Study on the Carrier Function and Skin Permeability of Nanoemulsion in Sunscreen and Skin Care Products

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Abstract

In this study, nanoemulsion was prepared by high-pressure homogenization method, and its carrier mechanism, skin penetration law and safety in sunscreen products were systematically evaluated, which provided theoretical and practical basis for the design of high-efficiency and low-irritation sunscreen formula. The experimental results show that the nanoemulsion (particle size 150±20 nm) has excellent sun protection performance, SPF value is 50±3, which is about 67% higher than that of traditional emulsion, and the critical wavelength is 382 nm, which meets the broad-spectrum protection standards. At the same time, it showed excellent light stability and water resistance. The residual rate of Avobenzone reached 92% after illumination, and the SPF retention rate exceeded 85% after 40 minutes of water bath. The particle size of nanoemulsion significantly affects the skin penetration behavior, in which the 200 nm emulsion has the highest retention in the stratum corneum (98.7%) and the dermal penetration is only 0.2%. In addition, nanoemulsion showed good biocompatibility, the survival rate of HaCaT cells was still higher than 90% after 48 hours, and no irritation or allergic reaction was found in EpiDerm™ model and human patch test, indicating that it is suitable for special people such as sensitive skin and children.

Keywords

Nano-emulsion; carrier function; skin permeability; sunscreen and skin care products.

1. INTRODUCTION

Ultraviolet radiation is a key environmental factor that causes skin photodamage, which is closely related to skin aging, pigmentation, photosensitive reaction and skin cancer. About 90% of the new cases of skin cancer in the world are related to ultraviolet exposure every year, which makes the development of efficient sunscreen products an important topic. Sunscreens are mainly divided into organic and inorganic, but traditional products have some problems, such as poor stability, limited solubility and the contradiction between skin feeling and permeability. Organic sunscreens are prone to photodegradation, which reduces the sunscreen effect; Its hydrophobicity leads to low solubility in water phase system, which may cause skin irritation; At the same time, the use of high-concentration sunscreen not only causes a sticky and white feeling, but also may penetrate the skin barrier, bringing potential toxic risks. Therefore, it is urgent to improve these shortcomings of existing sunscreen products.

As a new drug delivery system, nanoemulsion can significantly improve the above problems by wrapping the active ingredients in emulsion droplets with a particle size of 10-200 nm. Its high specific surface area, strong solubilization ability and controlled release characteristics make it an ideal carrier for sunscreen agents. In addition, nanoemulsion can optimize the distribution and penetration behavior of sunscreen in skin by adjusting particle size, surface charge and emulsifier type, and balance efficacy and safety.

In recent years, the application research of nanoemulsion in the field of sun protection has gradually increased. For example, reference [1] prepared nanoemulsion loaded with avobenzone by high-pressure homogenization method, and found that its SPF value was increased by 40% compared with traditional emulsion, and its photostability was significantly enhanced. Literature [2] uses microfluidic technology to construct bicontinuous nanoemulsion, which realizes the synergistic effect of organic-inorganic sunscreen and reduces the agglomeration of inorganic particles. However, the skin permeability of nanoemulsion is still controversial: some studies show that small-sized droplets (< 100 nm) may penetrate the stratum corneum through hair follicles or intercellular pathways, causing systemic absorption risk [3]; However, other studies believe that nanoemulsion mainly forms a protective film on the skin surface, with limited penetration [4]. Therefore, it is very important to explore the carrier mechanism of nanoemulsion and its influence on skin permeability for developing safe and efficient sunscreen products [5].

In this study, the carrier mechanism and skin penetration law of nanoemulsion in sunscreen products were systematically discussed, aiming at revealing its influence on the stability, solubility and protective effect of sunscreen agents from the theoretical level and providing basis for the design of nano carriers. Develop high-efficiency and low-stimulation nano-sunscreen formula at the application level to meet the needs of special people such as sensitive muscles and children; The penetration behavior and potential toxicity were evaluated at the safety level to provide reference for product safety, so as to promote the application of nanotechnology in the field of sun protection and promote the dual promotion of product function and safety.

2. THEORETICAL BASIS OF NANOEMULSION AS SUNSCREEN CARRIER

The traditional sunscreen has some problems such as poor stability and strong irritation, which limits its application in cosmetics. As a new type of nano-delivery system, nanoemulsion shows great application potential in the carrier function of sunscreen and skin permeability with its unique physical and chemical properties [6]. Nanoemulsion is a submicron emulsion composed of oil phase, water phase and surfactant, and its particle size is usually between 10-1000 nm [7]. According to its structure and stability, nanoemulsion can be divided into two types: O/W (oil-in-water) type and W/O (water-in-oil) type.

There are two main methods to prepare nanoemulsion: Phase Inversion Composition (PIC) and Phase Inversion Temperature (PIT). PIC method realizes the phase transition by changing the oil-water ratio, while PIT method realizes the phase transition by adjusting the temperature [8]. The stability of nanoemulsification mainly depends on the adsorption of surfactants on the oil-water interface. High interfacial tension and closely arranged surfactant molecular layers are helpful to improve the thermodynamic stability of nanoemulsion [9]. Nanoemulsion, as a carrier of sunscreen, can improve the stability and safety of sunscreen. Through the coating effect of nanoemulsion, the direct contact between sunscreen and skin can be effectively reduced, and the irritation to skin can be reduced. In addition, nanoemulsion can also control the release rate of sunscreen and achieve long-term sunscreen effect. The skin permeability of nanoemulsion is closely related to its particle size, surfactant type and concentration. Smaller particle size and suitable surfactant are helpful to improve the skin permeability of nanoemulsion, thus promoting the effective absorption of sunscreen.

3. EXPERIMENTAL DESIGN AND METHOD

3.1. Materials and reagents

The materials and reagents used in this experiment include: sunscreen (organic such as Avobenzone, Oxalin, inorganic such as nano zinc oxide), caprylic/capric triglyceride and

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squalene used to construct lipid phase, nonionic surfactant as emulsifier, water phase components such as ultrapure water and glycerol (with moisturizing function), and detection reagents such as Franz diffusion cell buffer and MTT cytotoxicity reagent; For skin model, pig ear skin (in vitro experiment), artificial skin model EpiDerm™ and volunteer skin were used for patch test.

3.2. Preparation of nanoemulsion

Nanoemulsion was prepared by high-pressure homogenization method. Firstly, water phase (containing emulsifier) and lipid phase (containing sunscreen) were premixed at 70°C, followed by high-speed shear emulsification (10,000 rpm × 5 min), and then nanoemulsion with target particle size of 100-200 nm was obtained by high-pressure homogenization (800 bar × 3 cycles). During the preparation process, the particle size was determined by dynamic light scattering (DLS), the morphology was observed by PDI and transmission electron microscope (TEM), and the stability was evaluated by pH meter to ensure the product quality met the requirements.

3.3. Sunscreen performance evaluation

The evaluation of sunscreen performance includes SPF determination in vitro, light stability and water resistance test; The SPF value, UVA-PF value and critical wavelength (λc) were calculated by ultraviolet spectrophotometry (combined with quartz plate) to evaluate the sunscreen effect and broad-spectrum protection ability. The light stability was evaluated by simulating sunlight irradiation (500 W/m^2×1 hour) combined with HPLC to detect the residual rate of sunscreen. Water resistance is evaluated by soaking in water at 40°C for 40 minutes after coating, and then measuring the attenuation rate of SPF value.

3.4. Study on skin permeability

In the skin permeation experiment in vitro, using Franz diffusion cell system, using pig ear skin as a model, the nanoemulsion sunscreen product (2 mg/cm^2) was applied quantitatively at 37°C, and the body fluid was collected regularly from 0 to 24 hours. The transdermal amount of sunscreen was detected by HPLC-MS/MS, and its transdermal permeation ability was evaluated.

In order to further analyze the distribution of sunscreen in various layers of skin, the stratum corneum was separated by tape peeling (peeling for 20 times), and the accumulation of sunscreen in epidermis and dermis was determined by mass spectrometry. At the same time, with the help of fluorescently labeled nanoemulsion, its permeation path in skin was observed by confocal microscope, so as to fully understand its skin permeation behavior and distribution characteristics.

3.5. Safety assessment

Human keratinocytes (HaCaT) were cultured in vitro, and the cell survival rate after 24 and 48 hours exposure was determined by MTT method to evaluate the cytotoxicity. In vitro skin irritation, the release of IL-1α inflammatory factor was detected by EpiDerm™ model, and the closed patch test of healthy volunteers (48 hours) was carried out in human trials to observe erythema and edema and make clinical scores. In terms of allergenicity, human monocyte activation test (h-CLAT) was used for preliminary screening, and the biocompatibility and safety of nanoemulsion sunscreen products were comprehensively evaluated.

4. RESULTS AND DISCUSSION

4.1. Analysis of sun protection performance

The experimental results in Table 1 show that the nanoemulsion (particle size 150±20 nm) has excellent sunscreen performance, and its SPF value is 50 3, which is about 67% higher than that of the traditional emulsion (SPF 30±2). Its critical wavelength is 382 nm, which meets the

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broad-spectrum protection standard. In addition, nanoemulsion showed good light stability, and the residual rate of Avobenzone after illumination was 92%, which was significantly higher than that of traditional emulsion (68%), and the water resistance was excellent. After 40 minutes of water bath, the SPF retention rate was over 85%, while that of traditional emulsion was lower than 70%.

The small size effect of nanoemulsion helps the sunscreen to disperse more evenly and reduce the loss caused by ultraviolet light scattering; At the same time, the interfacial film and phospholipid bilayer structure formed by emulsifier enhance the encapsulation and stability of sunscreen, especially for hydrophobic components such as OCL, thus improving the overall sunscreen effect and light resistance.

Table 1. Comparison of sun protection performance

Test item	Nanoemulsion	Traditional emulsion
SPF value	50±3	30±2
UVA-PF value	28±1	16±1
Avobenzone residue rate	92%	68%

4.2. Law of skin permeability

The experimental results show that the particle size of nanoemulsion significantly affects its skin penetration behavior (see Table 2). The emulsion with particle size of 200 nm has the highest retention in the stratum corneum (up to 98.7%), and the dermal penetration is only 0.2%, which is much lower than that in the 500 nm group (5.2%). The results of tape peeling showed that more than 95% of sunscreen agents were concentrated in the first five layers of stratum corneum, and confocal microscope observation further confirmed that nanoemulsion mainly accumulated in the hair follicle opening area.

Nanoemulsion with small particle size (100–200 nm) is easier to embed into the lipid gap of stratum corneum because of its high curvature structure, but it is difficult to penetrate the complete skin barrier, which has a low risk of system exposure. However, large particle size emulsion may increase the dermal penetration rate due to elastic deformation of skin. Hair follicle, as the main enrichment site, can be used as a local slow-release "reservoir" of sunscreen, which is helpful to improve efficacy and durability.

Table 2. Distribution ratio of sunscreen in all layers of skin (%)

Grain size	Horny layer	Living epidermis	Corium
100 nm	96.1±2.1	3.2±0.9	0.7±0.2
200 nm	98.7±0.8	1.1±0.3	0.2±0.1
500 nm	92.5±3.0	2.3±0.7	5.2±1.4

4.3. Safety evaluation

Nanoemulsion showed good biocompatibility, and the survival rate of HaCaT cells was still higher than 90% at 48 hours, which was significantly better than that of the free sunscreen group (75%). EpiDerm™ model test showed that the release of IL-1α was less than 10 pg/mg, which was in a negative control level. In the human patch test, 30 volunteers had no erythema or edema reaction, indicating that they had no irritation and sensitization risk. See Table 3 and Table 4 for details.

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Nano-carriers reduce the direct contact of sunscreen with skin through encapsulation, reducing toxicity and irritation; The selection of nonionic emulsifier (Tween 80/ Span 80) also enhanced the mildness of the formula. Particle size design needs to weigh the risk of cell uptake and dermal penetration, and emulsion below 200 nm has more advantages in safety.

Table 3. HaCaT cell survival rate (%)

Processing group	24 h	48 h
Nanoemulsion	98±2	92±3
Free sunscreen	85±4	75±5
No-treatment Control	100	100

Table 4. Human patch test results (48h)

Reaction type	Number of cases	Proportion
Nonresponse	30	100%
Mild erythema	0	0%

5. CONCLUSION

In this study, the theoretical basis, preparation method and application effect of nanoemulsion as a sunscreen carrier were discussed, including its influence on sunscreen performance, skin permeability and safety. Through experimental design and multi-angle analysis, we draw the following conclusions:

(1) Nanoemulsion can effectively improve the stability and light stability of sunscreen, reduce the loss caused by ultraviolet scattering, and enhance the sunscreen effect. The experimental results show that the SPF value of nanoemulsionSPF prepared is increased by about 67% compared with the traditional emulsion, and the light stability is significantly enhanced. The residual rate of Avobenzone after illumination is as high as 92%.

(2) The particle size of nanoemulsion has a significant effect on its skin penetration behavior. Small particle size (100–200 nm) nanoemulsion mainly accumulates in the hair follicle opening area, which has a low risk of systemic exposure, while large particle size emulsion may increase the dermal penetration rate. This characteristic is helpful to improve the durability and local sustained release ability of sunscreen effect.

(3) Nanoemulsification shows good biocompatibility, no toxic effect on cells, and no irritation and sensitization risk. HaCaT cells have a high survival rate, and all volunteers have no erythema or edema reaction in human patch test, which indicates that it is safe to be applied to skin.

To sum up, as a carrier of sunscreen, nanoemulsion can not only significantly improve the protective effect and light resistance of sunscreen products, but also optimize their skin permeability, while maintaining good biocompatibility and safety. These findings provide an important basis for developing high-efficiency and low-stimulation nano-sunscreen formula, which is of great significance to meet the needs of special people such as sensitive muscles and children. Future research can further explore the optimal formula design of different types of nanoemulsion, so as to realize the double improvement of the function and safety of sunscreen products.

REFERENCES

[1] Vishwas, S. , Bashir, B. , & Birla, DevendraKhandale, NikhilChaitanya, Motamarri Venkata Naga LalithaChellappan, Dinesh KumarGupta, GauravNegi, PoonamDua, KamalSingh, Sachin Kumar.

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(2024). Neuroprotective role of phytoconstituents-based nanoemulsion for the treatment of alzheimer's disease. Current topics in medicinal chemistry, 24(19), 1683-1698.

[2] Ahmad, N. , Albassam, A. A. , Khan, M. F. , Ullah, Z. , Buheazah, T. M. , & Alhomoud, H. S. , et al. (2022). A novel 5-fluorocuracil multiple-nanoemulsion used for the enhancement of oral bioavailability in the treatment of colorectal cancer. Saudi journal of biological sciences, 29(5), 3704-3716.

[3] Roy, A. , Nishchaya, K. , & Rai, V. K. (2022). Nanoemulsion-based dosage forms for the transdermal drug delivery applications: a review of recent advances. Expert Opinion on Drug Delivery, 19(3), 303-319.

[4] Pinheiro, M. G. T. , Gabriel, F. R. , & Veleirinho Maria BeatrizHonorato Luciana AparecidaRamos Roberta de OliveiraSilva Marcos Antnio SegattoKuhnen Shirley. (2023). In vitro evaluation of nanocomposites of linseed mucilage and k-carrageenan loaded with achyrocline satureioides nanoemulsion: a gradual-release candidate of antimicrobials for the treatment of bovine mastitis. The Journal of Dairy Research, 90(4), 376-381.

[5] Subir, M. B. M. , emailprotected, Emailprotected, E. M. , Subir, M. , Mahamud Subir * Mahamud SubirDepartment of Chemistry, Ball State University, Muncie, Indiana , United States*E-mail: emailprotectedMore by Mahamud Subirhttps://orcid.org/---, & ,and, et al. (2024). Molecular adsorption and physicochemical properties at liquid/liquid nanoemulsion soft interfaces: effect of charge and hydrophobicity. The Journal of Physical Chemistry B, 128(12), 3004-3015.

[6] Bayanati, M. , Khosroshahi, A. G. , Alvandi, M. , & Mahboobian, M. M. (2021). Fabrication of a thermosensitive in situ gel nanoemulsion for nose to brain delivery of temozolomide. Journal of Nanomaterials, 2021(4), 1-11.

[7] Nie, H. , Liao, H. , & Wen, F. D. X. (2024). Foeniculum vulgare essential oil nanoemulsion inhibits fusarium oxysporum causing panax notoginseng root-rot disease. journal of ginseng research, 48(2), 236-244.

[8] Souza, R. L. D. , Mengarda, A. C. , & Daniel B RoquiniCamila O MeloMayara C de MoraisMaria Cristina C Espírito-SantoDamio P de SousaJosué de MoraesElquio E Oliveira. (2023). Enhancing the antischistosomal activity of carvacryl acetate using nanoemulsion. Nanomedicine, 18(4), 331-342.

[9] Boaventura, Túlio Pacheco, De Oliveira, C. G. , dos Santos, Fábio Aremil Costa, Ricardo, D. O. C. , Sidney, D. S. S. , & Souza, André Sena, et al. (2024). Use of the essential oil of thymus vulgaris (thyme) and its nanoemulsion as an anesthetic during the cultivation of tambaqui (colossoma macropomum): anesthesia induction and recovery curve, physiology, performance, and feed consumption. Aquaculture International, 32(7), 9375-9391.