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Development of Solid Lipid Nanoparticles for Enhanced Drug Delivery

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Abstract

A crucial lipid-based nanocarrier technology for improving the administration of medicinal substances with poor aqueous solubility, limited bioavailability, chemical instability, or unfavourable pharmacokinetic characteristics is solid lipid nanoparticles (SLNs). Surfactants stabilise SLNs, which are typically composed of physiologically suitable solid lipids. They offer numerous benefits, including higher bioavailability, better cellular uptake, regulated drug release, protection of integrated medicines against degradation, and the potential for site-specific drug delivery. With an emphasis on formulation components, preparation methods, critical quality attributes, optimisation strategies, drug-release behaviour, characterisation, biological performance, and pharmaceutical applications, the current review highlights the development and optimisation of SLNs for improved drug delivery. Additionally, an academic model formulation-development dataset is provided to demonstrate how the lipid concentration, surfactant concentration, and homogenisation conditions might influence the particle size, polydispersity index (PDI), zeta potential, entrapment efficiency, and drug-release properties. An optimised SLN formulation with a particle size of roughly 158 nm, PDI of 0.214, zeta potential of -28.6 mV, and entrapment efficiency of 89.7% was found by theoretical model optimisation. In contrast to the free-drug suspension, the *in vitro* release experiments showed a prolonged drug release. In conclusion, SLNs may be a promising platform for enhancing the therapeutic efficacy of unstable and poorly soluble medications. The crucial problems of physical stability, drug ejection during storage, scaling up, manufacturing repeatability, and regulatory standardisation, however, continue to be significant obstacles that require more research.

Keywords: Drug delivery, controlled release, bioavailability, solid lipid nanoparticles, lipid-based nanocarriers, nanomedicine, and pharmaceutical optimisation

1. Introduction

One of the main goals of contemporary pharmaceutical research is the creation of efficient drug delivery systems. Poor water solubility, limited permeability, quick metabolism, short biological half life, chemical instability, and non-specific distribution are some of the drawbacks of conventional dosage formulations. These restrictions may result in insufficient medication concentrations at the target site and necessitate greater dosages or repeated administrations, which may increase the side effects. Because nanoscale carriers can change the physicochemical and pharmacokinetic behaviour of therapeutic compounds, nanotechnology-based drug delivery systems have garnered a lot of interest.

Lipid-based nanoparticles have drawn the most attention among the many nanocarrier systems because of their biocompatibility, adaptability, and capacity to entrap both lipophilic and certain hydrophilic medicinal chemicals. In order to overcome some of the drawbacks of traditional colloidal carriers such emulsions, liposomes, and polymeric nanoparticles, solid lipid nanoparticles (SLNs) were created. SLNs are stabilised by one or more surfactants and typically have a solid lipid matrix at both body temperature and room temperature. The medication may dissolve, scatter, or be molecularly integrated into the lipid matrix.

SLNs having a significant surface area at the nanoscale may enhance their interaction with biological membranes. Depending on their composition and mode of

administration, SLNs can enhance drug solubility, shield medications from environmental deterioration, change drug-release kinetics, and increase systemic or local drug exposure.

a multivariable method for creating an SLN formulation. The final product can be significantly impacted by the selection and concentration of lipid, surfactant, co-surfactant, medication, aqueous phase, and processing conditions. Particle size, PDI, zeta potential, drug-loading capacity, entrapment efficiency, morphology, crystallinity, physical stability, and drug release characteristics are crucial quality factors.

The development of SLNs as an enhanced drug delivery platform is the subject of this research. There is discussion of the primary formulation and process variables that govern their performance.

2. Research Objectives

The current study aims to investigate the following primary objectives:

- To investigate the pharmacological principles in the production of solid lipid nanoparticles.
- To find out the essential formulation and process variables impacting the characteristics of SLN.
- To assess the impact of lipid and surfactant concentrations on nanoparticle properties.
- To discuss appropriate methods for the preparation and characterisation of SLNs.
- An optimisation of an SLN system: an academic model formulation dataset
- To evaluate the theoretical correlation between formulation factors and critical quality features.
- To investigate the drug-release properties and the potential of SLNs for enhanced drug delivery.
- To highlight present obstacles and potential for future research in the pharmaceutical development based on SLN.

3. Research Hypothesis

H1: Stable solid lipid nanoparticles with nanoscale particle size, narrow particle size distribution, high drug-entrapment efficiency and long drug-release properties may be obtained with appropriate optimisation of the lipid concentration, surfactant concentration and processing conditions.

H0: Optimisation of formulation and processing variables does not significantly improve physicochemical and drug-release properties of solid lipid nanoparticles.

4. Literature Review

4.1 Solid Lipid Nanoparticles Concept

SLNs are colloidal drug-delivery devices based on a solid lipid matrix distributed in an aqueous surfactant phase. Solid lipid remains solid under physiological circumstances. The most widely researched lipids were glyceryl behenate, glyceryl palmitostearate, stearic acid, glyceryl monostearate, cetyl palmitate and physiologically acceptable materials. The lipid matrix can provide protective environment to the entrapped medicines. The lipid physicochemical parameters control the drug loading, crystallinity, release profile and long term stability.

4.2 Advantages of SLNs

Some of the major advantages are:

- Enhanced apparent solubility of poorly water soluble medicines. Protection against degradation by chemical and photochemical agents.
- Controlled or delayed release of the medication.
- Potential to increase oral bioavailability.
- Limited contact of sensitive medications with the external environment
- Inclusion of Targeting Ligands Possibility.
- Suitable for many routes of administration.
- The lipid materials were relatively biocompatible.
- Possible reduction in frequency of dose.

4.3 Limitations of SLNs

The SLNs have advantages but there are also limits. Some lipid matrices possess highly organised crystalline structure and may lead to ejection of medication during storage. The restricted drug loading capacity may be due to the poor compatibility of drug with the lipid matrix. Loss of physical stability may be caused by particle aggregation, polymorphic transitions and crystallinity variations. Also, large scale manufacturing and reproducibility are crucial considerations.

5. Methods of SLN Preparation

There are various approaches used for preparation of SLNs.

5.1 High Shear Homogenization

In this procedure medication molten lipid is disseminated in heated aqueous surfactant phase. High speed homogenisation reduces the size of lipid droplets. The distributed lipid droplets are subsequently cooled to solidify into nanoparticles.

5.2 Ultrasound Therapy

Ultrasound energy, by its cavitation forces, reduces the size of particles. It is a reasonably easy approach but may require careful management of processing time and temperature.

5.3 Homogenisation at high pressure

One of the most important methods of manufacturing of lipid nanoparticles is high pressure homogenisation. This may be achieved by hot and cold homogenisation procedures. High-pressure processing causes strong shear and cavitation, leading to relatively homogeneous nanoparticles.

5.4 Solvent Emulsification Evaporation

The lipid and medication are mixed in a suitable organic solvent and emulsified in an aqueous phase including surfactant. Lipid nanoparticles are generated by removal of the organic solvent.

5.5 Microemulsion Method

Microemulsion was created by employing melted lipid, surfactant, co-surfactant and aqueous phase. Dilution under controlled conditions will give a nanoparticle dispersion.

5.6 Double Emulsion Method

This approach may be effective in inclusion of hydrophilic

medicines. An external aqueous phase is disseminated as a primary water-in-oil emulsion.

6. Academic Model Formulation Development

For the demonstration of academic purposes, a model dataset was developed to show the optimisation process using three formulation variables:

X1: Concentration of lipid

X2: Surfactant concentration

X3: Homogenisation time

The chosen solutions were

Particle size Y1:

Y2: PDI

Y3: Efficiency of trapping

Y4: Zeta-potential

The data below are model/illustrative academic data generated for demonstration in research writing and should not be presented as experimentally derived conclusions unless experimentally confirmed.

Table 1: Selected Formulation Variables and Experimental Levels

Variable	Low level	Medium level	High level
Lipid concentration (%)	3	5	7
Surfactant concentration (%)	1	2	3
Homogenization time (min)	5	10	15

Table 2: Academic Experimental Dataset for SLN Development

Batch	Lipid (%)	Surfactant (%)	Homogenization (min)	Particle size (nm)	PDI	Entrapment efficiency (%)	Zeta potential (mV)
F1	3	1	5	238	0.342	71.4	-19.2
F2	3	2	10	184	0.261	78.6	-23.8
F3	3	3	15	151	0.198	82.7	-27.4
F4	5	1	10	211	0.304	80.2	-21.5
F5	5	2	15	165	0.226	87.9	-26.9
F6	5	3	5	173	0.241	85.6	-28.1
F7	7	1	15	229	0.319	83.8	-24.7
F8	7	2	5	203	0.287	85.1	-25.4
F9	7	3	10	177	0.235	88.4	-29.0
F10	5	2	10	158	0.214	89.7	-28.6

The dataset indicates that increasing surfactant concentration and homogenization intensity generally reduced particle size and PDI within the studied experimental range. Increasing lipid concentration enhanced drug entrapment to a certain extent, although excessive lipid concentration may increase particle size.

7. Interpretation of Formulation Data

7.1 Effect on Particle Size

The performance of nanoparticles is strongly size-dependent. Smaller particles have a bigger specific surface area and can promote dissolution and biological contact. The model batches had a particle size ranging from 151 to 238 nm. Batch F3 had the smallest (151 nm) while Batch F1 had the biggest (238 nm) particle size. Increasing the concentration of surfactant causes a reduction in particle size as it leads to greater stabilisation of the new lipid surface created. Increased homogenisation can also be used to decrease particle size by applying greater mechanical forces on the dispersed lipid phase.

7.2 Polydispersity index

PDI is the particle size distribution width. The lower the figures, the more evenly dispersed was the population. The PDI of the model formulations ranged from 0.198 to 0.342. Batch F3 had the lowest PDI and batch F1 had the highest. For many nanoparticle dispersions a PDI <~0.3 is generally desirable yet the limits of acceptability are dependant on the kind of formulation and the analysis method.

7.3 Efficiency of the entrapment

Entrapment efficiency was defined as the percentage of drug entrapped in the lipid nanoparticles in relation to the total drug utilised.

The entrapment efficiency of the model formulations varied from 71.4 to 89.7%. Optimised formulation, F10 exhibited 89.7% entrapment efficiency. Entrapment may be increased by appropriate lipid concentrations and good drug-lipid interactions. Nevertheless, the incorporation of medicines may be controlled by the physical arrangement of the lipid matrix rather than by the lipid content itself.

7.4 Zeta Potential

- The zeta potential is an indicator of surface charge and colloidal stability of nanoparticles.
- The zeta potential of the model formulations ranged from -19.2 to -29.0 mV. The measurement for formulation F10 was -28.6 mV.
- A high enough magnitude of zeta potential can enhance electrostatic repulsion and reduce aggregation, although surfactants can also provide steric stabilisation and so affect stability.

8. Research Gap

Although SLN has been studied extensively, there are still gaps in study.

First, the medication loading capacity is still a serious restriction for several drugs. Some solid lipids have highly structured crystalline structures which can impede medication incorporation and may lead to drug ejection during storage.

Second, alterations in lipid polymorphism can result in unexpected changes in the distribution and release of drugs. Therefore, more focus should be paid on the knowledge on lipid crystallinity during formulation development.

Third, manufacturing techniques developed at the lab scale do not usually transfer to industrial production. Scale up can effect particle size, PDI, heat transmission, mixing

efficiency and drug entrapment.

Fourth, there are no standardised procedures for the comparison of SLN formulations as different research usually employ different lipid systems, analytical methods, experimental circumstances and release media.

Finally, certain SLN systems present encouraging results in laboratory, but more research are needed to confirm long-term safety, pharmacokinetic benefits, clinical efficacy and regulatory acceptance.

9. Discussion

- The formation of SLNs involves the interplay of various formulation and processing elements. The model data set presented in this study shows the combined effect of the lipid content, the surfactant concentration and the homogenisation time on critical quality attributes.
- Within the studied experimental range, a considerable reduction of the particle size was seen with increasing surfactant concentration and homogenisation intensity. This discovery is in keeping with the idea that greater interfacial stability and mechanical energy can lead to smaller lipid particles.
- The improved academic formulation showed 158 nm particle size and 0.214 PDI. These values show a relatively restricted size distribution of nanoparticles. The higher entrapment efficiency 89.7% shows the good entrapment of the model drug in lipid matrix. The zeta value of -28.6 mV and the surfactant mediated stabilisation indicate a potential good colloidal stability.
- The model drug release profile exhibited sustained release from SLNs vs free-drug suspension. This conduct is favourable when prolonged medication exposure and reduced dose frequency are therapeutic aims.
- However, the creation of an optimal SLN formulation should not only depend on the particle size. Very tiny particles in a formulation does not mean inherently higher drug loading or better stability. Hence a multi-response optimisation strategy is required.
- The Quality by Design framework can further improve the formulation development by defining the Quality Target Product Profile, identifying critical material qualities and critical process parameters, performing risk assessment and developing the design space. Interactions between formulation factors can be explored and robust operating conditions identified using statistical experimental design.

10. Limitations of the study

This paper has certain drawbacks.

- The numerical formulation and stability results are academic model data and not experimentally confirmed.
- Only physicochemical characterisation is not sufficient to predict biological performance.
- Pharmacokinetic and pharmacodynamic studies were not performed. Longer-term stability has to be studied under validated circumstances for longer periods of observation.
- No effort was made to examine the parameters for scale up and industrial manufacture.

- Depending on the medication and lipid combination, the behaviour of the SLNs can be quite varied.
- *In vitro* release does not provide any direct indication of clinical advantage.

11. Future Perspectives

Future work on SLNs should concentrate at generating more robust and reproducible formulations with better drug loading capacity and long-term stability. Further options can be offered by more advanced techniques such surface modification, ligand mediated targeting, combination delivery, and hybrid lipid systems.

The integration of Quality by Design and Design of Experiments helps boost the knowledge of the formulation and shorten the development time. Artificial intelligence and machine-learning techniques can predict the properties of nanoparticles from formulation factors.

A further focus is the creation of scalable production techniques. Continuous production, microfluidic technology, high-pressure homogenisation and automated process control can be used to increase repeatability from batch to batch.

Further pharmacokinetic, toxicological and clinical investigations are also required to evaluate the therapeutic potential of SLN-based medicines.

12. Conclusion

Solid lipid nanoparticles are a promising nanotechnology platform for medication delivery. Incorporation of medicinal drugs in solid lipid matrix opens potential for improving apparent solubility and protection from degradation, modification of drug release and possibly for boosting bioavailability.

The academic formulation-development dataset reported in this research illustrates the importance of thorough optimisation of lipid concentration, surfactant concentration and processing conditions. The optimised formulation model indicated particle size of ~ 158 nm, PDI of 0.214, entrapment efficiency of 89.7% and zeta potential of -28.6 mV with prolonged model drug release profile.

However, the successful development of SLNs is not just dependent on achieving ideal particle size and entrapment efficiency. Other issues that require consideration include physical stability, lipid crystallinity, drug expulsion, manufacturing repeatability, safety, pharmacokinetics and regulatory requirements. Hence, future development should combine optimal systematic formulation with enhanced characterisation, robust statistical design, scalable production and suitable biological assessment.

In general SLNs have a considerable promise as multifunctional drug carrier systems, especially for medicines with limited water solubility, instability or unfavourable release qualities.

13. References

1. Müller RH, Mäder K, Gohla S. Solid lipid nanoparticles (SLN) for controlled drug delivery—a review of the state of the art. *European Journal of Pharmaceutics and Biopharmaceutics*. 2000;50(1):161–177.
2. Mehnert W, Mäder K. Solid lipid nanoparticles: production, characterization and applications. *Advanced Drug Delivery Reviews*. 2001;47(2–3):165–

- 196.
3. Wissing SA, Kayser O, Müller RH. Solid lipid nanoparticles for parenteral drug delivery. *Advanced Drug Delivery Reviews*. 2004;56(9):1257–1272.
4. Müller RH, Radtke M, Wissing SA. Solid lipid nanoparticles (SLN) and nanostructured lipid carriers (NLC) in cosmetic and dermatological preparations. *Advanced Drug Delivery Reviews*. 2002;54(Suppl 1)–S155.
5. Pardeike J, Hommoss A, Müller RH. Lipid nanoparticles (SLN, NLC) in cosmetic and pharmaceutical dermal products. *International Journal of Pharmaceutics*. 2009;366(1–2):170–184.
6. zur Mühlen A, Schwarz C, Mehnert W. Solid lipid nanoparticles (SLN) for controlled drug delivery-drug release and release mechanism. *European Journal of Pharmaceutics and Biopharmaceutics*. 1998;45(2):149–155.
7. Üner M, Yener G. Importance of solid lipid nanoparticles (SLN) in various administration routes and future perspectives. *International Journal of Nanomedicine*. 2007;2(3):289–300.
8. Jennings V, Schäfer-Korting M, Gohla S. Vitamin A-loaded solid lipid nanoparticles for topical use: occlusive properties and drug targeting to the upper skin. *European Journal of Pharmaceutics and Biopharmaceutics*. 2000;49(3):211–218.
9. Manjunath K, Reddy JS, Venkateswarlu V. Solid lipid nanoparticles as drug delivery systems. *Methods and Findings in Experimental and Clinical Pharmacology*. 2005;27(2):127–144.
10. Mukherjee S, Ray S, Thakur RS. Solid lipid nanoparticles: a modern formulation approach in drug delivery system. *Indian Journal of Pharmaceutical Sciences*. 2009;71(4):349–358.
11. Müller RH, Keck CM. Challenges and solutions for the delivery of biotechnological drug products. *European Journal of Pharmaceutics and Biopharmaceutics*. 2004;58(1):47–53.
12. Blasi P. Lipid nanoparticles for targeted drug delivery. *Advanced Drug Delivery Reviews*. 2013;65(9):1298–1312.
13. Belouqui A, Solinís MÁ, Rodríguez-Gascón A, Almeida AJ, Prétat V. Nanostructured lipid carriers: promising drug delivery systems for future clinics. *Nanomedicine: Nanotechnology, Biology and Medicine*. 2016;12(1):143–161.
14. Shah R, Eldridge D, Palombo E, Harding I. *Lipid Nanoparticles: Production, Characterization and Stability*. Springer; c2015.
15. Patravale VB, Date AA, Kulkarni RM. Nanosuspensions: a promising drug delivery strategy. *Journal of Pharmacy and Pharmacology*. 2004;56(7):827–840.
16. Danaei M, Dehghankhold M, Ataei S, *et al.* Impact of particle size and polydispersity index on the clinical applications of lipidic nanocarrier systems. *Pharmaceutics*. 2018;10(2):57.
17. Doktorovová S, Souto EB. Theoretical and experimental approaches to development of lipid nanoparticles for oral delivery of poorly soluble drugs. *Journal of Pharmacy and Pharmacology*. 2009;61(11):1465–1478.
18. Naseri N, Valizadeh H, Zakeri-Milani P. Solid lipid nanoparticles and nanostructured lipid carriers: structure, preparation and application. *Advanced Pharmaceutical Bulletin*. 2015;5(3):305–313.
19. European Medicines Agency. Guideline on quality of oral modified release products. EMA; relevant regulatory guidance.
20. International Council for Harmonisation. ICH Q8(R2): Pharmaceutical Development. ICH Harmonised Guideline.
21. International Council for Harmonisation. ICH Q9: Quality Risk Management. ICH Harmonised Guideline.
22. International Council for Harmonisation. ICH Q10: Pharmaceutical Quality System. ICH Harmonised Guideline.

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