Preparation, characterisation and in vitro antibacterial property of ciprofloxacin-loaded nanostructured lipid carrier for treatment of *Bacillus subtilis* infection

Petra Nnamani 1 1 * Agatha Ugwu 1 Emmanuel Ibezim 2 Simon Onoja 3 Amelia Odo 4

[AQ2] Maike Windbergs 4 Chiara Rossi 4 5 6 [AQ6] Claus-Michael Lehr 1 Anthony Attama 1

1 Department of Pharmaceutics, Faculty of Pharmaceutical Sciences, Drug Delivery and Nanomedicines Research Group, University of Nigeria, Nsukka, Nigeria;
2 Department of Human Nutrition and Dietetics, University of Nigeria, Nsukka, Nigeria;
3 Department of Human Kinetics and Health Education, University of Nigeria, Nsukka, Nigeria;
4 Department of Drug Delivery, Helmholtz Institute for Pharmaceutical Research Saarland (HIPS), Helmholtz Centre for Infection Research, Saarland University, Saarbrücken, Germany;
5 PharmBioTec GmbH, Saarbrücken, Germany;
6 Department of Biopharmaceutics and Pharmaceutical Technology, Saarland University, Saarbrücken, Germany

*CONTACT Petra Nnamani petra.nnamani@unn.edu.ng; obiomaeze@yahoo.com Department of Pharmaceutics, Faculty of Pharmaceutical Sciences, Drug Delivery and Nanomedicines Research Group, University of Nigeria, Nsukka 410001, Enugu State, Nigeria

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**ABSTRACT**

**Objective:** Study of controlled ciprofloxacin (CIPRO) nanostructured lipid carriers of Precirol® ATO 5/Transcutol® HP (batch A) and tallow fat/Transcutol® HP (batch B).

**Methods:** CIPRO concentrations C1–5 (0.0, 0.2, 0.5, 0.8, and 1.0% w/w) as AC1–5 and BC1–5 were prepared by hot homogenisation and characterised by zetasizer, differential scanning calorimetry, Fourier transform infra-red spectroscopy, in vitro drug release and growth inhibitory zone diameter (IZD) on agar-seeded *Bacillus subtilis*.

**Results:** AC5 achieved polydispersed particles of ~605 nm, 92% encapsulation efficiency (EE) and -28 mV similar to BC5 (~789 nm, 91% EE, and -31 mV). Crystallinity indices (AC5 and BC5) were low at 3 and 5%, respectively. CIPRO release in AC5 was ~98% in SGF (pH 1.2) and BC5 similarly ~98% in SIF (pH 6.8).

**Conclusions:** AC5 had superior growth inhibition of *B. subtilis* at lower concentration (1.2 µg/mL) than BC5 and CIPRO controls; hence could serve as possible sustained delivery system of CIPRO.

**KEYWORDS** Inhibition zone diameter; ciprofloxacin; *Bacillus subtilis*; nanostructured lipid carriers; antimicrobial activity

**Introduction**

Ciprofloxacin (CIPRO) hydrochloride is a broad spectrum fluoroquinolone antimicrobial agent, frequently used in most Gram positive and Gram negative infections of the urinary tract (complicated and non-complicated), skin and soft tissue, bone and joint, infectious diarrhoea, typhoid fever, chancroid, pneumonia caused by Gram negative bacte-
CIPRO is practically insoluble in water; very slightly soluble in ethanol, methylene chloride and soluble in dilute acetic acid. Its melting point lies between 255 °C and 257 °C with decomposition. Based on today’s knowledge, fur‐
yly employs between 250–500 mg, 500–750 mg, and/or 750–1000 mg every 12 h for 7–14 days. Due to dose frequen‐
cy (at least twice daily) of these large doses of CIPRO, compliance to long treatment course remains an issue in addi‐
tion to so many side effects (on gastrointestinal tract, skin, central nervous system, kidney, and blood) and interaction
with many possible concomitant drugs (such as analgescics, antacids, antineoplastics, immunosuppressants, etc.)
(Chono et al. 2011). In other words, non-compliance would imply development of bacterial resistance to this impor‐
tant all-purpose drug which invariably leads to loss of potency.

CIPRO is a fluoroquinolone, its antibacterial action occurs by inhibiting the bacterial topoisomerase II (DNA
zyme. Topoisomerases are responsible for continuous introduction of negative supercoils into DNA which is an ATP-dependent reaction that requires both strands of the DNA to be cut to permit passage of a segment of DNA
through the break before the break is then resealed. Fluoroquinolone such as CIPRO therefore decreases the introduc-
tion of negative supercoils into DNA and causes rapid cessation of DNA synthesis by interfering with the propaga-
tion of DNA replication. On the other hand, CIPRO is well absorbed when given orally with a bioavailability of 70%
and peak plasma concentration of 1.2 µg/mL achieved after single dose of 250 and 500 mg respectively within 1–2 h
of administration (Dillen et al. 2004, 2006, Chono et al. 2011). Absorption is delayed when CIPRO is given with a
meal. CIPRO has wide distribution in the tissues (placenta, lung, skin, fat, muscle, cartilage, bone, and genital tis-
ues) and body fluids (breast milk, saliva, lymph, peritoneal fluid, bile, prostatic and bronchial secretions) as well as
partly metabolised in the liver (Chono et al. 2011). The plasma half-life is about 3.5–4.5 h but may be prolonged in
severe renal insufficiency and in the elderly. The dose of CIPRO varies according to severity of infection but gener‐
ally employs between 250–500 mg, 500–750 mg, and/or 750–1000 mg every 12 h for 7–14 days. Due to dose freque-
cy (at least twice daily) of these large doses of CIPRO, compliance to long treatment course remains an issue in addi‐
tion to so many side effects (on gastrointestinal tract, skin, central nervous system, kidney, and blood) and interaction
with many possible concomitant drugs (such as analgescics, antacids, antineoplastics, immunosuppressants, etc.)
(Chono et al. 2011).

Overall, the present work aims to present NLC formulations of graded concentrations of CIPRO (0.0, 0.2, 0.5, 0.8,
and 1.0% w/w) in two different optimised nanoparticle carriers of Precirol® ATO 5/Transcutol® HP (batch A) and tallow fat/
Transcutol® HP (batch B) at 3:1 combination respectively to achieve 15% w/w lipid composition. The resultant NLC
formulations (AC1-3 and BC1-5) were characterised and assessed for in vitro CIPRO release in bio-relevant media
(simulated gastric fluid, SGF, pH 1.2 and simulated intestinal fluid, SIF, pH 6.8) as well as in vitro antibacterial
growth inhibition of Bacillus subtilis on seeded agar plates. Bacillus subtilis is a ubiquitous bacterium (Gram-positive
and catalase-positive) commonly recovered from water, soil, air, and decomposing plant residue (Edberg 1991). The
bacterium produces an endospore that allows it to endure extreme conditions of heat and desiccation in the environ‐
mant. Given its ubiquity in nature and the environmental conditions under which it is capable of surviving, B. subtilis
could be expected to temporarily inhabit the skin and gastrointestinal tract of humans, but it is doubtful that this or‐
ganism would colonise other sites in the human body (Edberg 1991). Though B. subtilis is not a frank human patho-
gen, yet it has on several occasions been isolated from human infections including bacteraemia, endocarditis, pneu-
monia, and septicaeimia especially in patients with compromised immune states followed by inoculation in high num-
bers of B. subtilis (Edberg 1991, Yang et al. 2011). There also have been several reported cases of food poisoning
attributed to large numbers of B. subtilis contaminated food (Edberg 1991, Oggoni et al. 1998, El-Feky et al. 2009).
Even though B. subtilis does not produce significant quantities of extracelullar enzymes or other factors that would
predispose it to cause infection unlike several other species in the genus, still it does produce the extracellular enzyme
subtilisin that has been reported to cause allergic or hypersensitivity reactions in individuals repeatedly exposed to it
(Edberg 1991, Oggoni et al. 1998). Meanwhile, CIPRO has not been listed as first-line treatment for Bacillus infec-
tion; instead, antibiotics which appear especially useful in the treatment of Bacillus infections are clindamycin and
vancomycin, to which the vast majority of strains are susceptible in vitro (Edberg 1991). Unfortunately, these agents
are more costly and less available than CIPRO. Therefore, to investigate the potential of CIPRO-loaded NLCs in inhibiting bacterial growth \textit{in vitro}, \textit{Bacillus subtilis} was seeded in agar plates. The success associated with this investigation would provide basis to make CIPRO also effective against this particular microorganism, by improving its delivery across the ordinarily very hard and impermeable walls of the \textit{B. subtilis} endospore. This envelop surrounding the DNA and other internal cell structures makes them inaccessible to extreme temperatures, chemicals, environmental factors, and even some types of radiation (Oggioni \textit{et al.} 1998, Yang \textit{et al.} 2011). In the light of the above, fewer side effects and possibility to reduce dose and frequency of CIPRO are expected, allowing for better compliance and more effective oral administration.

\textbf{Materials and methods}

\textbf{Materials}

Ciprofloxacin hydrochloride was obtained from Hangzhou Dayang Chem. Co., Ltd. (Hangzhou, China), Polysorbate® 80 (Merck, Darmstadt, Germany), while Precirol® ATO 5 and Transcutol® HP were donated by Gattefossé (Saint-Priest, France). Phospholipon® 90G (P90G) was a gift from Phospholipid GmbH (Cologne, Germany) whereas Poloxamer® 188 and Solutol® HS (BASF, Ludwigshafen, Germany) were received as donations. Tallow fat was obtained from a batch processed in the Department of Pharmaceutics, University of Nigeria Nsukka (UNN). The biorelevant media, SGF (pH 1.2) and SIF (pH 6.8) were prepared without pepsin and pancreatin, respectively. Stock cultures of \textit{Bacillus subtilis} were obtained from the Pharmaceutical Microbiology Unit of Department of Pharmaceutics, UNN. Distilled water was used throughout the study.

\textbf{Lipid screening}

Bulk lipids of tallow fat, Precirol® ATO 5, Phospholipon® 90G (P90G), Transcutol® HP and their binary mixtures as well as CIPRO were investigated by differential scanning calorimetry (DSC) using a differential scanning calorimeter (NETZSCH DSC 204 FI, Waldkraiburg, Germany). Briefly, lipids were weighed (HH.W21 – Cr42II, Adventurer Ohaus, Shanghai, China), into a crucible and melted together on a hot plate (SR1 UM 52188, Remi Equip., Mumbai, India) at 70 °C and stirred until solidification. Thermal properties were obtained in the range of 35–190 °C at 10 °C/min under a 20 mL/min nitrogen flux with sample sizes of 3–5 mg while using a reference standard of empty aluminium pan. Optimised binary mixtures were obtained at 3:1 combinations of Precirol® ATO 5/Transcutol® HP (batch A) and tallow fat/Transcutol® HP (batch B), respectively.

\textbf{Production of lipid nanocarriers}

All particles were produced by hot homogenisation of optimised matrices of Precirol® ATO 5/Transcutol® HP (batch A) and tallow fat/Transcutol® HP (batch B), each melted at 90 °C and loaded with graded concentration of CIPRO (0, 0.2, 0.5, 0.8, and 1% w/w). To the melted lipid phase, Solutol® HS 15 (5% w/w) and polysorbate 80 (Tween® 80, 2% w/w) were added to enhance CIPRO-solubility whereas Poloxamer® 188 (3% w/w) was added to the aqueous phase and heated to the same temperature before addition to the molten lipid phase. This was followed by high shear homogenisation (Ultra-Turrax, T18 basic, IKA, Staufen, Germany) at 25 000 rpm for 15 min to produce an o/w emulsion which was allowed to cool at room temperature. NLCs containing no drug were also prepared to serve as negative control.

\textbf{Differential scanning calorimetry}

Differential scanning calorimetry was used to analyse the crystallinity of particles using a DSC (NETZSCH DSC 204 FI, Waldkraiburg, Germany) with an empty standard aluminium pan as reference, after baseline correction. Prior to analysis, samples were weighed in aluminium pan to contain solids in the range of 3–5 mg and analysed with a heating rate of 10 °C/min from 35 to 250 °C. During this period, pans were purged by nitrogen gas (20 mL/min) while empty pans served as reference standards. Recrystallisation index (RI %) was calculated using the modified Equation (3) (Freitas and Müller 1999, Keck \textit{et al.} 2014, Nnamani \textit{et al.} 2014).

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where $\Delta H_{\text{aqueous lipid nanoparticle dispersion}}$ and $\Delta H_{\text{bulk material}}$ refer to enthalpies (–mW/mg) of the aqueous lipid nanoparticle (NLC) dispersion and bulk materials of Precirol® ATO 5 and/or tallow fat, respectively. Concentration of solid lipid phase means the actual amount of the solid lipid in the total dispersion (e.g. 15% w/w) dispersion of 3:1 mixture of solid:liquid lipids.

**Percentage yield and encapsulation efficiency**

Each batch of NLC was weighed after formulation to get the yield while percentage (%) yield was calculated using the formula:

$$\% \text{Yield} = \frac{W_1}{W_2 + W_3} \times 100 \quad (2)$$

where $W_1$ is the weight of the NLC formulated (g), $W_2$ is the weight of the drug added (g), and $W_3$ is the weight of the lipid matrix and surfactant (g).

Encapsulation efficiency (% EE) of CIPRO in NLCs was determined by UV/VIS spectrophotometry after centrifugation (Heraeus Multifuge® x1R Centrifuge, Yardley, PA) of aliquot sample (5 mL) through centrifugal filter units (Amicon® Ultracel filters, 50 kDa, Darmstadt, Germany) at $2260 \times g$ at room temperature until at least 1 mL of aqueous phase filtrate was collected. This was used to quantify the amount of non-incorporated CIPRO in aqueous solution by UV-VIS spectrophotometry (6405 Jenway Spectrophotometer, Staffordshire, UK) at $\lambda_{\text{max}}$ of 285.5 nm which was the maximum absorption of CIPRO in aqueous acid (0.1 N HCl). A standard curve of CIPRO in aqueous acid (0.1 N HCl) was used to determine the concentration of CIPRO which was compared with the drug-free NLCs used as control. Considering the amount of CIPRO initially loaded into the NLC formulations and subtracting the free CIPRO remaining in the filtrate, the amount of CIPRO incorporated into the NLCs was determined; hence the % EE was calculated by Equation (2):

$$\% \text{EE} = \frac{\text{total amount of CIPRO} - \text{free CIPRO in the filtrate}}{\text{total amount of CIPRO}} \times 100 \quad (3)$$

**Particle characterisation**

Particles were analysed by photon correlation spectroscopy (PCS) using a zetasizer nano-ZS (Malvern Instrument, Worcechire, UK). Samples were diluted with double-distilled water to obtain a suitable scattering intensity, before PCS analysis to obtain size mean diameter ($z$-average, nm), polydispersity index (PDI), and zeta potentials (ZPs, $n = 3$) via electrophoretic mobility measurements while applying the Helmholtz–Smoluchowski equation.

**pH-dependent stability of formulations**

Time-dependent pH analysis (pHep® Hana Instrument, Padova, Italy) of NLC dispersions were performed post 24 h preparation period and upon room temperature storage at 3 and 6 months respectively for each batch of formulation.

**Scanning electron microscopy (SEM)**

The morphologies of NLCs (optimised) were determined using SEM measurement (Hitachi S-4000 Microscope, Tarrytown, NY). Samples were diluted with double-distilled water and deposited on film-coated copper grids to air-dry overnight at room temperature. The dried samples were visualised under SEM.

**Fourier transform infra-red spectroscopy (FTIR)**

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The NLC dispersions and pure CIPRO were evaluated using Shimadzu FTIR 8300 spectrophotometer (Shimadzu, Tokyo, Japan). All samples were run in triplicates with several controls run in parallels. A background run was performed as a negative control to remove the background noise of the instrument while free CIPRO analysis served as the positive control alongside NLCs. Spectra were recorded in the wavelength region of 4000–400 cm$^{-1}$ with spectral resolution of 4 cm$^{-1}$.

**In vitro release profile and kinetics of release**

*In vitro* drug release studies for the batches of NLCs loaded with CIPRO were studied in 250 mL each of SGF and SIF with the temperature and speed of rotation of each medium maintained at 37 ± 2 °C and 100 rpm, respectively. A quantity of the NLCs containing 100 mg of CIPRO was weighed separately and placed in a polycarboxanated dişalis membrane (MWCO 6000–8000, Spectrum Labs, Breda, The Netherlands) which was pre-treated by soaking in distilled water 24 h prior to use. The NLC-containing dialysis membrane was securely tied with a thermo-resistant thread and placed in the appropriate medium. At pre-determined time interval (1–24 h), 5 mL portion of the dissolution medium was withdrawn and absorbance determined at appropriate wavelengths (285.8 and/or 322 nm) in the UV Spectrophotometer (6405 Jenway, Stone, UK). To keep the volume of the dissolution medium constant, 5 mL of fresh medium was added after each withdrawal. The amount of drug released at each time point was calculated with reference to the relevant Beer’s plot.

The kinetics and mechanisms of CIPRO release from formulations were studied using different release models (zero order, first order, Higuchi, and Ritger–Peppas) according to standard protocols to describe Higuchi release model (cumulative % drug release versus square root of time), first order (log cumulative of percentage drug remaining versus time), zero order (cumulative percentage drug release versus time) and Ritger–Peppas (Fickian and/or non-Fickian release through Log (Mt/M$\infty$) = Log $k + n \log t$) (Nnamani et al., Agubata et al. 2015).

**Release as a function of inhibition zone diameter**

The plate agar diffusion method was used for this study conducted after 1 month of NLC formulation (Attama et al. 2009, Nnamani et al. 2013). Briefly, three loopfuls of Bacillus subtilis was introduced into different sterile Petri dishes, to which 20 mL of sterile molten nutrient agar was poured separately, swirled gently and allowed to solidify. A sterile cork borer was used to bore holes on the solidified sterile agar plates. Different concentrations of pure sample of CIPRO and unknown concentration of the formulated NLC-loaded CIPRO were introduced into the corresponding holes and/or cups. The plates were allowed a pre-diffusion period of 30 min upon standing before incubation at 37 °C for 24 h. The resultant growth IZD of each hole was measured and recorded. The procedure was repeated using a commercial brand of CIPRO (Ciprotab®, as control. The concentration of the formulated NLC-loaded CIPRO was determined by the graphical method (Attama et al. 2009, Nnamani et al. 2013).

**Statistical analysis**

Results were expressed as mean ± standard deviation. One-way ANOVA was used to assess the difference between groups while Microsoft Excel and STATA II software packages were used for all analyses. Statistical significance was determined using Student’s $t$-test, with $p < 0.05$ considered to be statistically significant.

**Results**

**Lipid screening and thermal properties of formulations**

Bulk materials of tallow fat and Precirol® ATO 5 as well as optimised binary matrices (3:1) of Precirol® ATO 5/Transcutol® HP (batch A) and Tallow fat/Transcutol® HP (batch B) are shown in Figure 1. Selection was based on lower values of enthalpy as an index of low crystallinity. Thermal properties of formulations are shown in Table 1.

Figure 1. DSC thermograms of lipid matrices. (A) Tallow fat (m. pt 56.4 °C and enthalpy 27.84 -mW/mg), (B) Precirol® ATO 5 (m. pt 71 °C and enthalpy 37.59 -mW/mg), (C) Tallow fat + Transcutol® HP matrix (m. pt 56.5 °C and enthalpy 9.5 -mW/mg), (D) Precirol® ATO 5 + Transcutol® HP (m. pt 143.7 °C and enthalpy 5.6 -mW/mg). Less crystalline matrices have low enthalpy values (selected from Table 1).
Table 1. Thermal properties of formulations and bulk materials.

| Lipid matrix          | Melting peak (°C) | Enthalpy (–mW/mg) | Onset melting point (°C) | Enthalpy (–mW/mg) | Recrystallisation index (%) |
|-----------------------|-------------------|-------------------|--------------------------|-------------------|-----------------------------|
| CIPRO                 | 155.6             | 7.17              | 255                      | 7.17              | –                           |
| AC1 (blank formulation)| 134.6             | 10.92             | –                        | –                 | 3.49                        |
| AC2                   | 248.2             | 17.54             | 95.5                     | –                 | 3.48                        |
| AC3                   | 59.7              | 14.15             | –                        | –                 | 4.52                        |
| AC4                   | 60.3              | 20.27             | –                        | –                 | 6.47                        |
| AC5                   | 145.2             | 22.31             | 56.5                     | 9.48              | 3.03                        |
| BC1 (blank formulation)| 56.2              | 42.56             | –                        | –                 | 10.06                       |
| BC2                   | 57.5              | 24.95             | –                        | –                 | 5.90                        |
| BC3                   | 55.5              | 23.87             | –                        | –                 | 5.64                        |
| BC4                   | 61.2              | 32.40             | –                        | –                 | 7.66                        |
| BC5                   | 53.4              | 21.80             | –                        | –                 | 5.16                        |
| Precirol® ATO 5       | 71.0              | 37.59             | –                        | –                 | –                           |
| Tallow fat            | 56.4              | 27.84             | –                        | –                 | –                           |
| Transcutol® HP        | 164.4             | 26.76             | 130.3                    | 13.63             | –                           |
| Precirol + Transcutol® HP (3:1) | 143.7 | 14.15 | 59.7 | 5.551 | – |

Screening of (A) single entity lipids (Precirol® ATO 5, Tallow fat, Transcutol® HP and P90G®) and drug (CIPRO); (B) mixtures (binary lipids: tallow fat + P90G® and Precirol + P90G®); (nanostructured lipids: tallow fat + Transcutol® HP and Precirol + Transcutol® HP). Mixtures were obtained at different ratios of 1:1, 1:2, and 1:3 ratios (data not shown). Low crystallinity of matrices based on enthalpy values was used as criteria for selection (N = 3). Nanostructured lipid of Tallow fat + Transcutol® HP and Precirol + Transcutol® HP were less crystalline than binary mixtures of tallow fat + P90G® and Precirol + P90G®.
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### Particle characterisation

Table 2 shows general particle properties of NLCs. It could be seen that the particle size for batches of AC1–5 was smaller (~320–903 nm) than those of BC1–5 (~789 nm–3158 µm), even though both batches were polydispersed with PDI above 0.25. Besides, the NLC particles were very stable (about ~30 mV) even upon storage at room temperature for over 6 months despite slight fluctuations in the pH of the dispersion. The particles also generally had high yield (%) and % EE. The pH stability results of all NLC formulations generally showed all samples post 24 h preparation as having higher pH values than upon storage for 3 and 6 months.

| Batches | Zeta potential (mV) ± SD | Polydispersity index (PdI) ± SD | Z-Ave (nm) ± SD | Encapsulation efficiency (% v/v) ± SD | Yield (%) ± SD |
|---------|--------------------------|-------------------------------|----------------|-------------------------------------|----------------|
| AC1 (Blank) | –29.0 ± 0.28 | 0.52 ± 0.39 | 903.2 ± 27.22** | – | 44.1* ± 0.01 |
| AC2 | –27.8 ± 0.21 | 0.49 ± 0.25 | 319.2 ± 5.09 | 81.4 ± 0.11 | 58.4 ± 0.20 |
| AC3 | –27.1 ± 0.11 | 0.46 ± 0.28 | 825.9 ± 17.05 | 75.2 ± 0.13 | 60.8 ± 0.12 |
| AC4 | –27.0 ± 0.18 | 0.40 ± 0.22 | 437.9 ± 9.91 | 89.4 ± 0.21 | 86.2 ± 0.23 |
| AC5 | –28.2** ± 0.01 | 0.42 ± 0.32 | 604.7 ± 12.06** | 92.4** ± 0.31 | 85.7** ± 0.24 |
| BC1 (Blank) | –34.8 ± 0.31 | 0.68 ± 0.54 | 927.2 ± 25.24* | – | 35.3* ± 0.19 |
| BC2 | –18.9 ± 0.27 | 0.85 ± 0.79 | 3158 ± 32.33 | 77.8 ± 0.12 | 43.9 ± 0.17 |
| BC3 | –30.2 ± 0.09 | 0.81 ± 0.73 | 1428 ± 30.41 | 81.5 ± 0.13 | 81.2 ± 0.24 |
| BC4 | –28.2 ± 0.15 | 0.88 ± 0.82 | 1672 ± 28.73 | 82.4 ± 0.15 | 83.3 ± 0.15 |
| BC5 | –30.5** ± 0.01 | 0.67 ± 0.43 | 788.7 ± 14.22** | 90.8** ± 0.21 | 86.2** ± 0.11 |

SD: standard deviation.

Optimised formulations (AC5** and BC5**) reflect outstanding performance of the CIPRO batches compared to blank formulations AC1* and BC1* (p < 0.05). n = 3.

### Microscopy

SEM measurement was used to study morphology of NLC optimised formulations (Figure 2). It could be seen that the CIPRO-loaded NLCs of AC5 and BC5 as well as blank NLCs (AC1 and BC1) appeared spherical and/or elliptical (Nnamani et al. 2014).

Figure 2. SEM images (AC5) Optimized CIPRO-NLC from Precirol® ATO5 + Transcutol® HP; (BC5) Optimized CIPRO-NLC from Tallow fat + Transcutol® HP; (AC1) Blank formulation of Precirol® ATO5 + Transcutol® HP; (BC1) Blank formulation of Tallow fat + Transcutol® HP.
To demonstrate the possibility of incorporation of CIPRO into NLC, IR spectra of NLC matrices, CIPRO-loaded NLCs (AC₅ and BC₅), and bulk entity of CIPRO were obtained and presented in Figure 3.

Figure 3. FTIR spectra. TT means Tallow fat/Transcutol® HP; PT means Precirol® ATO₅ and Transcutol® HP; BC® implies optimized CIPRO formulation from TT batch; AC₅ implies optimized CIPRO formulation from PT batch.
In vitro drug release and mechanism of kinetics

The in vitro release profile of optimised NLCs was determined in SGF (pH 1.2) and SIF (pH 6.8) and shown in Figure 4. Within the first 10 h of release study, only CIPRO amount (<30%) was released across all samples and media despite inclusion of both water-soluble (Poloxamer® 188) and oil-soluble surfactants (Solutol® HS and Polysorbate 80) which ordinarily could increase porosity of the matrix for easier fluid penetration and release (Agubata et al. 2015). Overall, the kinetics of CIPRO release from NLCs showed that Higuchi was the predominant mechanism of release (Table 3) having recorded the highest $R^2$ values generally in all media despite having very slow release of CIPRO (<30%) in 10 h of release study. This was not surprising considering the high EE (%) of CIPRO in the low crystalline NLCs which could make it inaccessible immediately for release until much later (post 20 h).

Figure 4. (A) In vitro release profile of ciprofloxacin in SGF ($n = 3$) and (B) in vitro release profile of ciprofloxacin in SIF ($n = 3$).
Table 3. Kinetics of CIPRO release from NLC.

| Drug | Media | Batches | Zero order ($R^2$) | First order ($R^2$) | Higuchi ($R^2$) | Ritger–Peppas parameters |
|------|-------|---------|-------------------|-------------------|---------------|-------------------------|
|      |       |         |                   |                   |               | $R^2$ | $N$ |
| CIPRO | SGF   | AC<sub>5</sub> | 0.903          | 0.626           | 0.919         | 0.920 | 1.002 |
|       |       | BC<sub>5</sub> | 0.990          | 0.895           | 0.963         | 0.840 | 0.359 |
|       | SIF   | AC<sub>5</sub> | 0.909          | 0.936           | 0.951         | 0.980 | 1.001 |
|       |       | BC<sub>5</sub> | 0.979          | 0.6129          | 0.975         | 0.956 | 1.01  |

Release was predominantly Higuchi model, based on porosity of matrices, followed by the Peppas model.

**Release study as a function of inhibition zone diameter**

Post 24 h incubation of the *B. subtilis* seeded agar plates with CIPRO-loaded NLCs, our observations showed that AC<sub>5</sub> recorded the overall highest (mean) IZD (24 mm) on *B. subtilis* at much lower concentration (1.2 µg/mL) than the pure drug (7.5 µg/mL) and/or commercial sample (7.5 µg/mL), which had IZDs of 22 mm respectively, as shown in Figure 5. Comparatively AC<sub>5</sub> recorded higher IZD (24 mm) than BC<sub>5</sub> (18 mm) even at equal concentration (2.2 µg/mL).

Figure 5. (A) IZD (mm) of pure CIPRO sample and optimised NLCs (AC<sub>5</sub> and BC<sub>5</sub>) and (B) IZD (mm) of commercial CIPRO sample and optimised NLCs (AC<sub>5</sub> and BC<sub>5</sub>).
The crystallinity of the NLCs could be confirmed using DSC by comparing the melting enthalpy of bulk materials with those of NLC which were much smaller. While the bulk lipids contained 100% of solid lipids of Precirol® ATO 5 and/or tallow fat, the NLCs only consisted of 15% of the lipid mixture at 3:1 of solid lipid (11.25 g) and liquid lipid (3.75 g), respectively. NLC batch A produced from Precirol® ATO 5/Transcutol® HP was named AC1–5 whereas batch B corresponding to Tallow fat/Transcutol® HP was termed BC1–5 to describe the CIPRO-graded concentrations of 0, 0.2, 0.5, 0.8, and 1% w/w in each batch. Matrix crystallinity was independent of CIPRO concentration. In order
words, AC5 and BC5 each containing 1% w/w concentration of CIPRO in each batch of NLC had the least enthalpy values of −9.48 and −21.8 mW/mg respectively when compared to other formulations. To better estimate the degree of crystallinity, the RI was ascertained at 3 and 5% for both AC5 and BC5, as the least among their respective batches of formulation. This suggests that despite low crystallinity of NLCs, there was still slight degree of crystallinity remaining which could rightly describe the definition of lipid nanoparticles as being solid at body temperature (Müller et al. 2011). Besides, decreased crystallinity corresponded to lower particle sizes (Puglia et al. 2013, Keck et al. 2014). Zeta potential predicts physical stability of dispersions and the higher the value (positive or negative) the better the stability to avoid aggregation of particles. Since the particles existed in the neighbourhood of −30 mV, they could be said to be stable. Overall in batch A, AC5 had the highest yield (85.7%) and EE (92.4%) whereas in batch B, BC5 similarly had 86.2% Y and 90.8% EE. This agreed with the thermal properties of AC5 and BC5 with least values of enthalpy (−9.48 and −21.8 mW/mg) and recrystallisation indices of 3% and 5%, respectively, confirming their propensity for higher drug payload without expulsion even upon storage; hence the high ZP (−28 and −30.3 mV) values which also could attest to stability of the systems.

AC1–5 samples had pH in the range of 4.2–6.1 whereas those of BC1–5 had 3.2–5.4. However, there were slight changes in pH upon storage but this trend was worse in the BC1–5 samples. The AC5 and BC5 were most stable upon storage in agreement with other observations from particle characterisation and thermal analysis. It could therefore be said that AC5 and BC5 be regarded as the optimised samples for further evaluations and that entrapment of CIPRO into the NLC particles did not affect their morphology as well. There was nanoparticle aggregation in the blank formulation shown in Figure 2 (AC1 and BC1) whereas optimised formulations of AC5 and BC5 generally showed polydispersed particles. The shape of solid lipid nanocarriers has been reported to be dependent on the purity of the lipids used (Nnamani et al. 2014) and particles prepared using chemically polydispersed lipids are typically spherical (Nnamani et al. 2014). The lipid matrix used consisted of a mixture of solid lipids (Precirol® ATO 5 and Tallow fat) and liquid lipid (Transcutol® HP), which suggests that the lipid matrix was chemically polydispersed as well as highly pure.

The interaction study (Figure 3) showed principal peaks at wave numbers 2800–3000, 2220–2255, 1703–1619, and 1267 cm⁻¹ (KBr pellets) as due to the vibration of functional groups (C–H, C≡N, C–O, and CC acyclic, aliphatic chain vibration) present in the structure of CIPRO which could also be seen in the FT-IR spectra of the crystalline CIPRO and NLC matrices (PT and TT). Spectra of blank NLCs without CIPRO did not show these peaks, indicating successful incorporation of drug into the CIPRO-containing NLC formulations.

The poor initial release of CIPRO (Figure 4) from the oily-core of the NLC lipid matrix could perhaps be due to efficient encapsulation (Uner and Yener 2007). This is supported by the fact that as time progressed, release became more consistent and post 20 h, there was fast release of CIPRO attesting to its efficient localisation in the oily-core of the particles. This raises hope in actualising a regimen that can comfortably be administered once daily, to improve penetrate the endospore surrounding the DNA and other internal cell structures of B. subtilis bacteria within 24 h of incubation (Figure 5), thereby decreasing the introduction of negative supercoils into DNA; hence rapid cessation of

**In vitro** growth inhibition study showed that AC5 released enough CIPRO that diffused out of the NLC matrix to penetrate the endospore surrounding the DNA and other internal cell structures of B. subtilis bacteria within 24 h of incubation (Figure 5), thereby decreasing the introduction of negative supercoils into DNA; hence rapid cessation of
DNA synthesis through interference with the propagation of DNA replication. Additionally, the presence of surfactants both hydrophilic and lipophilic could have aided fluidisation of the cell membrane of this organism thereby facilitating penetration of the drug (Krugliak et al. 1995, Rama Prasad et al. 2003, Koga et al. 2006). These observations agree with literature and could probably have aided growth inhibition of B. subtilis (AC5 > BC5) even in lower CIPRO concentration compared to those of pure drug and/or commercial sample (Krugliak et al. 1995, Baek and An 2011, Kim and An 2012, Hsueh et al. 2015). This was rather not surprising from the point of view of the high drug EE of 92%, in vitro drug release in bio-relevant media (~98%) and high negative values of ZP (–28.2 to –30) which could predict good permeation through the cell wall of the film-forming bacteria (Krugliak et al. 1995, Rama Prasad et al. 2003, Pinto et al. 2014).

Conclusions

CIPRO-NLC formulation is acceptable alternative that can reduce the disadvantages of CIPRO-powder/capsule and/or tablets such as frequent dosing of large doses, long treatment courses (7–14 days), non-compliance and development of resistance. CIPRO-NLCs prepared using two solid fats (Precirol® ATO 5 and Tallow fat) and a liquid lipid (Transcutol® HP) produced nanoparticles with acceptable properties. Lower doses of AC5 (1.2 µg/mL) showed better in vitro growth inhibition of B. subtilis than BC5 (3.25 µg/mL) and pure CIPRO powder and/or commercial tablet (7.5 µg/mL). CIPRO-NLC formulations are efficient carriers for oral delivery of CIPRO, with targeted uptake through the lymphatics. This avoids wide distribution (in tissues, body fluids and the liver) associated with conventional marketed CIPRO-tablet forms. In an outlook for further studies, safety tests and cell penetration studies will prove this concept.

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Petra Nnamani http://orcid.org/0000-0001-7978-7745
Claus-Michael Lehr http://orcid.org/0000-0002-2524-7224

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