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# Role of Vesicular Polarity Transport in Organogenesis: Mechanisms and Functions

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**Abstract** Vesicular polarity transport plays a critical role in intracellular material transport and organogenesis. This study outlines the fundamental mechanisms of vesicular transport, including budding, trafficking, and fusion, with a particular focus on the significance of polarity in organ formation, especially in establishing apical-basal polarity in epithelial cells, tissue patterning, and morphogenesis. It also explores the molecular regulatory networks involved in vesicular transport, such as Rab GTPases and SNARE proteins, as well as the roles of cytoskeletal elements like actin and microtubules and their spatial regulation. By discussing advancements in experimental models and imaging techniques, this study summarizes effective approaches for investigating vesicular polarity transport. It further highlights the potential applications of emerging technologies in polarity research and their implications for therapeutic development. This comprehensive perspective deepens the understanding of the mechanisms and functions of vesicular polarity transport in organogenesis, providing valuable insights for diagnosing and treating related diseases.

**Keywords** Vesicular polarity transport; Organogenesis; Molecular regulatory networks; Epithelial cell polarity; Imaging techniques

## 1 Introduction

Vesicular transport is a very important process in cells. It refers to the movement of small membrane-like packets (vesicles) inside the cell, transporting proteins, lipids and other macromolecules from one place to another. This step is critical for the normal functioning of cells. Polarized exocytosis is a special type of vesicle transport that helps vesicles to be precisely delivered to specific locations on the cell membrane. This process requires the cooperation of the cytoskeleton and some signaling molecules, such as small GTPases of the Rho family (Zeng et al., 2017). The movement of vesicles switches between random diffusion and directional movement, which is very helpful for the formation of cell polarity (Bressloff and Xu, 2015). A protein combination called the "extravesicular complex" is also very important. It consists of 8 proteins that help vesicles to be accurately delivered to the target location.

Cell polarity is very important for the formation of organs. Organs are structures composed of different cells in multicellular organisms. Polarity allows cells to have a clear division of labor in space and time, so that tissues and organs can develop normally. For example, in epithelial cells, the top and bottom regions of the cell are different, and this partitioning is important for both tissue shape and material transport (Gwilt and Thiagarajah, 2022). Vesicle transport is also important in regulating cell polarity, and it also affects cell differentiation and signaling, processes that are related to many body functions (Polgar and Fogelgren, 2018). In polarized cells (such as endothelial and epithelial cells), macromolecules are transported by endocytosis, which also shows that vesicle transport plays an important role in maintaining the microenvironment of normal organ development (Fung et al., 2018).

This study mainly wants to explore how vesicle polar transport is carried out and what role it plays in organ formation. We hope to understand how vesicle transport helps cells establish and maintain polarity and see what impact this has on organ development. We will also study the function of extravesicular complexes, the relationship between vesicular and non-vesicular transport, the special transport modes in different cell types, and the manifestation of vesicle transport in disease. Finally, we will also discuss its possibility as a therapeutic target, hoping to provide inspiration for the development of medicine and biotechnology.

## 2 The basis of Polar Transport of Vesicles

### 2.1 How vesicle transport is carried out

Vesicle transport is a common process in cells. It includes three steps: vesicle formation (called budding), movement (transport) and binding to the destination membrane (fusion). At the beginning, the vesicle will bulge from the "origin" membrane. This step requires the help of some proteins, such as coat proteins and Rab proteins. After the vesicle is formed, it will be transported along the "tracks" in the cell, like a train. These tracks are the cytoskeleton. There are special "cargo proteins" such as motor proteins in the transport process, which will carry the vesicles forward. The whole process is strictly regulated, and the purpose is to send the vesicles to the right place (Murray et al., 2016). When the vesicle reaches the target membrane, it must first "approach" this membrane. This is called "docking" or "binding", which requires the help of some special proteins, such as binding factors and Rab proteins. The last step is "membrane fusion", which means that the vesicle and the target membrane are attached together to release the contents inside. This step relies on SNARE proteins (Koike and Jahn, 2019; 2022).

### 2.2 Molecules that play a role in vesicle transport

In the process of vesicle transport, there are several important proteins involved: Rab GTPase, SNARE protein and binding factor. Rab protein is like a transport dispatcher. It changes state (active state and inactive state) to control the whole process from vesicle generation to fusion. Normally, Rab protein is in the "closed" state (that is, bound to GDP), and it is in the cell fluid. Sometimes, another factor (GDF) will "open" it (change to GTP state) and send it to the membrane to play a role. SNARE protein is critical in the final membrane fusion (Figure 1) (Hervé nad Bourmeyster, 2018; Homma et al., 2020). They are like zippers, pulling the vesicle and the target membrane closer and bringing them together. Binding factors (such as extracellular complexes) will also appear when the vesicle just reaches the target membrane. They help the vesicle find the right position and cooperate with Rab and SNARE proteins to make the transport fast and accurate (Ungermann and Kümmel, 2019).

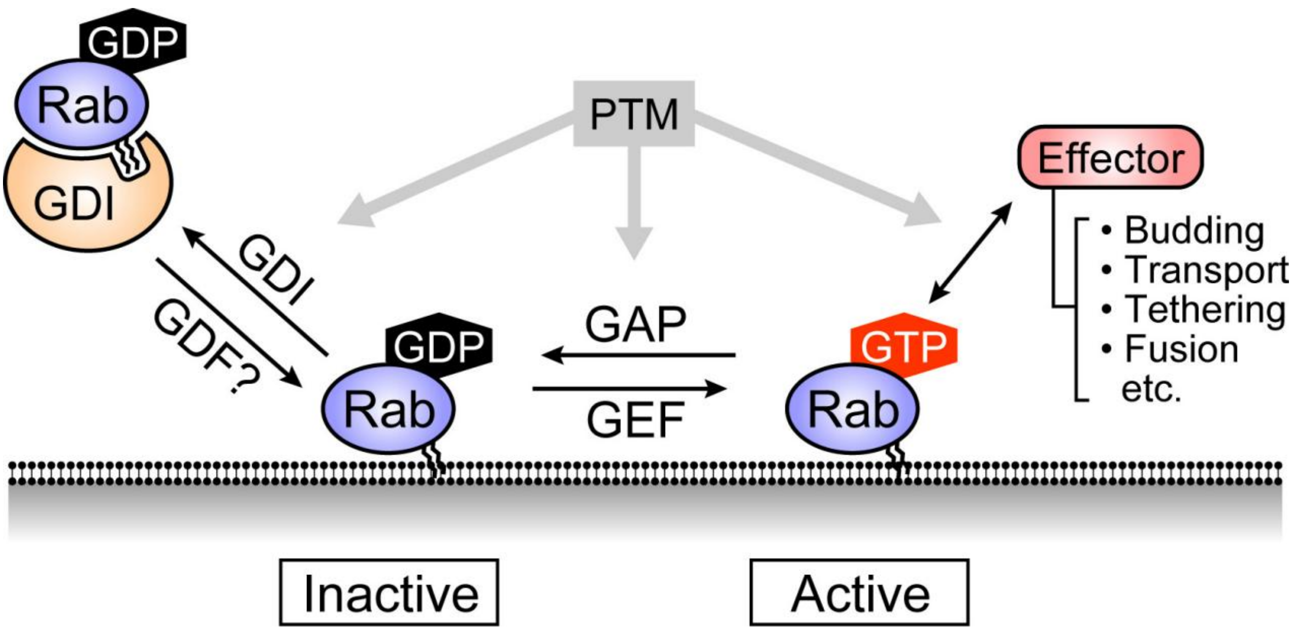


Figure 1 The Rab GTPase cycle (Adopted from Homma et al., 2020)

### 2.3 Different types of vesicles involved in transport

Different vesicles have different tasks in cells. Endocytic vesicles are mainly responsible for bringing in things outside the cell and then sending them to endosomes or lysosomes for processing or recycling. Exocytic vesicles deliver proteins or lipids made by the cell from the Golgi apparatus to the cell membrane or outside the cell (Zheng et al., 2015). There are other special vesicles, such as secretory vesicles (responsible for releasing signal substances) and autophagosomes (responsible for cleaning up cell garbage) (Polgar and Fogelgren, 2018). These vesicles can find the correct "delivery address" mainly because of the different Rab proteins and SNARE proteins they carry. These proteins are like navigation systems, telling the vesicles where to go (Menaceur et al., 2023).

# 3 The Role of Polar Vesicle Transport in Organ Development

## 3.1 Establishment of epithelial cell apical-basal polarity

Epithelial cells have upper and lower ends, and their polarity is very important for normal cell function and tissue formation. They can separate the internal and external environments and regulate the transport of substances and changes in cell shape (Pu et al., 2015). This polarity is established by the asymmetric distribution of some components in the cell, such as the Na+/K+-ATPase pump. These components help the formation of the apical membrane through signaling pathways such as Ror2, ERK1/2, and LKB1. Some proteins, such as Cdc42, Par6B, and PAK4, also play a key role in the formation of apical junctions. In animals such as hydra, this polarity is slowly established after cell aggregation, starting with the expansion of the apex and the formation of junction structures (Seybold et al., 2016).

## 3.2 The role of vesicle transport in tissue and shape changes

### 3.2.1 Establishment of planar cell polarity (PCP)

Planar cell polarity refers to the direction in which cells are arranged in the same plane. Vesicle transport is critical to the establishment of this polarity. For example, the two proteins Vangl2 and Frizzled6 are packaged into different vesicles in the cell and then sent to specific locations so that they can work in the cell plane. The transport of Frizzled-6 is also regulated by a protein called SAR1A in the endoplasmic reticulum, which ensures that it reaches the cell surface correctly (Tang et al., 2020).

### 3.2.2 Effects on cell movement and tissue elongation

PCP signals also affect how cells move and how tissues elongate. In Xenopus, some PCP proteins (such as Vangl2 and Disheveled) can help cells insert into tissues, which is important for the development of early embryos and the nervous system. PCP signals work with microtubules inside cells to help proteins be distributed asymmetrically and make cell movement more orderly (Mathewson et al., 2019).

### 3.2.3 Coordination of polar transport and morphogenetic signals

Vesicular transport can also work with morphogenetic signals to help tissues form the correct structure. For example, in fruit flies, there is a protein called Scribbled that regulates the activity of the BMP signaling pathway, which affects cell morphological changes by controlling the location of BMP receptors and the process of entering vesicles (Gui et al., 2016). In the development of mouse limbs, the Wnt5a signal provides information about the direction of the PCP, and another signal from the ectoderm ridge, Fgf, also participates to help the tissue grow in the right direction (Gao et al., 2018) .

## 3.3 Coordinating signals between cells in organ development

Vesicle transport also helps cells exchange information, especially during organ formation. A protein called MCAM can prove this. It can regulate cell polarity, help form tubular structures, and promote the formation of cilia. MCAM also affects the transport of FGF4, allowing related genes to be activated, thereby starting the process of lumen development (Gao et al., 2017). It is very important for the establishment of left-right symmetry and morphology in animals such as zebrafish and African clawed frogs.

# 4 Polarity Regulation Mechanism of Vesicle Transport

## 4.1 Spatial control of vesicle transport

Vesicles in cells need to move in the right direction, which is very important for the normal functioning of cells. The Golgi apparatus plays a big role in this process. It helps lipids and proteins move to specific locations in the cell so that the cell can maintain its normal structure and direction. The outside of the Golgi apparatus is combined with the cytoskeleton (such as actin and microtubules) (Ravichandran et al., 2019). These skeletons are like scaffolds, determining where and how the organelles are placed. Different types of microtubules can be recognized by specific motor proteins, helping to make the inside of the cell more orderly. For cells like neurons, this precise spatial regulation is very important because they have particularly high requirements for the direction of transport (Barlan and Gelfand, 2017).

### 4.2 The role of the cytoskeleton in vesicle transport

The cytoskeleton includes microtubules and actin, which are the "tracks" and "guide lines" for vesicle transport. Microtubules are like highways, allowing vesicles to travel long distances, pulled by some "motor proteins" such as dynein and kinesin (Mayya et al., 2022). Actin is like a small road, mainly responsible for short-distance transport, especially the docking and fusion of vesicles when they are about to reach the end point. When cells move or divide, these two skeleton structures must work together to maintain the shape and direction of the cell. They interact with each other through cross-linking, fixation, etc., and this process is controlled by many regulatory factors (Dogterom and Koenderink, 2018). For example, when T cells move and perform functions, they need the cooperation of these two skeletons to ensure the smooth transport of vesicles.

### 4.3 Signaling pathways that regulate the direction of vesicle transport

Some signal transduction pathways regulate the direction of vesicle transport. These pathways include many regulatory molecules, such as polarity regulators and proteins that connect membranes to the skeleton. Together, they can control how the vesicles move, how far they go, and where they go (Mastrogiovanni et al., 2020). The work of the dynein complex is also regulated by these pathways, such as when it is pulled onto the microtubules, when it is activated, how to recognize and put down the cargo, etc (Liu, 2017). Proteins such as Rho GTPase and myosin can also affect the direction of vesicle transport by changing the skeleton structure (Logan and Menko, 2019). The Golgi apparatus itself is also like a signaling station, which can link transport and signal transmission when the cell undergoes polarity changes.

## 5 Role in Different Organs

### 5.1 Role of vesicle polarity in neural tube formation

Vesicle polarity is very important for neural tube formation. This process mainly relies on a signaling pathway called PCP. Vangl2 is a key protein that belongs to this pathway. If mice do not have Vangl2 in their bodies, their embryos will die due to problems with the neural tube (Rocque et al., 2015). This shows that this protein is critical for the development of the nervous system. PCP signals can help cells align and form a normal neural tube.

### 5.2 Role of vesicle polarity in kidney development

Vesicle polarity also plays an important role in kidney development. In particular, PCP signals are critical in the formation and function of nephrons. Proteins like Vangl2 can help glomerular epithelial cells (podocytes) form normal structures and can also affect the arrangement of glomerular basement membranes. In this process, vesicles help transport substances and promote the formation of collecting ducts (Short and Smyth, 2020). These collecting ducts will send urine from the nephron to the bladder. This process also requires the cooperation of ureteric bud cells and nephron progenitor cells to allow the nephron to develop normally.

### 5.3 Importance of vesicle polarity in lung development

Lungs also need vesicle polarity to develop. Lungs need to form many branches, which form a complex epithelial structure for gas exchange. The formation and direction of branches are influenced by many signals, extracellular substances and the cytoskeleton (Lang et al., 2021). Vesicles help cells form an "up and down" direction through transport, which is very important for the structure and function of the lungs (Gwilt and Thiagarajah, 2022). This process works together to help the respiratory system develop normally and allow the body to breathe smoothly.

## 6 Vesicle Polarity Transport Disorders and Diseases

### 6.1 Effects of genetic mutations on vesicle transport

Some gene mutations disrupt vesicle polarity transport, which can affect the normal functioning of cells and may cause problems in organ development. For example, a gene called Vangl2, if mutated, will cause serious problems in the kidney tubules during the embryonic period. The kidney tubules may become wide and may grow small vesicles because the cells have problems in stretching and contracting (Derish et al., 2020).

When Vangl2 is missing, the kidney tubules become wide and misshaped. There are two reasons: first, the cells are not arranged neatly; second, the cells cannot shrink into a normal cone shape. This leads to abnormal development of the renal tubules (Figure 2) (Derish et al., 2020). There is also a gene called ClC-5. If it does not work properly, it will cause a disease called Dent's disease. The manifestations of this disease include: problems with renal tubular transport, lysosomes in cells cannot work properly, cells experience oxidative stress, and they will become different from their original appearance (Devuyst and Luciani, 2015). For example, mutations in the ZnT2 gene affect the formation and secretion of vesicles in mammary epithelial cells. This may make it difficult for mothers to secrete milk, and the baby will be zinc deficient (Lee et al., 2017).

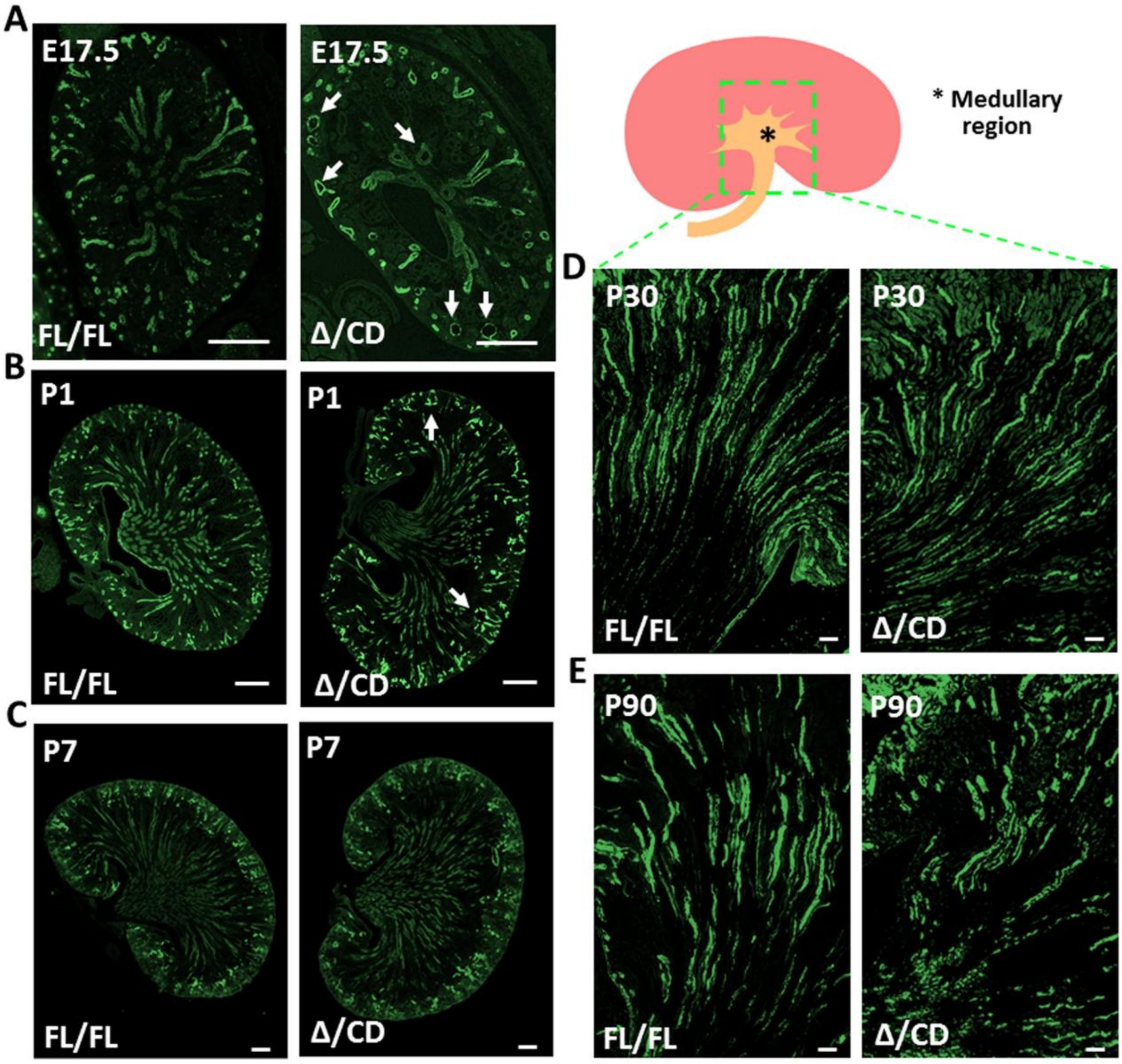


Figure 2 Morphology of collecting duct tubules in conditional Hoxb7-Cre; *Vangl2*$^{Δ/CD}$ mice (Adopted from Derish et al., 2020)
Image caption: (A) E17.5 *Vangl2*$^{Fl/Fl}$ (control) and *Vangl2*$^{Δ/CD}$ (mutant) kidneys stained with DBA (collecting duct marker, green); dilated tubules are indicated by arrows. Scale bars, 100 µm. (B) Postnatal day 1 (P1) *Vangl2*$^{Fl/Fl}$ and *Vangl2*$^{Δ/CD}$ kidneys stained with DBA (green); dilated tubules are indicated by arrows. Scale bars, 100 µm. (C) P7 *Vangl2*$^{Fl/Fl}$ and *Vangl2*$^{Δ/CD}$ kidneys stained with DBA (green); Scale bars, 100 µm. (D) P30 kidney medullary region stained with DBA (green), Scale bars, 100 µm. (E) P90 kidney medullary region stained with DBA (green), Scale bars, 200 µm (Adopted from Derish et al., 2020)

### 6.2 Relationship with developmental diseases

If there is a problem with vesicle transport, many developmental diseases may occur. For example, if the PCP signal is disrupted, it may cause polycystic kidney disease (PKD), a disease in which cysts grow due to abnormal development of the renal tubules. PCP signaling is critical for kidney development, such as ureteral budding and nephron formation. If there is a problem with the PCP gene, the kidneys and urinary tract may have congenital defects (Torban and Sokol, 2021). The vesicle transport mechanism is also important for epithelial cells and endothelial cells. If the transport system is disrupted, many developmental abnormalities may occur (Fung et al., 2018).

### 6.3 Relationship between cancer and loss of cell polarity

If cells lose polarity, cancer is prone to occur. And errors in vesicle transport are an important cause of this problem. The vesicle transport system regulates many cell functions, such as how cells communicate with each other and how cell polarity is maintained. All these processes require the help of the endosomal sorting complex (ESCRT) (Juan and Fürthauer, 2017). If these transport processes are disrupted, the polarity of the cell will be affected, which may make cancer cells more likely to spread and metastasize (Zeng et al., 2017). In addition, ZnT2 works with a protein called vacuolar H+-ATPase to maintain the polarity of mammary epithelial cells. If the interaction between the two goes wrong, it will not only affect the secretion function, but also make cancer more likely to occur.

## 7 Experimental Models and Techniques

### 7.1 Using in vitro models to study polar transport of vesicles

In vitro models are particularly helpful when studying vesicle transport. For example, using Caenorhabditis elegans, we can find some transport-related molecules. These molecules make the apical cell membrane and PAR complex polar, but they themselves are not directly involved in the apical sorting process. Through these models, researchers can observe and analyze how polar membranes are formed. This can also better understand how vesicles maintain membrane polarity through synthesis and recycling (Zhang et al., 2023). In addition, yeast is also often used to study this transport process. It can help us understand what role the vesicle complex plays in this process, and this mechanism is similar in many eukaryotic organisms.

### 7.2 Using imaging technology to observe the transport process of vesicles

In order to see how vesicles move clearly, scientists use some imaging techniques. These techniques allow us to directly see the movement of vesicles in living cells. For example, they used light control methods to track the direction of F-actin and vesicles. This will allow us to know whether changes in actin affect how the vesicles move and the distribution of the apical membrane components (Jafari et al., 2023). Another way is to combine quantitative mass spectrometry with imaging, so that we can know what proteins are in the vesicles at the same time, and see their locations and changes. This is also helpful for analyzing receptors and ligands in the process of vesicle transport.

### 7.3 Genetic and biochemical tools for studying functions

To understand the specific functions of vesicle transport, we still have to rely on some genetic and biochemical methods. For example, scientists used Caenorhabditis elegans to conduct genetic screening and found the key molecules that can control the transport of vesicles to the top of the cell. Some proteins such as Rab GTPases are also important. They can help vesicles form, move, approach the target membrane, and finally fuse with the membrane. Especially Rab27, it plays a role in many disease processes (Menaceur et al., 2023; Wang et al., 2024). In addition, there is a complex composed of 8 proteins that fixes the vesicle to the membrane before it is ready to be released. Scientists have used genetic methods to study this process in depth. With these tools, we can better understand the molecular mechanisms behind vesicle trafficking and see its relationship with cell polarity and organ formation.

## 8 Future Directions for Vesicle Polarity Research

### 8.1 New technologies for a clearer view of vesicle polarity

Imaging techniques are now more advanced than ever before, such as microscopes that can see very small structures and methods that can take “videos” of living cells. These technologies allow scientists to see how vesicles move and are guided in cells, as well as how they interact with the cytoskeleton. In addition, some new tools (such as CRISPR-Cas9) can precisely modify genes, so that people can study the role of specific genes in vesicle transport.

### 8.2 Using a systematic approach to understand how vesicles are transported

Scientists now analyze a lot of information such as genes, proteins, and metabolites together, which is called “systems biology”. With this data, they can draw a “road map” of vesicles moving in cells. In this way, if a link goes wrong, it can be predicted that it will affect the entire system. This method can also help us find where are the key control points, and understand how different modes of transport affect each other. With these models and analytical tools, we can better understand the mechanisms that control vesicle polarity.

### 8.3 Possible uses of vesicle polarity research in disease treatment

Studying vesicle polarity is not just for fun, it also has promise in treating certain diseases. For example, some drugs do not easily enter the brain, but if vesicles can help them cross the blood-brain barrier, the effect will be much better. Some cancer cells will "use" the transport method of vesicles to help themselves spread. If we can change the path of these vesicles, we may be able to prevent the spread of cancer cells. Therefore, understanding the principles of vesicle polarity may lead to new treatments.

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## Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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