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Review Article

Overview Of Liposomes: Versatile Nanocarriers For Drug Delivery And Beyond

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ABSTRACT

Liposomes, microscopic lipid-based vesicles, represent a versatile platform in the realm of drug delivery and biomedical research. This review article provides a concise overview of liposomes, encompassing their historical evolution, structural intricacies, multifaceted applications, and recent strides in the field. Historically, Dr. Alec D. Bangham's groundbreaking work in 1961 laid the foundation for liposome research. These nanoscale structures consist of lipid bilayers, formed by amphipathic phospholipids, enveloping an aqueous core. Variations in size and lamellarity allow for tailoring liposomes to specific applications. Small Unilamellar Liposomes (SUVs), Large Unilamellar Liposomes (LUVs), and Stealth Liposomes are just a few of the types with unique attributes. Liposomes have revolutionized drug delivery. They encapsulate hydrophilic and hydrophobic compounds, enhancing drug solubility and stability. The controlled release minimizes side effects and maximizes therapeutic efficacy. Pharmaceutical formulations employ liposomes for a spectrum of drugs, including anticancer agents, antibiotics, and antifungals. Beyond drug delivery, liposomes are invaluable in biological research. They mimic cell membranes, serving as crucial tools for studying cell membrane behavior and isolating membrane proteins. They are also used for developing assays to assess various biological processes. In cosmetics and skincare, liposomes improve the penetration of active ingredients into the epidermis. Additionally, liposomes are explored as carriers for vaccines, which can enhance the immune response and vaccine effectiveness. Recent developments encompass advanced targeting mechanisms, encapsulation of multiple drugs, and drug conjugation, advancing liposomes toward multipurpose drug delivery platforms. Integration with nanotechnology, applications in immunotherapy, and a focus on biocompatible materials are indicative of the evolving landscape. While liposomes present numerous advantages, they face challenges related to stability and manufacturing complexity.

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The future holds promises of even more innovative liposomal drug delivery, personalized medicine, and increased use of gene therapy and immunotherapy, offering transformative solutions to complex healthcare dilemmas.

INTRODUCTION

Drug delivery systems (DDSs) can improve a drug's therapeutic index by boosting its concentration, lengthening its half-life in target cells, and reducing its adverse effects.1. A variety of natural, organic, and inorganic materials, such as ceramics, polymers, metals2, and lipids that produce nanoparticles like liposomes and micelles, are utilized to form NPs.(3,4,5), Liposomes are small, artificial, spherical, microscopic lipid-based vesicles that have revolutionized the fields of pharmaceuticals, biotechnology, and biomedical research. They are usually 50-500 nanometer-sized particles with a diameter. (6,7). Their unique structure, which mimics cell membranes, has made them versatile tools for drug delivery, biological research, and therapeutic applications. As drug vehicles, liposomes exhibit outstanding properties, such as protecting the encapsulated substances from physiological degradation, extending the half-life of the drug, controlling the release of drug molecules, and excellent biocompatibility and safety. Furthermore, liposomes can selectively deliver their payload to the diseased site through passive and/or active targeting, thus decreasing the systemic side-effect, and elevating the maximum-tolerated dose. Early conventional liposomes were mainly constituted by natural phospholipids such as phosphatidylcholine (PC), sphingomyelin, and monosialoganglioside. However, this formulation was subjected to several critical issues, such as the instability in plasma and short blood circulation half-life, due to their interaction with high- and low-density lipoproteins that resulted in the rapid release of the encapsulated drug into the plasma. Moreover, in most cases, negatively charged liposomes have a shorter half-life in the blood than neutral liposomes and positively charged liposomes are toxic and quickly removed from circulation(1,2). This overview delves into the fascinating world of liposomes, covering their history, structure, applications, and the latest advancements in this field.

History of Liposomes

The concept of liposomes was first introduced by British hematologist Dr. Alec D. Bangham in 1961. Bangham and his colleagues discovered that phospholipids, the building blocks of cell membranes, could spontaneously form spherical bilayers when exposed to water. These bilayers encapsulate an aqueous core, creating a closed vesicle structure. Bangham's work laid the foundation for the development of liposomes as artificial vesicles with a wide range of applications.

The history of liposomes can be divided into three periods: genesis, middle age, and modern era:

- Genesis (1968-75): During this era, liposomes were used to analyze the properties of biological membranes. A thin lipid membrane hydration method was developed to prepare liposomes.
- Middle age (1975-85): During this era, the advantages, stability, and interaction characteristics, physical and chemical properties of liposomes, as well as their interaction with cells and their behavior in vivo were studied carefully
- Modern era (after 1985): Today, liposomes are used in different scientific fields, such as biophysics (characteristics of cell membranes and channels), mathematics, biochemistry (functions of membrane proteins), theoretical physics (topology of two-dimensional surfaces floating in a three-dimensional continuum) and biology (excretion, cell function, signal transduction, gene delivery, and function)(8,9).

Structure of Liposomes

Liposomes consist of a lipid bilayer that surrounds an aqueous core. The lipid bilayer is composed of

amphipathic molecules called phospholipids. Each phospholipid molecule has a hydrophobic (water-repellent) tail and a hydrophilic (water-attracting) head. When phospholipids are placed in an aqueous environment, they self-assemble to form a lipid bilayer, with the hydrophobic tails oriented inward and the hydrophilic heads facing the aqueous environment. Phospholipids, both synthetic and natural, can be used to create liposomes. The properties of liposomes, such as particle size, stiffness, fluidity, stability, and electrical charge, are significantly influenced by their lipid makeup. Every phospholipid molecule has a head that attracts water and a tail that is hydrophobic, or water-repellent. Put phospholipids in an aqueous solution, and they self-assemble to form a lipid bilayer, with the hydrophobic tails oriented inward and the hydrophilic heads facing the aqueous environment. Stability is provided by the hydrophilic group's charge through electrostatic repellents. The length, symmetry, and saturation of the acyl chain in the hydrophobic group of lipids varies. (10,11).

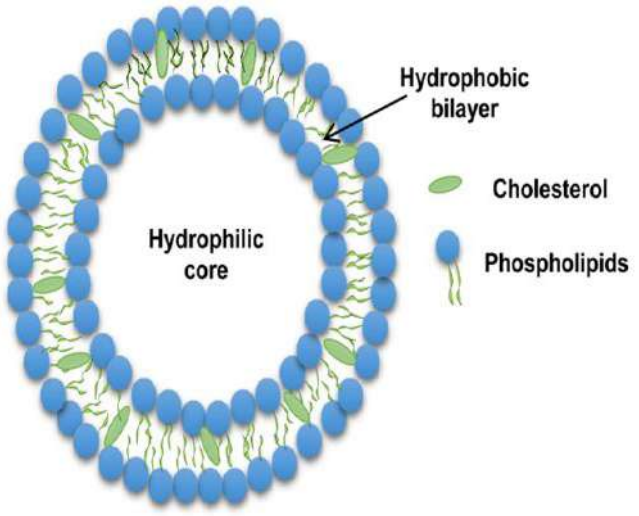

Fig 1: Schematic diagram of liposome7

TYPES OF LIPOSOME:

Different forms of liposomes exist depending on their size, lamellarity (number of lipid bilayers), and specific applications. These liposome varieties are made to serve various functions and provide special benefits. Here's an explanation of some common types of liposomes:

- Small Unilamellar Liposomes (SUVs): These liposomes are relatively small, typically with a diameter of 20-100 nanometres.Structure: SUVs comprised of a single lipid bilayer surrounding an aqueous core. SUVs are a type of liposome characterized by their small size and single lipid bilayer structure. These vesicles are widely used in various fields due to their advantageous properties:
  - Size: Their small size provides a high surface area to volume ratio, making them suitable for drug delivery applications where precise targeting and efficient delivery are crucial.
  - Biocompatibility: SUVs composed of natural lipids are biocompatible and less likely to provoke an immune response, which is beneficial for drug delivery and other biomedical applications.
  - Encapsulation: SUVs can encapsulate both hydrophilic and hydrophobic substances within their aqueous core or lipid bilayer, allowing them to carry a wide range of drugs, genes, or imaging agents.
  - Cellular Uptake: Due to their small size, SUVs can penetrate cells more efficiently than larger liposomes, aiding in drug delivery to specific intracellular targets.
  - Stability: While they may not have the long circulation times of some larger liposomes, SUVs offer stability in terms of storage and delivery.
  - Their size and properties make SUVs valuable in pharmaceuticals, especially for targeted drug delivery systems, diagnostics, and research applications like studying cell membranes and interactions with biomolecules. These vesicles can be engineered and modified for specific purposes, such as enhancing stability,

targeting specific cells or tissues, or controlling the release of encapsulated substances in response to environmental triggers like pH or temperature changes12.

- Large Unilamellar Liposomes (LUVs): LUVs are larger than SUVs, with diameters ranging from 100-1000 nanometres.Structure: Like SUVs, they have a single lipid bilayer.
  - Size and Encapsulation: LUVs have a larger size compared to small unilamellar vesicles (SUVs) but still contain a single lipid bilayer. This size allows them to encapsulate a more significant volume of drugs, genetic material, or other substances, making them useful for delivering larger payloads.
  - Drug Delivery: Their size allows for the encapsulation of a wider range of therapeutic agents, including larger molecules or multiple compounds. This makes them beneficial for drug delivery systems where a higher drug load is required.
  - Stability: LUVs are relatively stable structures, which is advantageous for the long-term storage of encapsulated substances and ensuring their integrity during transport and handling.
  - Research Applications: They are used in various research areas, including studies related to cell membrane dynamics, lipid-protein interactions, and investigations into the behavior of liposomal structures in biological systems.
  - Targeting and Controlled Release: Like other types of liposomes, LUVs can be engineered and modified for targeted delivery to specific cells or tissues. They can also be designed to respond to environmental stimuli, enabling the controlled release of encapsulated contents at desired locations or under specific conditions.
  - Diagnostic Applications: LUVs can be utilized in diagnostic imaging techniques, such as encapsulating contrast agents for imaging purposes like MRI or fluorescence imaging.
  - Their larger size compared to SUVs provides advantages in certain applications where a higher drug payload or specific targeting is required. However, their circulation time in the body may be different due to their size, which can influence their suitability for drug delivery applications. Tailoring their properties and surface modifications allows for customization to suit particular needs in pharmaceuticals, diagnostics, and fundamental research13.
- Multilamellar Liposomes (MLVs): These liposomes have a range of sizes, and they consist of multiple concentric lipid bilayers.Structure: MLVs have an onionlike structure with several lipid bilayers.
  - Size Range: MLVs can vary widely in size, typically ranging from several hundred nanometres to a few micrometers in diameter, depending on the method of preparation.
  - Encapsulation Capacity: Due to their multilayered structure, MLVs have ample space between the lipid bilayers to encapsulate a significant volume of both hydrophilic and hydrophobic substances. This makes them suitable for carrying diverse payloads, including drugs, genes, or imaging agents.
  - Stability: MLVs are relatively stable lipid structures, beneficial for long-term storage of encapsulated compounds. They can withstand some variations in environmental conditions without compromising their integrity.
  - Drug Delivery and Research Applications: MLVs are utilized in drug delivery systems,

especially for sustained or controlled release of encapsulated substances. They are also used in research contexts to study lipid-protein interactions, membrane dynamics, and the behavior of lipid-based structures in biological systems.

- Preparation Methods: MLVs can be prepared through various methods, such as thin-film hydration, sonication, or extrusion techniques, allowing for control over their size and properties.
- Biomedical Applications: They find applications in pharmaceuticals for targeted drug delivery, vaccine development, and cosmetics for controlled release of active ingredients.
- Diagnostic Uses: as other forms of liposomes, MLVs can also be used in diagnostic imaging by encapsulating imaging agents for different imaging modalities as fluorescence imaging or MRI.
- Their multilayered structure and ability to encapsulate a large volume of substances make MLVs useful in diverse fields, offering advantages for specific drug delivery requirements, research studies, and biomedical applications where sustained release or the encapsulation of multiple agents is necessary. Their versatility in encapsulating both water-loving and water-hating compounds makes them a valuable tool in pharmaceutical and research settings(14,15,16).

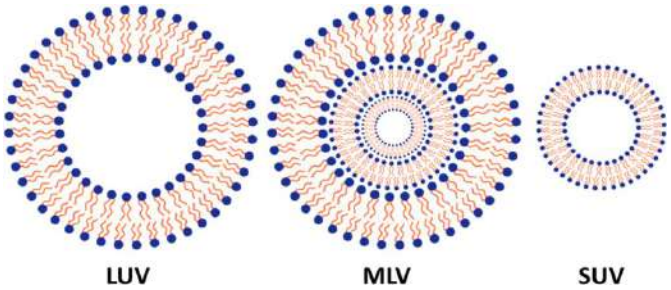

Fig.2: Different sizes and types of unilamellar vesicles13

- **Stealth Liposomes (PEGylated Liposomes):** Polyethylene glycol (PEG) coatings of these liposomes are frequently applied to their surface. Compared to traditional liposomal medications, stealth stabilized liposomes demonstrated a longer circulation duration and improved target accumulation. Synthetic polymers, glycoproteins, polysaccharides, or particular receptor ligands are used to decorate their surfaces in order to accomplish targeted distribution and accumulation at the desired location. Stealth liposomes are liposomes that have been pegylated. The first pegylated liposome-based product to be successful was Doxil.(17,18).
  - Extended Circulation Time: The PEG coating reduces the recognition and clearance of liposomes by the body's immune system, particularly by macrophages in the liver and spleen. This prolongs their circulation time in the bloodstream, allowing for a more extended period for drug delivery or imaging agents to reach their target sites.
  - Decreased Immunogenicity: By reducing the recognition by the immune system, PEGylation helps decrease the immunogenicity of liposomes, making them less likely to provoke an immune response or cause adverse reactions.
  - Improved Stability: PEGylation enhances the stability of liposomes by providing a protective layer on the surface, reducing aggregation and premature degradation in physiological conditions.
  - Enhanced Targeting: Stealth liposomes can also be modified further to incorporate targeting ligands or antibodies on the PEG chains, enabling specific binding to receptors on target cells or tissues. This combination of stealth properties with targeting ligands results in improved

accumulation at the desired site while evading immune recognition.

- Controlled Release: They can be engineered to have controlled release properties, delivering encapsulated substances more selectively at the target site due to the prolonged circulation and the potential for triggered release in specific environments.
- Biomedical Applications: Stealth liposomes find extensive applications in drug delivery systems, particularly for cancer therapy, where they can enhance the accumulation of therapeutic agents in tumors through the enhanced permeability and retention (EPR) effect.
- Diagnosis and Imaging: These modified liposomes can also be employed in diagnostic imaging by encapsulating contrast agents for various imaging techniques such as MRI, CT scans, or fluorescence imaging.
- The addition of PEG to liposomes has revolutionized their biomedical applications by improving their pharmacokinetics, reducing toxicity, and enhancing their efficacy in delivering therapeutic agents to specific sites within the body. Stealth liposomes have become a crucial tool in modern pharmaceutical research and development for targeted drug delivery and diagnostic purposes(19,20).

- **Cationic Liposomes:** Because cationic lipids are present in these liposomes, their surface is positively charged(21).Because of their negative charge and relatively large size, cationic liposomes are well suited for the delivery of a variety of negatively charged macromolecules, including RNA, DNA, and oligonucleotides(22). They are thought to be a possible means of administering treatments to the brain(23, 24). By adding polyethylene glycol (PEG) to their surface, these liposomes are shielded from circulating proteins, increasing the duration of systemic circulation and lowering immunogenicity, both of which contribute to improved medication efficiency.(25,26).
- **Anionic Liposomes:** These liposomes have a negative surface charge due to the presence of anionic lipids. In comparison to neutral and cationic liposomes, anionic liposomes are less stable in the circulation(27,28). Since anionic liposomes have better penetration capabilities through the skin's stratum corneum, they are typically used for transdermal medication delivery(29).
- **pH-sensitive Liposomes**: These liposomes exhibit changes in structure and drug release in response to variations in pH levels. They are particularly useful for drug delivery to specific tissues or cells with differing pH environments30.
- **Fusogenic Liposomes:** Fusogenic liposomes can fuse with cell membranes. They are designed for the efficient delivery of drugs or genetic material into target cells31.
- **Stable Liposomes:** These liposomes are engineered to have increased stability, which is crucial for long-term storage and extended shelf life.

The choice of liposome type depends on the specific requirements of the application, such as the nature of the cargo (hydrophilic or hydrophobic), target tissue or cell, release kinetics, and desired circulation time. Researchers and pharmaceutical scientists carefully select the appropriate type of liposome to optimize drug delivery or address research needs effectively32.

LIPOSOME PREPARATION

Liposomes can be prepared using various methods, including:

- ThinFilm Hydration: Lipids are dissolved in an organic solvent using this process, and the solvent is then evaporated to form a thin lipid

film33. After that, an aqueous buffer solution is utilized to hydrate the resulting thin film above the chosen lipid's transition temperature (Tm). A hydrophilic medication or drugs to be inserted into the liposome's aqueous center may be present in the hydration solution. The efficiency of drug encapsulation is determined by the rate of hydration34; the higher the encapsulation efficiency, the slower the rate of hydration.35.

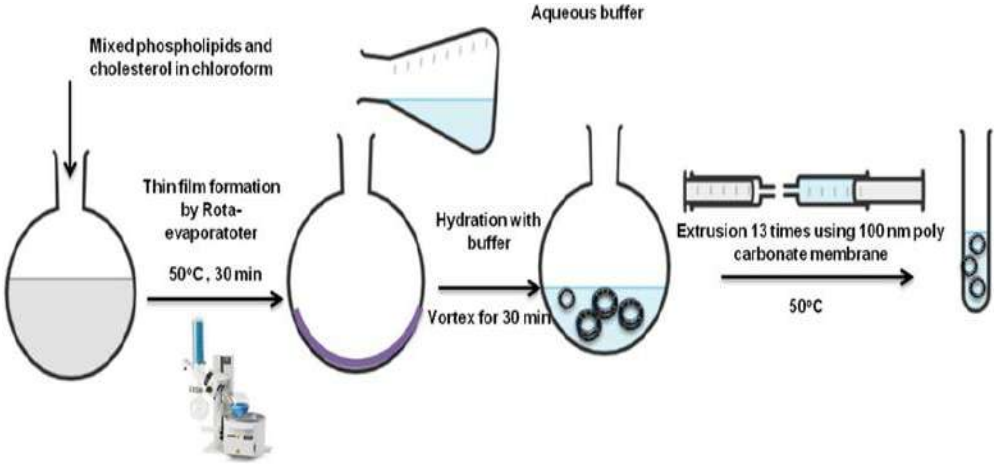

Fig.3: a pictorial representation of thin film hydration36.

- E**xtrusion:** Particle distribution, lamellarity types, and liposome resizing can all be regulated by extrusion through a polycarbonate membrane with predetermined pore diameters. Higher encapsulation efficiency and stability of liposomes are guaranteed by this extrusion technique37.
- **Reverse Phase Evaporation:** Drugs that are hydrophobic can be encapsulated using this technique. By creating a water-in-oil emulsion, the reverse-phase evaporation technique is typically employed as a substitute for thin-film hydration38. The hydrophilic medication is first mixed directly with an aqueous buffer after the lipids have been dissolved in an organic solvent. Lipid vesicles distributed in the aqueous solution were formed as a result of the organic solvent evaporating in a rotary evaporator operated at lower pressure39. High molecular weight compounds are best suited for this40.
- **Sonication:** Sonication is the most widely used method for the preparation of SUVs41. At higher energy levels, the average size of vesicles is further reduced. Here, the MLVs are exposed to ultrasonic irradiation. Two types of sonicators are used i.e. a Probe sonicator and a Bath sonicator42. A probe sonicator is used for dispersions having energy in small volumes (for example- high lipoidal concentration or a viscous aqueous phase)43. The energy supplied by the probe tip into the lipid dispersion is very high. Bath sonicators are used for large volumes of diluted lipids. The prepared SUVs are purified by ultracentrifugation. Disadvantages of the sonication method are low encapsulation efficiency, metal pollution from the probe tip, phospholipid degradation, and the presence of some MLVs along with SUVs44.
- **Solvent injection method:** Depending on the kind of organic solvent utilized, the injection techniques were categorized45. The hydrophobic active substances and lipids were dissolved by an organic solvent that was quickly introduced into an aqueous phase. Direct solvent evaporation during mixing is made possible by diethyl ether at a temperature higher than the solvent's boiling point46. The majority of liposomal formulations with greater polydispersity indices (PDI) were created using this approach.47.

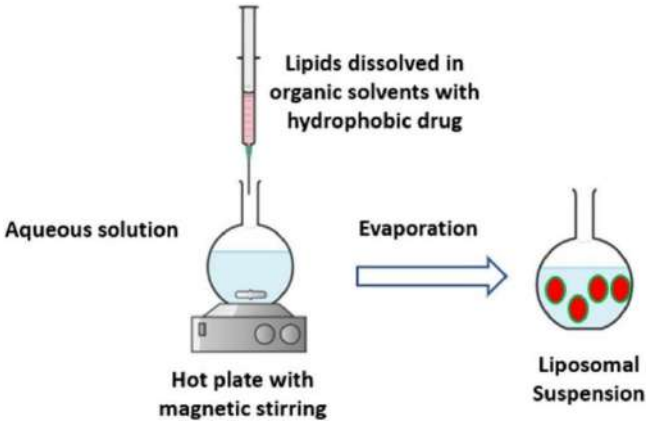

Fig.4: setup of the method of solvent injection method45

- **Detergent removal method:** Lipids and a surfactant with a high critical micelle concentration (CMC) were dissolved in an appropriate organic solvent using this approach. After the solvent was gently evaporated, a thin coating was found at the flask's bottom48. The lipid film was subsequently hydrated in an aqueous solution containing the drug molecules to produce a mixed micelles solution49. The surfactant is subsequently eliminated using dialysis, adsorption onto hydrophobic beads, size-exclusion chromatography, or dilution(50,51,52,53). This process is employed in the creation of LUVs.
- **Dehydration rehydration method**: Sonication is an organic solvent-free process for creating LUVs. This process involves sonicating an aqueous solution containing drug molecules after the lipids are directly dispersed at low quantities into it54. In order to form a multilayered film that entraps the drug molecules, the first stage in the dehydration process is to evaporate water under nitrogen. The next stage of hydration is to create big vesicles that contain the medication molecules(55,56).
- **Heating method:** It is also a method free of organic solvents. This approach involves hydrating lipids directly with an aqueous solution and heating them for a minimum of one hour above the phospholipids' transition temperature (Tm) in the presence of 3-5 percent hydration agents. When incorporating cholesterol into the recipe, the suspension can be heated to a maximum of 100°C 57.
- The stabilizing and isochronizing effects of the hydrating agents stop the coagulation of nanoparticles. The heating technique is an effective way to make powder inhalable liposomes since the hydrating chemicals also have a cryoprotective effect58.
- **pH jumping method:** The pH jumping approach is another solvent-free technique for liposome synthesis. This approach converts MLVs into SUVs by subjecting the aqueous solution of phosphatidic acid and phosphatidylcholine to an almost four-fold increase in pH over a brief period of time.(59,60).
- **Microfluidic channel method:** A new technique for preparing liposomes has been developed recently: the microfluidic channel method. This technique involves dissolving lipids in ethanol or isopropanol, and then injecting the resulting solution into the micro-channels either vertically or in the opposite direction to the aqueous media. This process creates liposomes by continuously axially mixing the organic and aqueous solutions. Microfluidic channel techniques regulate the organic and aqueous phase mixing process to produce liposomes that are reproducible and have the right average size, polydispersity, morphology, and lamellarity61.
- **Supercritical fluidic method:** In place of organic solvents, this technique used carbon dioxide (CO2), a supercritical fluid, to dissolve lipids. The aqueous phase is continuously pumped into a cell containing the supercritical lipid solution by means of a high-performance liquid pump, facilitating

the phase transition of the dissolved phospholipids62. After eliminating all CO2, liposomes will form upon a sudden drop in pressure. This approach produced encapsulation efficiencies that were five times greater.63.

Post Preparation Handling Methods:

- Freeze-thaw cycles: This method is typically applied to liposome preparations in order to improve liposome lamellarity and encapsulation efficiency. This method made use of freeze-thaw cycles in liquid nitrogen between -196 °C and below the chosen material's transition temperature (Tm). lipids and phospholipids (64,65).
- Lyophilization (Freeze drying): The purpose of this treatment is to enhance the shelf stability and maintain the liposomal goods. When the liposome suspension is mixed with a cryoprotective (often 5–10% sucrose or trehalose(66), it is deep frozen. This process is known as freeze-drying. Sublimation was then used to turn the liquid samples into fluffy solid particles at a very low temperature and a lowered vacuum.

LIPOSOME APPLICATIONS

- Drug Delivery: One of the most significant applications of liposomes is drug delivery. Liposomes can encapsulate a wide range of compounds, both hydrophilic and hydrophobic, making them ideal for transporting drugs to specific target cells or tissues. They offer several advantages, including:
  - Improved drug solubility and stability.
  - Controlled drug release.
  - Reduced side effects by targeting specific sites.
  - Enhanced therapeutic efficacy.
- Liposomal formulations have been developed for various drugs, including anticancer agents, antibiotics, and antifungals(67,68).
- Cancer Therapy: Cytotoxic drugs can be distributed non-specifically throughout the body, leading to the death of normal as well as malignant cells. Entrapment of these drugs into liposomes resulted in increased circulation lifetime and enhanced deposition in the infected tissues. To target tumors, liposomes must be capable of leaving the blood and accessing the tumor. Liposomal entrapment of these drugs showed reduced cardiotoxicity, dermal toxicity, and better survival of experimental animals. Such beneficial effects have been observed by liposomal formulations regardless of their lipid concentrations(69).
- Antimicrobials: Antibiotics can only act against intracellular infections if they can penetrate the phagocytic cells. when administered by intramuscular route, it resulted in sustained release from the injection site, providing prolonged plasma concentrations of the drug(70,71.
- Biomedical Research: Liposomes play a crucial role in biological and medical research. They are used for Studying Cell Membrane Behavior: Liposomes mimic cell membranes and are invaluable in studying membrane properties and behavior.
- Membrane Protein Isolation: Researchers use liposomes to isolate and study membrane proteins in a controlled environment.
- Assays and Assay Development: Liposomes serve as platforms for developing assays to assess various biological processes.
- Cosmetic and Skincare Products: Liposomes are utilized in the cosmetic and skincare industry for their ability to enhance the delivery of active ingredients to the skin. These formulations help improve the penetration of compounds, such as vitamins and antioxidants, into the epidermis.

- Vaccines: Liposomes have been investigated as carriers for vaccines. By encapsulating antigens within liposomes, researchers aim to enhance the immune response and improve the effectiveness of vaccines(72,73).

RECENT DEVELOPMENTS AND ADVANCES

The field of liposome research continues to evolve, leading to exciting developments:

- Targeted Drug Delivery: Advanced surface modifications allow for precise targeting of liposomes to specific cells or tissues, minimizing off-target effects.
- CoEncapsulation: Researchers are exploring the encapsulation of multiple drugs or compounds within liposomes to enhance therapeutic outcomes.
- LiposomeDrug Conjugates: Conjugating liposomes with drugs or other molecules enhances drug delivery and bioavailability.
- Nanotechnology Integration: Liposomes are increasingly integrated with nanotechnology for more advanced and multifunctional drug delivery systems.
- Immunotherapy: Liposomes are being employed in cancer immunotherapy, leveraging their ability to stimulate the immune system against cancer cells.
- Gene Therapy: Several systemic diseases are caused by a lack of enzymes, and factors due to missing or defective genes. Gene delivery systems are designed to control the location of administered therapeutic genes within the patient's body(74,75). However, there is always the potential risk that the viruses won't become replication-competent and therefore infectious. These liposomes were generally more effective in transfecting genes than micelles of the same lipid composition, thus suggesting a role for the bilayer structure in facilitating transfection.
- Biocompatible Materials: The development of biocompatible and biodegradable liposome materials is an emerging trend for minimizing toxicity76.

CHALLENGES AND FUTURE DIRECTIONS:

Despite their many advantages, liposomes face challenges, including stability issues, manufacturing complexity, and limitations in encapsulating certain drug types. Ongoing research is focused on addressing these challenges and improving liposomal formulations. In the future, we can expect to see further innovation in liposome-based drug delivery, the development of more personalized medicine using liposomes, and increased applications in the field of immunotherapy and gene therapy(77,78).

CONCLUSION

Liposomes have proven to be an effective medication delivery method for treating a variety of illnesses, from pain control to cancer treatment. This review demonstrated that phospholipids, both synthetic and natural, have been used to create liposomes, and that cholesterol is typically included as a membrane stabilizer. Liposomes have had a profound impact on the fields of pharmaceuticals, biotechnology, and biomedical research. Their ability to serve as versatile drug delivery vehicles, as well as their applications in research and cosmetics, make them a critical component of modern science and medicine. Ongoing advancements in liposome research are sure to expand their utility, providing new solutions to complex challenges in healthcare and beyond by understanding and controlling liposomal behavior. This facilitates the application of liposomes in a wide variety of drugs used for the treatment and diagnosis of diseases

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