishment of cell polarity. Through its dynamic changes, microtubules provide tracks for intracellular substance transport, influence the positioning and distribution of organelles, and participate in cellular signal transduction and regulation, thus contributing to the formation and maintenance of cell polarity. Abnormalities in the dynamic assembly of the microtubule skeleton can lead to the loss or abnormality of cell polarity, which is closely related to the development of various diseases. An in-depth study of the relationship between the dynamic assembly of microtubule skeleton and cell polarity will help to further reveal the mysteries of cellular life activities, and provide new theoretical basis and targets for the diagnosis, treatment and drug development of related diseases. Future studies need to further explore the fine regulatory mechanisms of microtubule skeleton dynamic assembly and its interactions with other cytoskeletal components and cellular signalling pathways, in order to more comprehensively understand the complex process of cell polarity establishment and maintenance.

Disclosure statement

The author declares no conflict of interest.

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