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ADVANCEMENTS IN PHARMACEUTICAL DRUG DELIVERY SYSTEMS WITH FOCUS ON LIPOSOMES, NANOPARTICLES, VESICULAR CARRIERS AND NOVEL TABLET FORMULATIONS

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ABSTRACT

Pharmaceutical drug delivery has been changing radically and now includes multidisciplinary strategies to improve therapeutic effectiveness, adherence by the patient and local action. This review will cover in detail the current innovations in the different delivery systems available including vesicles and nanoparticle systems and novel oral dosage delivery systems. In the first instance, the concept of modern-day drug delivery was created via the targeting approach that optimizes the therapeutic benefits and limits the toxicity to the system. Liposomes, as well as other vesicular systems have proved to be incredibly versatile in the encapsulation of hydrophilic and lipophilic drugs in order to increase the bioavailability and to release the drugs in a controlled manner. In like manner, another use of the vesicular carrier is the extension of application of proniosomes and other vesicles in delivering drugs to the lungs and nose. With the development of nanoparticles, the pharmaceutical field has also received a boost, as it enables specific regulation of the drug release speed, enhanced stability, and subcellular and submolecular action. Implementing solid lipid systems, such as solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), have been able to fill the gap between polymeric and lipid-based formulations and guarantee a higher degree of biocompatibility. In the meantime,

novel oral forms of delivery including mouth-dissolving tablets, chewable and effervescent formulations and microencapsulated systems meet patient-oriented demands, which guarantee quick absorption and longer-term therapeutic protocols. These developments are still enhanced in a controlled and sustained release technology with an eye on precision of drug disposition and better therapeutic consistency. These inventions, together, mark a novel stage in the history of the pharmaceutical sciences of the 21st century, with nanotechnology in conjunction with materials science and formulation engineering redefining contemporary therapeutics.

KEYWORDS: Drug delivery systems, Liposomes, Nanoparticles, Vesicular carriers, Novel oral formulations.

1. Introduction to Modern Drug Delivery Systems

The recent drug delivery systems have revolutionized pharmacotherapy with special emphasis on guided and controlled release processes which augment therapeutic efficacy and reduce systemic adverse effects. Targeting is a main argument whose rationale is to bring an active pharmaceutical ingredient (API) to the desired site of action, keeping it in the best concentration and targeting it as long as possible.[1] The concept focuses on the drawbacks of the traditional dosage forms that are usually associated with low bioavailability, quick degeneration, and unselective diffusion.

Research[1] highlights that there is the passive, active, and ligand-mediated approaches, which are aimed at enhancing site-specific delivery via physiological and molecular recognition. The strategies increase the concentration of drugs in the diseased location and decrease the undesirable concentration in the normal areas. Additionally, the justification of such approaches lies in the aim to enhance patient adherence and decrease the frequency of the dosage.

Elaborating on these basics, Vyas and Khar[2] refer to the main principles of controlled drug delivery describing how simple sustained release formulations to more sophisticated responsive systems based on the usage of polymers, nanoparticles, and liposomal carriers have developed. All these new technologies work towards ensuring the maintenance of therapeutic drug levels, optimal pharmacokinetics, and predictable drug release profiles. Therefore, the combination of the concept of targeting and the controlled delivery

mechanisms can be seen as an important basis of developing contemporary, efficient, and patient-centered drug delivery systems.

2. Vesicular Drug Delivery Systems

One of the most advanced and flexible carriers when it comes to the contemporary therapeutics is the vesicular drug delivery system that can encapsulate both hydrophilic and lipophilic molecules to increase bioavailability and specificity. This notion was initiated by Bangham et al. (1965), who at the time proved that phospholipid bilayer vesicles, or liposomes, could be formed, which was the crucial breakthrough in the controlled drug delivery profession.[3]

Akbarzadeh et al. (2013) developed this and further categorized the liposomes as conventional, stealth, cationic, and immunoliposomes, based on their composition and functionalization. Their efforts pointed at the different preparation methods including thin-film hydration, reverse-phase evaporation as well as the solvent injection which aimed at attaining desired particle size and stability.[4] Such formulations have played a key role in enhancing the solubility of drugs, their longer circulation duration, and site-selectivity.

Torchilin (2005) has placed greater emphasis on clinical importance of liposomes as pharmaceutical carriers especially in anticancer and antifungal drugs. The liposomal systems have controlled release, lower toxicity, and capacity to overcome multidrug resistance, which are some of the important characteristics that have resulted in a number of liposomal systems gaining FDA approval.[5] Additionally, Allen and Cullis (2013) spoke about the process of the translation of liposomal technology concept to the clinical context, highlighting such improvements in it like PEGylation that react on the systemic stability, as well as pharmacokinetic characteristics.[6]

Proniosomes and niosomes have also become useful non-ionic surfactant-based vesicles systems in addition to liposomes. Sengar et al. state that proniosomes are better than liposomes in their stability and long-term ease of handling[6], which forms niosomes during hydration and provides a sustained release with better bioavailability.[7]

Moreover, vesicular systems are also being developed to deliver drugs to the lungs and to the nasal mucosa, described by Sengar, Jagrati, and Khatri (2024), in which liposomal and niosomal vesicles are employed to maximize local drug delivery in the lung and nasal

mucosa. These methods have vast potentials in the treatment of respiratory diseases and to allow non-invasive delivery of the system in the body.[8]

All in all, vesicular carriers have been of great success in terms of targeted and controlled delivery in that they have demonstrated versatility, biocompatibility, and applicability in various therapeutic systems.

3. Nanoparticle-Based Drug Delivery

The application of nanoparticles in enhancing drug delivery has turned into a necessity in the development of state of the art drug development because they are capable of enhancing solubility, stabilisation of unstable drugs and controlled and targeted release. Kaur and Mehta (2017) overviewed the development of the nanoparticles and underscored the multiplicity of their structure, such as polymeric, metallic, and lipid-based nanoparticles, as well as dendrimeric systems, which can be used in precision medicine with multiple benefits. Their paper emphasized the role of the nanoscale size, which enables such carriers to pass through the biological barriers, including the bloodbrain barrier, and provides better pharmacokinetics and biodistribution of therapeutic molecules.[9]

Continuing on this, Prajapati et al. (2024) have answered why nanoparticles can be seen as the next-generational technology in drug delivery and biomedical innovation because of their versatility in encapsulation of small molecules, peptides, and nucleic acids. The researchers have highlighted the combination of surface alteration methods like PEGylation and ligand conjugation to obtain active targeting and systemic circulation.[10]

One of the major issues in the delivery of nanoparticles lies in the oral delivery of peptides and proteins which are prone to the breakdown within the gastrointestinal tract. Zhu et al. (2021) examined such approaches as enzyme inhibitors, permeation enhancers, and nanoencapsulation techniques that can be used to protect therapeutic macromolecules against enzymatic degradation and increase their trans-epithelial uptake. In their findings, they highlight the benefits of nanocarriers in increasing the oral bioavailability of biomolecules and maintaining their structural integrity.[11]

Moreover, Sengar et al. (2024) emphasize the ability of effervescent nanocarrier systems to become an innovative approach to oral formulations and assist in the fast dispersion of a previously poorly soluble drug and enhance its palatability and action onset. Such effusive

activities combined with nanoparticles have synergistic efficacies to patient adherence and therapeutic efficacy.[12]

Altogether, drug delivery systems that use nanoparticles are at the center of the pharmaceutical innovation, the interface between nanotechnology and pharmacology that allows to achieve personalised, effective and safe therapeutic results.

4. Solid Lipid Systems

Solid lipid systems, especially Solid Lipid Nanoparticles (SLNs) and Nanostructured Lipid Carriers (NLCs), mark a significant leap in the creation of drug delivery systems that are both effective and safe. The use of these lipid-based nanocarriers results in the stability of the drug, its slow release, and the favorable interaction of the carrier with living tissues thus they are being considered as the carriers in both, pharmaceutical and cosmetic formulations. Müller et al. (2002) were the pioneers who first introduced the notion of SLNs and NLCs as the substitutes to polymeric nanoparticles, pointing out their capacity to conceal lipophilic drugs inside the solid lipid framework. The researchers validated that SLNs' give a release profile that is controlled and thus enhances the solubility of the drug coming from the poor than the extent of being swallowed, while NLCs develop the remaining drug- that is, the excipient- capacity and cut down on the release during the storage period.[13]

The past few years have also been the development and refinement period for the lipid-based carriers—writing more about their preparation techniques and characterization methods to make sure they are reproducible and scalable. Has and Sunthar (2020) conducted a detailed examination of the state-of-the-art production methods, such as high-pressure homogenization, solvent evaporation, and microemulsion-based techniques, among others, pinpointing the need for microscopic control over the size and shape of the particles to be able to predict the release of drugs from the formulation.[14] Moreover, their review has also claimed that the lipid chemistry and process engineering advancements are paving the way for the next-generation lipid carriers that will be capable of specific tissue targeting or even overcoming the complex biological barriers for the delivery purposes.

In the same vein, SLNs and NLCs are the living proof of the collaboration of lipid science and nanotechnology, hence the new bright and promising way of the delivery of bioactive compounds with high stability, safety, and therapeutic efficiency across a broad spectrum of medical applications.

5. Innovative Oral Dosage Forms

The introduction of innovative oral dosage forms in the drug administration has changed the whole picture by putting the patient first, having a rapid onset of action, and increasing the availability of the drug in the body. One of the innovative approaches for oral dosage forms has been mouth-dissolving tablets (MDTs) which have gained more and more attention from the pharmaceutical industry. Patel and Patel (2007) produced MDTs based on cinnarizine, showing that superdisintegrants make the oral cavity disintegrate quickly without water, thus increasing patient compliance and drug absorption through the buccal mucosa.[15] Also, Mishra and Patel (2007) were able to optimize the formulation parameters to get quicker disintegration times in combination with greater mechanical strength, thus pointing out the promising usage of MDTs in elderly and pediatric patients.[16]

Going further with this idea, Sengar, Yadav, and Niranjan (2024) came up with mouth-dissolving films of propranolol hydrochloride focusing on their rapid dissolution, accurate dosing, and trouble-free administration to patients who have difficulty swallowing. Their research highlighted the contribution of polymeric film-forming agents to getting the perfect balance between flexibility and dissolution characteristics.[17] In another example, Yadav and Mote (2008) showed how β-cyclodextrin inclusion complexes can be used in the formulation of ondansetron hydrochloride MDTs to increase solubility and taste masking, which, in turn, leads to better flavoring and therapeutic effectiveness.[18]

Moreover, Kamboj et al. (2013) did some more studies and reported that they compared the use of different superdisintegrants in the preparation of amlodipine besylate MDTs, and they concluded that the selection of excipient played a crucial role in the disintegration rate and drug release profile.[19] Kumar and Singh (2012) looked at effervescent tablets of paracetamol and concluded that the patient acceptance of these pills was better, the release of active substance was more rapid and the dissolution rate was accelerated by the CO_2.[20]

One more option is chewable tablets, which are the combination of pleasantness and accessibility. Sengar et al. (2024) talked about the formulation strategies that maximize the mechanical strength and the taste masking which are especially helpful for kids and patients undergoing long-term treatment.[21] There is another method of drug delivery called controlled oral systems, which includes pulsatile and multiparticulate release formulations and has been created to allow site- and time-specific drug release. Sharma and Pawar (2006) created a low-density multiparticulate system for meloxicam that floats and allows pulsatile

drug release for chronotherapeutic benefits.[22] Moreover, Singh et al. (2010) described microencapsulation methods to control the release and safeguard the active ingredients, thus allowing precision dosing and less side effects.[23]

Oral innovations have become a paradigm shift towards patient-centered formulations that integrate convenience, compliance, and pharmacological performance mirroring the changing demands of the modern therapeutics.

6. Controlled and Sustained Release Technologies

The development of controlled and sustained release technologies marked the beginning of the era of modern drug delivery. They provide the main benefits of constant gross and therapeutic plasma drug concentrations over long periods and at the same time, they refill, if needed, with the therapeutic amount of the drug, so the patient does not have to take it as often. These systems work by keeping the amplitude of the drug in the plasma within the therapeutic range limiting it to a minimum thus—fluctuations typical for conventional dosage forms are virtually eliminated.

Gupta and Mishra (2011) took a look back at the journey of oral drug delivery systems, pointing out the gradual change from immediate-release formulations to advanced technologies that fast-dissolve and control-release. They not only considered the future of drug delivery but also emphasized the importance of polymer science, coating, and granulation in the design of formulations that precisely target the conditions of the human body—thereby providing better bioavailability and assuring the patients' compliance.[24] They also mentioned that continuous-release systems are very different from regular formulations in that they are exclusively based on the use of polymeric matrices and osmotic principles for controlling the rate of drug diffusion or degradation.

Taking it a step further, Jagrati and Sengar (2024) presented the incorporation of liposomal vesicular carriers as an avant-garde addition to the sustained release mechanisms. Owing to the bilayered phospholipid structure, liposomes can effectively trap both water-soluble and fat-soluble drugs, thus prolonging their circulation and enabling precise delivery with less waste. The research underlined how the lipid composition, the charge, and the vesicle size can all be manipulated to regulate the release profile and consequently the therapeutic.[25]

The combination of these release systems both controlled and sustained shows the pharmaceutical industry's commitment to accuracy, reliability, and patient-oriented treatment. Through the use of materials science and nanotechnology progress, formulations of modern times are able to deliver drugs in a temporally and spatially controlled way— i.e. a shift towards more intelligent and efficient therapeutics.

CONCLUSION

The transition of drug delivery systems from one stage to another has changed the pharmaceutical industry landscape by blending scientific creativity with patient-oriented design. The backbone of modern drug delivery is in the targeted and controlled systems that achieve therapeutic effect maximization while minimizing side effects.[1,2] The vesicular delivery systems, liposomes being the most prominent, have altered the pharmacological potency through increased bioavailability and targeted delivery, which was made possible by improved design and technique of the composition.[3–8] The use of nanoparticles in drug release has enabled the more precise and stable control of the release, allowing for the controlled targeting of drug molecules at the cellular level.[9–12] The solid lipid systems like SLNs and NLCs have acted as a bridge between the traditional and nanotechnology approaches by offering biocompatibility and sustained release at the same time.[13,14] In addition, new oral drug delivery systems like mouth-dissolving, effervescent, chewable, and pulsatile have made it easier for the patient to take the medicine and have also made the therapy more efficient by improving the pharmacokinetics.[15–23] Moreover, the use of controlled and sustained release technologies leads to drug availability that is both prolonged and predictable, and through maintaining steady plasma concentrations, it thus enhances therapeutic outcomes.[24,25]

All in all, the above-mentioned innovations have made it possible to switch from the traditional drug delivery forms to the new smart, responsive, and efficient systems. The combination of nanotechnology, vesicular carriers, and advanced oral formulations marks the beginning of the next generation of pharmaceutical development, which not only brings in new ideas but also provides better patient experience along with the best therapeutic performance.

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4. Solid lipid systems
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6. Controlled and sustained release technologies

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