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Title Page

Supersaturated silica-lipid hybrid (super-SLH) oral drug delivery systems: Balancing drug loading and in vivo performance

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Running Title Page

Running Title: Super-SLH: Balancing drug loading/oral in vivo performance

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Nonstandard abbreviations: BCS - Biopharmaceutics Classification Scheme; HPLC – high-performance liquid chromatography; IBU – ibuprofen; IVIVC - *in vitro – in vivo* correlation; LBF – lipid based formulation; PK – pharmacokinetic; SD – standard deviation; SE – standard error; SEM – scanning electron microscopy; S_{eq} – equilibrium solubility; SLH – silica-lipid hybrid; SNEDDS – self nano-emulsifying drug delivery system; super-SLH – supersaturated silica-lipid hybrid; ISTD – internal standard.

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Abstract

Supersaturated silica-lipid hybrid (super-SLH) drug carriers are a recent strategy to improve the drug loading of oral solid lipid based formulations, however they are yet to be studied *in vivo*. This study investigated the *in vivo* pharmacokinetics (PK) of super-SLH containing ibuprofen (IBU), as a model Biopharmaceutics Classification Scheme (BCS) class II drug, analysing the influence of supersaturated drug loading on oral bioavailability and assessing *in vitro – in vivo* correlation (IVIVC). In addition, super-SLH was directly compared to spray-dried SLH and Nurofen, to explore its potential advantages over the well-established and commercial formulations. Fasted male Sprague-Dawley rats were administered formulation suspensions (10 mg/kg IBU) via oral gavage and blood samples were acquired and plasma was analysed for IBU concentrations over 24 hours. *In vivo*, super-SLH with drug loads of 9.5 (99.5% saturated) and 19.3% w/w (227% saturated) achieved bioavailabilities equal to spray-dried SLH and 2.2-fold greater than Nurofen. This effect diminished for super-SLH with a drug load of 29.1% w/w (389% saturated), which exhibited a bioavailability of less than Nurofen due to its greater extent of supersaturation and larger content of crystalline IBU. The super-SLH containing 19.3% w/w IBU provided the greatest PK performance, achieving the same degree of bioavailability enhancement as spray-dried SLH and requiring 63% less formulation. A significant positive IVIVC was observed between the performances of the formulations. These findings indicate the potential of super-SLH as an improved oral solid lipid based formulation strategy for enhancing oral bioavailability of other BCS class II drugs.

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Introduction

Solid lipid-based formulations (LBF) continue to emerge as effective oral formulation strategies for the ever-increasing number of Biopharmaceutics Classification Scheme (BCS) class II drugs (i.e. poor solubility, high permeability) arising from the drug discovery pipeline (Mandić et al., 2017; Joyce et al., 2018a). They retain the beneficial properties of conventional liquid LBF by delivering the drug to the gut in a solubilized state, bypassing the rate limiting step of dissolution, where the lipid component is digested by gastrointestinal lipases, creating a lipophilic and drug solubilizing environment that mimics the post-prandial effects of dietary fats and oils improving drug solubilization and hence absorption (Chakraborty et al., 2009; Feeney et al., 2016). Additionally, solid LBF possess the added benefits of existing as powders, which are beneficial for improved stability, dosage precision and manufacturing (Jannin et al., 2008; Tang et al., 2008). Solidification of LBF as a dry powder can be achieved through the adsorption to a solid carrier e.g. silica, polymers, nanostructured carbon, carbonates and aluminosilicates, often up to 50% w/w (Tan et al., 2013; Dening et al., 2016a; Bremmell and Prestidge, 2018). Further dilution of the LBF occurs when additional excipients are incorporated to form powders with suitable properties for tablet compression (Bremmell et al., 2013). Consequently, this leads to reduced drug loading capacities within solid LBF, limiting their clinical use for drugs with high doses and low potency.

The maximum LBF drug load is limited by the drug's solubility in the lipid formulation (Porter et al., 2007; LaFountaine et al., 2016). The drug is commonly loaded below its equilibrium solubility (S_{eq}) (e.g. 75-80%), to ensure the drug remains solubilized within the formulation and avoids re-crystallization (Christensen et al., 2004; Thomas et al., 2012). Drug re-crystallization is generally regarded as unsuitable for effective oral delivery, due to re-introducing a dissolution step of crystalline drug (Porter et al., 2004; Pouton, 2006) which limits the rate of absorption *in vivo*, as only the solubilized drug present in the aqueous phase is available for absorption (Khan et al., 2016). Previously, a liquid LBF was supersaturated, loading simvastatin at up to 200% of its S_{eq} by dissolving the drug at an elevated temperature, to form supersaturated self nano emulsifying drug delivery systems (super-SNEDDS) (Thomas et al., 2013). It was reported that no drug re-crystallization was observed within the super-

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SNEDDS over 10 months due to the high viscosity of the lipids and that super-SNEDDS demonstrated superior *in vivo* performance compared to the standard SNEDDS (Thomas et al., 2013).

Recently, we have applied a supersaturation method to the silica-lipid hybrid (SLH) solid LBF to load drug above its S_{eq} and form super-SLH to overcome the limitation of low drug loading (Schultz et al., 2018). SLH are a well-established solid LBF, existing as porous micro-particulate dry powders, fabricated by spray drying or lyophilising silica-stabilised Pickering emulsions (Simovic et al., 2009; Tan et al., 2009; Dening et al., 2016b; Meola et al., 2018). Despite their proven effectiveness in enhancing bioavailability of many BCS class II drugs *in vivo* (Tan et al., 2011; Nguyen et al., 2013; Rao et al., 2014; Joyce et al., 2017), including a phase I human clinical trial (Tan et al., 2014), the low drug loading capacities of SLH (often less than 5%) have limited their broader clinical application to drugs with high doses and low potency. The super-SLH formulation overcomes this limitation by improving drug loading through supersaturation of the model BCS class II drug ibuprofen (IBU). IBU possesses a pKa of ~4.5 (Avdeef et al., 1998) and a Log P of ~4 (Avdeef et al., 1999) and it's S_{eq} in water is pH dependent, with approximately 46 µg/mL at pH 1.5 (sparingly soluble), while increasing to >300 µg/mL above pH 7 (more than slightly soluble) (Potthast et al., 2005). Super-SLH were prepared containing drug loads of 8.7 to 44.8% w/w, substantially greater than the spray-dried SLH with an IBU load of 5.6% w/w previously reported (Tan et al., 2014). Super-SLH fabrication involved dissolving drug in the lipid at an elevated temperature (i.e. 60 °C) followed by subsequent encapsulation of the lipid-drug mixture within the pores of mesoporous silica particles to inhibit the re-crystallisation of drug crystals and maintain the supersaturated state at room temperature (Schultz et al., 2018). Portions of drug re-crystallised in the formulations, proportional to the drug load which influenced *in vitro* dissolution kinetics at pH 2.1, where all super-SLH formulations exhibited superior dissolution to the spray-dried SLH and commercial product Nurofen.

Therefore, in the current study, we aim to explore the *in vivo* pharmacokinetics (PK) of super-SLH containing IBU, analysing the influence of supersaturated drug loading on oral bioavailability and assessing *in vitro – in vivo* correlation (IVIVC). In addition, super-SLH was directly compared to spray-dried SLH and Nurofen, exploring the potential advantages of an enhanced drug load on oral

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bioavailability over the well-established LBF and commercial formulations. This study marks the first *in vivo* investigation into the oral delivery performance of super-SLH and an important step forward in encouraging the clinical application of solid-state LBF.

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Materials and Methods

Materials

The drug of interest, ibuprofen (IBU) (≥98%, GC), and internal standard flufenamic acid (ISTD) (analytical grade), were purchased from Sigma Aldrich (Castle Hill, Australia). Commercially available Nurofen tablets (Reckitt Benckiser, Sydney, Australia) were crushed into a uniform powder before use. The lipid, Capmul PG8 (propylene glycol caprylate), was sourced from Abitec (Columbus, USA). Glacial acetic acid (analytical grade) was purchased from Chem-Supply (Gillman, Australia). Silica nanoparticles (Aerosil 300 Pharma), with a surface area of 300 ± 30 m^2/g were donated by Evonik (Melbourne, Australia). Nano-porous silica microparticles (Parteck SLC 500), with a 9-11 µm particle size and 6 nm pore size, were donated by Merck (Bayswater, Australia). Soybean lecithin and liquid chromatography grade methanol were purchased from Merck (Bayswater, Australia). Heparin sodium (5000 IU/5 mL) was purchased from Pfizer (Perth, Australia). High purity Milli-Q water was acquired from a Milli-Q water purification system (Merck, Bayswater, Australia).

Fabrication of Formulations

Spray-dried SLH

A previously established method was followed to prepare the spray-dried SLH containing IBU (Tan et al., 2014). Soybean lecithin (emulsifier) (6% w/w) and Capmul PG8 were weighed into a glass vial and sonicated for 10 min. IBU was subsequently added to the lipid at 75% S_{eq} (S_{eq} = 211 mg/mL) and sonicated until dissolved. Milli-Q water was added to the lipid to form a coarse emulsion which was homogenised at 1000 bar for 5 cycles with an Avestin EmulsiFlex-C5 Homogenizer (ATA Scientific, Taren Point, Australia) to form a submicron oil-in-water emulsion. A 5% silica in water suspension (Aerosil Pharma 300) was prepared by sonication overnight. The 5% silica suspension was added to the emulsion to yield a final lipid:silica ratio of 2:1 w/w and was magnetically stirred overnight. The emulsion was then spray-dried using a Büchi Mini Spray Dryer B-290 apparatus (Postfach, Switzerland) to remove the water phase and obtain a dry SLH powder. The following spray drying conditions were maintained: an inlet temperature of 160 °C, an outlet temperature of 65 °C, aspirator setting of 100, pump set to 20% and a product flow rate of 6 mL/min.

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Super-SLH

A previously established method was used to prepare the super-SLH (Schultz et al., 2018). IBU and lipid were weighed into glass vials and heated to 60-70°C in an oven for approximately 10 min with intermittent shaking to dissolve the IBU. Porous silica microparticles (Parteck SLC 500) were added directly weighed into the vials containing hot lipid and were immediately physically mixed to obtain a white dry powder. As displayed in Table 1, the target composition of super-SLH A, B and C were 10, 20 and 30% w/w IBU, respectively, with a constant 1:1 w/w ratio of lipid to silica.

Drug Load Determination

Solvent extraction followed by HPLC analysis was performed to extract the IBU from the spray-dried SLH, super-SLH and crushed Nurofen tablets. Approximately 10 mg of the formulation was weighed into a glass vial to which 10 mL of methanol was added. The contents of the vial were sonicated for 30 min to extract the IBU. A 500 µL sample was removed from the vial and centrifuged for 20 min at 7270 x *g* to separate any undissolved material. The supernatants containing the extracted IBU in methanol were diluted with mobile phase prior to HPLC analysis to determine the drug load of the IBU formulations. This was performed in triplicate.

Surface Morphology Characterization

A scanning electron microscope (SEM) (Carl Zeiss Microscopy Merlin with a GEMINI II column) (Oberkochen, Germany) operating at 1.0–2.0 kV at a working distance of 5–10 mm was used to observe the surface morphology of the spray-dried SLH and super-SLH formulations. The formulations were held in place with double sided adhesive carbon tape and sputter coated with gold (10 nm) before imaging.

In Vitro Dissolution Study

Dissolution studies were performed using a Vankel USP Type II Paddle Apparatus (Agilent Technologies, Santa Clara, USA). Formulation samples containing 20 mg of IBU were dosed in 450 mL of pH 2.1 HCl media. The media was stirred at 50 RPM and maintained at 37 ± 0.5 °C. 5 mL aliquots were removed at fixed time points and replaced with fresh media. The aliquots were immediately filtered using a 0.45 µm

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syringe filter to remove any undissolved material. The filtered samples were diluted with mobile phase prior to HPLC analysis for IBU content. This was performed in triplicate.

High Performance Liquid Chromatography

IBU was analysed using a Shimadzu high-performance liquid chromatograph (HPLC) (Kyoto, Japan) system and a Pheno Sphere Next 3 µm C18 column (150 x 4.6 mm) (Torrance, USA) equipped with a column guard. The system was maintained at 40 °C, used an injection volume of 50 µL and eluted the mobile phase at a flow rate of 0.5 mL/min. The mobile phase contained 80% methanol and 20% water adjusted to pH 2.1 with glacial acetic acid. Each sample was analysed over 13.5 min and at a UV wavelength of 223 nm. The retention time of the IBU and ISTD (used in plasma samples only) were determined to be 9.1 min and 11.5 min, respectively. The concentration of the samples were determined by using calibration curves produced by a set of IBU standards in mobile phase (9-900 µg/mL) or plasma (0.15-15 µg/mL containing a fixed concentration of ISTD).

In Vivo Pharmacokinetic Study

All animal experiments were approved by the South Australian Animal Ethics Committee under approval number U07-17. An oral PK study was performed on five groups of male Sprague-Dawley rats aged 6-8 weeks (273-463g), sourced from the Animal Resources Centre (Canning Vale, Australia). Each group was administered one of the five formulations via the oral route: crushed Nurofen tablets, 7.1% w/w spray-dried SLH, 9.5% w/w super-SLH, 19.3% w/w super-SLH and 29.1% w/w super-SLH. All treatments were suspended in Milli-Q water by sonicating for 5 min immediately before administration to the rats at an IBU dose of 10 mg/kg (in 1-2 mL water) via oral gavage. Each group contained 4 rats, except for one group which contained 5 rats that were administered Nurofen.

The rats were caged in groups of 3 and fasted overnight prior to dosing to remove their gut of residual food (Vermeulen et al., 1997) and feeding was recommenced after the 2 h time point. Water was provided ad libitum throughout the study period. Eight blood samples (0.2 mL) were taken from the saphenous vein at -12 h pre-dose and 0.5, 1, 1.5, 2, 4, 10 and 24 h post-dose. A needle was used to puncture the veins and blood was collected in pre-heparinised 1.5 mL centrifuge tubes to prevent blood clotting. Plasma

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(approximately 70 µL) was harvested immediately by centrifugation at 7270 x *g* (5 min at room temperature) and stored at -80 °C until further analysis.

Plasma Sample Preparation

50 µL of the plasma sample was combined with 90 µL of methanol and 10 µL of ISTD (0.3 mg/mL in methanol) in a 1.5 mL centrifuge tube to precipitate the plasma proteins. The sample was vortex mixed for 60 sec and subsequently centrifuged at room temperature for 10 min at 7270 x *g* to separate the proteins from the plasma. 50 µL of the supernatant was transferred into a fresh tube with 50 µL of mobile phase and vortex mixed for 30 sec prior to HPLC analysis. The plasma sample dilution factor was 6 and the resulting ISTD concentration was 10 µg/mL.

Blank rat plasma was used to produce a calibration curve of spiked plasma standards (0.15-15 µg/mL). The procedure followed the same protocol as the plasma sample preparation, however the 50 µL of plasma sample was replaced with 50 µL of spiked plasma standard (i.e. 45 µL blank plasma vortex mixed with 5 µL IBU standard for 30 sec). After analysis with HPLC, the calibration curves were prepared using the ratio of HPLC response between the IBU analyte and the ISTD (R^2 >0.998) and were used to determine the unknown IBU concentrations in the plasma samples.

Pharmacokinetic Data Analysis

The maximum observed plasma concentrations (C_{max}) of IBU and the time for their occurrence (T_{max}) were noted directly from the individual plasma concentration versus time profiles. The area under the plasma concentration versus time profiles ($AUC_{0–10\ h}$) were calculated using the linear trapezoidal method (Gabrielsson and Weiner, 2012) using GraphPad Prism, Version 7.03 (La Jolla, USA). Due to the IBU plasma concentrations at 10 and 24 h being below the limit of quantification of the assay after plasma sample preparation (150 ng/mL), accurate determination of $AUC_{0–24\ h}$ was not possible. The relative bioavailability was calculated with respect to Nurofen, i.e. formulation $AUC_{0–10\ h}$ / Nurofen $AUC_{0–10\ h}$.

Statistical and Correlation Analyses

All statistical and correlation analyses were performed using GraphPad Prism Version 7.03.

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The areas under plasma concentration-time curves (*in vivo* $AUC_{0\text{-}10\ h}$) were plotted against the areas under the solubilization-time curves (*in vitro* $AUC_{0\text{-}1\ h}$) (values provided in Supplemental Table 1). The Pearson correlation coefficient was calculated to determine if IVIVC existed between the *in vivo* and *in vitro* performances of the IBU formulations.

Statistically significant differences in AUC, C_{max} and t_{max} were determined by one-way ANOVA followed by Tukey's post-test for multiple comparisons. Differences were considered statistically significantly when $p < 0.05$.

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Results

Formulation Characterization

The super-SLH and spray-dried SLH were successfully fabricated as described in Table 1. Super-SLH A, B and C, contained 9.5, 19.3 and 29.1% w/w IBU respectively, and possessed SD ≤ 0.4% w/w and loading efficiencies ≥ 95%. The S_{eq} of IBU in lipid (Capmul PG8) is 211 mg/g (Schultz et al., 2018). The drug loads of the formulations were also reported in terms of % of the S_{eq}, to compare the degree of supersaturation of the formulations. Super-SLH A, B and C contained IBU at 99.5%, 227% and 389% of the S_{eq}, respectively. The spray-dried SLH was found to possess a drug load of 7.1% w/w (unsaturated) and the crushed Nurofen tablet was found to contain 44.7% w/w IBU.

The SEM images, displayed in Figure 1, illustrate the differences in the surface morphologies of the spray-dried SLH and super-SLH. The spray-dried SLH appeared consistent with previous reports (Bremmell et al., 2013; Rao et al., 2015; Dening et al., 2016b), displaying spherical porous microparticles composed of many silica nanoparticles. In contrast, the super-SLH formulations displayed larger, irregular-shaped, silica microparticles, with no evidence of incomplete lipid or drug loading as seen in previous super-SLH studies (Schultz et al., 2018). As super-SLH A, B and C all appeared similar under SEM, only the super-SLH A SEM image is displayed.

In Vitro Dissolution Study

Figure 2A illustrates the *in vitro* dissolution profiles of the IBU formulations in pH 2.1 media. The super-SLH A, B and C and Nurofen data produced by Schultz et al. (2018) was included with permission, and the spray-dried SLH data was collected in the current study. It is clear that the spray-dried SLH possesses rapid dissolution kinetics compared to the other formulations. The spray-dried SLH released 90% of the IBU load within 10 min and plateaued at ~92% by 15 min. Conversely, the other formulations demonstrated more sustained release, i.e. 28-37% of IBU released in 10 min and were expected to continue releasing beyond 60 min. The differences in the dissolution profiles of super-SLH A, B and C have previously been described (Schultz et al., 2018). Briefly, the dissolution decreased with an increase in supersaturated drug load which was associated with an increase in crystalline IBU content.

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Figure 2B displays the areas under the solubilization-time curves (*in vitro* $AUC_{0\text{-}1\ h}$) of each formulation relative to Nurofen. The *in vitro* AUCs of spray-dried SLH and super-SLH A and B were significantly greater than Nurofen ($p < 0.0001$). Spray-dried SLH achieved the greatest *in vitro* AUC, approximately 2-fold greater than Nurofen. Super-SLH A and B achieved similar relative *in vitro* AUCs ($p = 0.5653$), less than spray-dried SLH but approximately 1.3-fold greater than Nurofen. Conversely, super-SLH C achieved a relative *in vitro* AUC of 0.85, significantly less than Nurofen ($p = 0.0078$) and super-SLH A and B ($p < 0.0001$).

***In Vivo* Pharmacokinetic Study**

The oral PK profiles of the IBU formulations dosed to fasted male Sprague-Dawley rats are displayed in Figure 3A, the areas under the plasma concentration-time curves (*in vivo* $AUC_{0\text{-}10\ h}$) (relative bioavailability) of each formulation relative to Nurofen is depicted in Figure 3B, and the corresponding PK parameters are displayed in Table 2.

Nurofen was used to compare the formulations performances to a current commercial product, while spray-dried SLH was used to compare the formulations performances to a well-established LBF that has been used clinically. Nurofen achieved a C_{max} of 7 µg/mL at a t_{max} of 0.9 h, and an AUC of 21.1 µg/mL.h. The performance of the spray-dried SLH was superior to the Nurofen, exhibiting the greatest C_{max} of 17.6 µg/mL at a t_{max} of 1.0 h and *in vivo* AUC of 48.0 µg/mL.h.

The super-SLH A and B were comparable, reaching statistically equivalent C_{max} of 14.1 and 13.7 µg/mL, respectively ($p = 0.9985$). Their C_{max} were approximately 100% greater than Nurofen and 20% less than the spray-dried SLH. The AUC for super-SLH A and B respectively were 47.1 and 47.0 µg/mL.h, which led to relative bioavailabilities of 2.23 and 2.22 in comparison to Nurofen, these relative bioavailabilities were equivalent to that of spray-dried SLH, 2.27 ($p = 0.9985$ and $p = 0.9976$).

Conversely, the *in vivo* performance of super-SLH C was poor compared to super-SLH A and B, attaining a C_{max} of 8.2 µg/mL and AUC of 19.3 µg/mL.h. The *in vivo* AUC was 60% less when compared to the super-SLH A and B and spray-dried SLH. Despite exhibiting a higher C_{max}, the super-SLH C possessed a relative bioavailability of 0.91 when compared to Nurofen.

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The t_{max} of the different formulations ranged from 0.5 to 1.4 h with standard deviations ranging from 0 to 0.8 h. The different formulations did not cause statistically significant differences in IBU t_{max} (all $p \geq 0.9668$).

In Vitro - In Vivo Correlation

In an attempt to explore the IVIVC between the *in vitro* dissolution and *in vivo* PK data, the areas under plasma concentration-time curves (*in vivo* $AUC_{0\text{-}10\ h}$) were plotted against the area under the solubilization-time curves (*in vitro* $AUC_{0\text{-}1\ h}$) and displayed in Figure 4 The Pearson correlation coefficient indicated a strong positive correlation between the measured *in vitro* AUC and measured *in vivo* AUC data ($r = 0.9137$, $p = 0.0109$).

Additionally, the relative AUCs for the *in vitro* dissolution and *in vivo* PK data were compared in Figure 5. Greater relative AUCs were observed *in vivo* than *in vitro*. Furthermore, for each formulation, the difference between the *in vitro* and *in vivo* relative AUC was statistically significantly different for super-SLH A and B, however not for Nurofen, spray-dried SLH or super-SLH C.

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Discussion

Super-SLH is a strategy to improve the drug loading of solid-state LBF through drug supersaturation of the lipid followed by encapsulation in the mesopores of silica microparticles. While the super-SLH drug loads are greater than spray-dried SLH, the supersaturated levels of drug may influence the *in vitro* and *in vivo* performance of the formulation. Hence, super-SLH containing three IBU supersaturation levels (99.5, 227 and 389% S_{eq}) and spray-dried SLH were fabricated and directly compared *in vitro* and *in vivo*. Nurofen was also investigated to determine whether super-SLH outperforms the current commercial IBU product.

Formulation Drug Loading and Crystalline Content

Super-SLH with target drug loads of 10, 20 and 30% w/w (super-SLH A, B and C) were fabricated using the reported method (Schultz et al., 2018). They contained slightly greater drug loads, 9.5, 19.3 and 29.1% w/w, than previously reported due to higher drug loading efficiencies. Super-SLH are known to possess different proportions of crystalline IBU as previously reported, with super-SLH A containing no crystalline IBU and super-SLH B and C containing small amounts of crystalline IBU (C containing more than B) (Schultz et al., 2018). This difference in crystalline drug content between the formulations is owing to their drug loads, where the greater the extent above the S_{eq}, the greater the crystalline drug content of the super-SLH (Table 2). Spray-dried SLH was fabricated using an established method (Tan et al., 2014), however the lipid Capmul PG8 was used rather than a mixture of lipids (Captex 300, Capmul MCM and soybean oil) for direct comparisons to super-SLH, leading to a greater drug loading of 7.1% w/w compared to 5.6% w/w as reported previously. As spray-dried SLH was fabricated containing an IBU concentration below its S_{eq}, it was expected that the IBU was molecularly dispersed and no crystalline drug was present. The Nurofen tablets contained crystalline IBU, which were ground into a fine powder prior to use.

In Vitro Dissolution Performance

After *in vitro* dissolution for 60 min at pH 2.1, the rankings of the formulations in respect to AUC were spray-dried SLH >> super-SLH A ≈ super-SLH B > Nurofen > super-SLH C, as shown in Figure 2B. Two formulation parameters were identified as major influencers of dissolution: i) crystalline IBU content and ii) particle morphology. The crystalline drug content within the formulation had an inverse effect on

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dissolution performance. Crystalline drug, as opposed to non-crystalline (molecularly dispersed) drug, requires greater energy to overcome the intermolecular forces within the crystal lattice to undergo dissolution. Spray-dried SLH containing molecularly dispersed IBU exhibited excellent *in vitro* performance, while Nurofen containing crystalline IBU exhibited poor performance. The super-SLH exhibited a decrease in dissolution with an increase in crystalline content. However, despite super-SLH A containing molecularly dispersed IBU and super-SLH B containing a small proportion of crystalline IBU, the difference between super-SLH A and B was not significant, suggesting a small portion of crystalline drug will not substantially influence the overall dissolution of a formulation. Interestingly, the super-SLH C which contained portions of crystalline and molecularly dispersed IBU performed poorer than Nurofen containing crystalline IBU. This may be contributable to Nurofen containing additional solubilizing excipients, such as the surfactant sodium lauryl sulphate, to assist in dissolution (Medicines and Healthcare Products Regulatory Agency, 2017), and a potentially smaller crystal size due to the grinding of the tablets (Meola et al., 2018).The large difference in the rate and extent of dissolution between the spray-dried SLH and the super-SLH can be explained through the differences in the particle morphology. The super-SLH is composed of mesoporous microparticles loaded with lipid and drug, resulting in slow partitioning of the drug from the lipid, located inside the pores, into the dissolution media. Conversely, the spray-dried SLH is composed of porous microparticles, comprised of a matrix of nanoparticles and submicron lipid droplets containing drug, which when placed in dissolution media, allow rapid drug release due to their large surface area (Tan et al., 2009).

While the dissolution conditions employed were not a bio-relevant representation of the environment within the gastrointestinal tract, they were adequately discriminatory for the IBU formulations and enabled differentiation between the IBU formulations' dissolution kinetics. The conditions did not take into consideration the different pH conditions present throughout the gastrointestinal tract, the digestion of the lipid that occurs by gastrointestinal lipases, or the dynamic absorption of the drug from the gut driving further IBU release from the formulation (Porter and Charman, 2001). *In vitro* lipolysis studies were considered to obtain a more bio-relevant representation of the solubilization capacity of the super-SLH formulations under digestive conditions (Fatouros and Mullertz, 2008), however due to ionization and high

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solubility of IBU in the fasted state lipolysis medium (pH 7.5) (~7.7 mg/mL), discriminatory non-sink conditions were not possible without dosing an excessive amount of IBU formulation (Dening et al., 2018). Therefore, the next logical step was to conduct oral PK studies in rats to compare the performance of super-SLH, spray-dried SLH and Nurofen *in vivo*.

In Vivo Oral PK Performance

After orally administering the formulation suspensions to rats in the *in vivo* PK study, the rankings of the formulations in respect to AUC (bioavailability) were spray-dried SLH ≈ super-SLH A ≈ super-SLH B > Nurofen > super-SLH C, as shown in Figure 3B. The bioavailabilities of super-SLH A and B and spray-dried SLH were comparable, achieving an approximate 2.2-fold increase in bioavailability compared to that of Nurofen. This suggests that super-SLH A and B retain the beneficial properties of a spray-dried formulation, despite the differences in particle morphology, drug load and crystalline drug content. This is promising as this may translate to other super-SLH benefits previously demonstrated by spray-dried SLH, including improved bioavailability for a range of BCS class II drugs in *in vivo* rat and dog models as well as in humans (Tan et al., 2011; Nguyen et al., 2013; Rao et al., 2014; Tan et al., 2014). Super-SLH A and B and spray-dried SLH were expected to achieve bioavailabilities greater than that of Nurofen, due to the beneficial properties of LBFs and containing molecularly dispersed drug, rather than crystalline IBU, as described in literature (Balakrishnan et al., 2009; Kim et al., 2012). However, this was not the case for super-SLH C, which did not perform better than the Nurofen. As mentioned above, this was due to super-SLH C containing a high proportion of crystalline IBU, limiting dissolution and hence absorption. This demonstrates that super-SLH is an effective solid-state LBF strategy to enhance the bioavailability of IBU and outperforms the commercial product Nurofen which suggests the formulation has commercial potential. However, the degree of crystallinity has demonstrated to be an important factor in *in vitro* and *in vivo* performance and must be taken into consideration.

The formulations that achieved the highest bioavailability enhancement, i.e. spray-dried SLH and super-SLH A and B, had different drug loads and hence different formulation doses were administered to achieve the same IBU dose. To achieve the same 2.2-fold improvement in bioavailability, 140.8 mg of spray-dried

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SLH (7.1% w/w IBU), 105.2 mg of super-SLH A (9.5% w/w IBU) and 52.4 mg of super-SLH B (19.3% w/w) were dosed to rats. Super-SLH B required 50% less formulation than super-SLH A and 63% less formulation than spray-dried SLH. Of the formulations investigated, super-SLH B was considered the superior formulation, achieving the highest bioavailability and drug load, translating to considerably smaller formulation doses (less tablets/capsules) in a clinical setting, leading to better patient compliance and quality of life (Williams et al., 2005; Ingersoll and Cohen, 2008). It also translates to benefits for the pharmaceutical industry, including a more efficient medication and requirement for lower quantities of active ingredient and excipients. Large-scale manufacture is expected to be achievable utilizing commonly employed industrial processes and fabrication approaches, involving simple solution preparation and heating, and mixing with excipients.

IVIVC

The Pearson correlation coefficient confirmed a strong IVIVC (r = 0.9137, p = 0.0109) between the IBU formulations' *in vitro* dissolution and *in vivo* PK performances. The correlation suggests that the *in vitro* dissolution study in pH 2.1 media may offer a simple initial test to predict the performance of these formulations *in vivo*. This was despite the significant difference between the *in vitro* and *in vivo* performance of super-SLH A and B that resulted in a change in the performance (AUC) ranking of the formulations. All IBU formulations exhibited greater improvements in relative AUC *in vivo* than *in vitro*. This is owing to the advantages of the LBF exhibited *in vivo*, i.e. enhanced drug solubilization due to lipid digestion products, inhibition of P-glycoprotein-mediated drug efflux, promotion of lymphatic transport and increased gastrointestinal membrane permeability (Hauss, 2007). Super-SLH A and B performed 78 and 85% greater *in vivo* than *in vitro* respectively, a significant improvement (p < 0.0001), as their full potential was not demonstrated *in vitro*, due to slow drug partitioning from the lipid within the silica pores into the dissolution medium. This is a slow process due to the relatively larger lipid droplets with low surface area contained within the pores, compared to the submicron lipid droplets distributed throughout the spray-dried SLH microparticles with high surface area (Joyce et al., 2018b). *In vivo*, this process of drug partitioning played a far smaller role, as lipolysis drove the release of IBU. An insignificant increase in AUC was observed by

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super-SLH C *in vivo* compared to *in vitro*, as it contained a large proportion of crystalline IBU that must undergo dissolution, limiting the advantageous effects that can be achieved by the LBF.

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Conclusion

The *in vivo* performance of IBU was significantly enhanced by the super-SLH formulation, achieving equivalent bioavailability to spray-dried SLH and 2.2-fold greater bioavailability than Nurofen. A super-SLH formulation containing a drug load of 19.3% w/w IBU (supersaturated at 227% of the S_{eq}), 2.7-fold greater than spray-dried SLH, allowed a 63% reduction in administered formulation. Supersaturated drug loading influenced the *in vivo* performance of super-SLH, as a decrease in bioavailability was observed by the super-SLH C due to its larger content of crystalline drug. Strong positive IVIVC was observed, suggesting that the simple *in vitro* dissolution study in pH 2.1 media approximates the *in vivo* bioavailability of super-SLH in rats. Super-SLH has potential to be applied to other BCS class II drugs to form solid LBF that enhance bioavailability and reduce the pill burden on patients due to its improved drug loading.

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Authorship Contributions

Participated in research design: Schultz, Kovalainen, Peressin and Prestidge.

Conducted experiments: Schultz, Kovalainen and Peressin.

Contributed new reagents or analytic tools: N/A

Performed data analysis: Schultz and Prestidge.

Wrote or contributed to the writing of the manuscript: Schultz, Kovalainen, Peressin, Thomas and Prestidge.

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Footnotes

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Legends for Figures

Figure 1: SEM images of the surface morphology of (A and B) spray-dried SLH and (B) super-SLH A (representing super-SLH B and C).

Figure 2: The *in vitro* dissolution of IBU formulations in pH 2.1 HCl media, dosed at 20 mg of IBU. (A) The dissolution profiles of the IBU formulations over 1 h (mean ± SD, n=3). Adapted with permission from (Schultz et al., 2018). (B) The area under the solubilization-time curves (*in vitro* $AUC_{0\text{-}1\ h}$) of each formulation relative to Nurofen (mean ± SE, n=3). **** and ** indicates significantly greater than Nurofen, $p < 0.0001$ and $p = 0.0078$, respectively.

Figure 3: *In vivo* PK data for IBU formulations orally administered to Sprague-Dawley rats at a dose of 10 mg/kg. (A) The PK profiles of the IBU formulations over 10 h (24 h data is supplied in Supplemental Figure 1) (mean ± SE, n=4 or 5 (Nurofen)). (B) The area under the plasma concentration-time curves (*in vivo* $AUC_{0\text{-}10\ h}$) of each formulation relative to Nurofen (relative bioavailability) (mean ± SE, n=4 or 5 (Nurofen)). **** indicates significantly greater than Nurofen where $p < 0.0001$ and ns indicates not significantly greater than Nurofen, $p = 0.9746$.

Figure 4: *In vitro−in vivo* correlation plotted as area under the IBU plasma concentration−time curve following oral administration to fasted male Sprague-Dawley rats (mean ± SE, n = 4 or 5 (Nurofen)) versus the area under the IBU dissolution concentration−time curve (mean ± SE, n = 3). The data points represent the following formulations: spray-dried SLH (blue square), super-SLH A (green circle), super-SLH B (gold triangle), super-SLH C (purple upside down triangle) and Nurofen (red diamond).

Figure 5: A comparison between the *in vitro* and *in vivo* relative AUCs achieved by the SLH formulations relative to Nurofen (mean ± SE) (for *in vitro* data n=3, for *in vivo* data, n=4 or 5 (Nurofen)). ns denotes that the AUC *in vitro* and *in vivo* are not significant. **** denotes that the AUC *in vitro* and *in vivo* are significant, $p < 0.0001$.

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Tables

Table 1: The target compositions and measured drug compositions and loading efficiencies of the formulations used in the *in vivo* PK study. A dash (–) indicates not applicable. ND (not determined) indicates that the parameter was not measured. Each drug load represents mean ± SD, n=3.

	Target Composition			**Measured Composition**		
Formulation	Drug (% w/w)	Lipid (% w/w)	Silica (% w/w)	Drug (% w/w)	Drug Loading Efficiency (%)	IBU S_{eq} in Lipid (%)
Super-SLH A	10	45	45	9.5 ± 0.3	95.0	99.5
Super-SLH B	20	40	40	19.3 ± 0.4	96.5	227
Super-SLH C	30	35	35	29.1 ± 0.3	97.0	389
Spray-dried SLH	9.5	60	30	7.1 ± 0.1	74.4	ND
Nurofen	-	-	-	44.7 ± 1.7	-	-

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Table 2: PK parameters for IBU formulations following oral administration at 10 mg/kg to fasted male Sprague-Dawley rats.[a]

	Nurofen	**Spray-dried SLH**	**Super-SLH A**	**Super-SLH B**	**Super-SLH C**
C_{max} (µg/mL)	7.0 ± 3.0	17.6 ± 2.9*	14.1 ± 3.7*	13.7 ± 4.5*	8.2 ± 1.9
t_{max} (h)	0.9 ± 0.4	1.0 ± 0.4	0.5 ± 0.0	1.4 ± 0.8	0.5 ± 0.0
$AUC_{0\text{-}10\ h}$ (µg/mL.h)	21.1 ± 2.5	48.0 ± 5.1*	47.1 ± 7.1*	47.0 ± 5.3*	19.3 ± 2.3
Relative Bioavailability[b]	1.00	2.27	2.23	2.22	0.91

[a]Data represents mean ± SD, except for $AUC_{0\text{-}10\ h}$ (µg/mL.h) where data represents mean ± SE, n=4 or 5 (Nurofen).

[b]The relative bioavailability in comparison to Nurofen as determined by the ratio of the $AUC_{0\text{-}10\ h}$ data.

*$p < 0.0001$ statistically significant different compared to Nurofen

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Figures

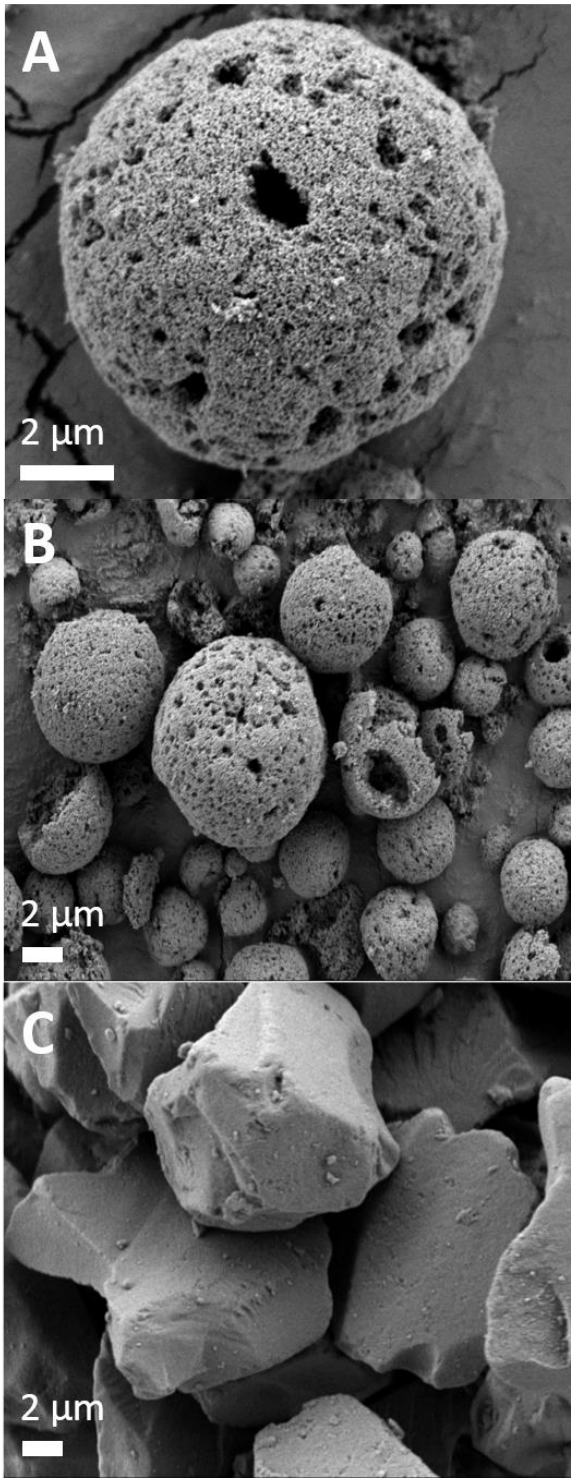

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Figure 1

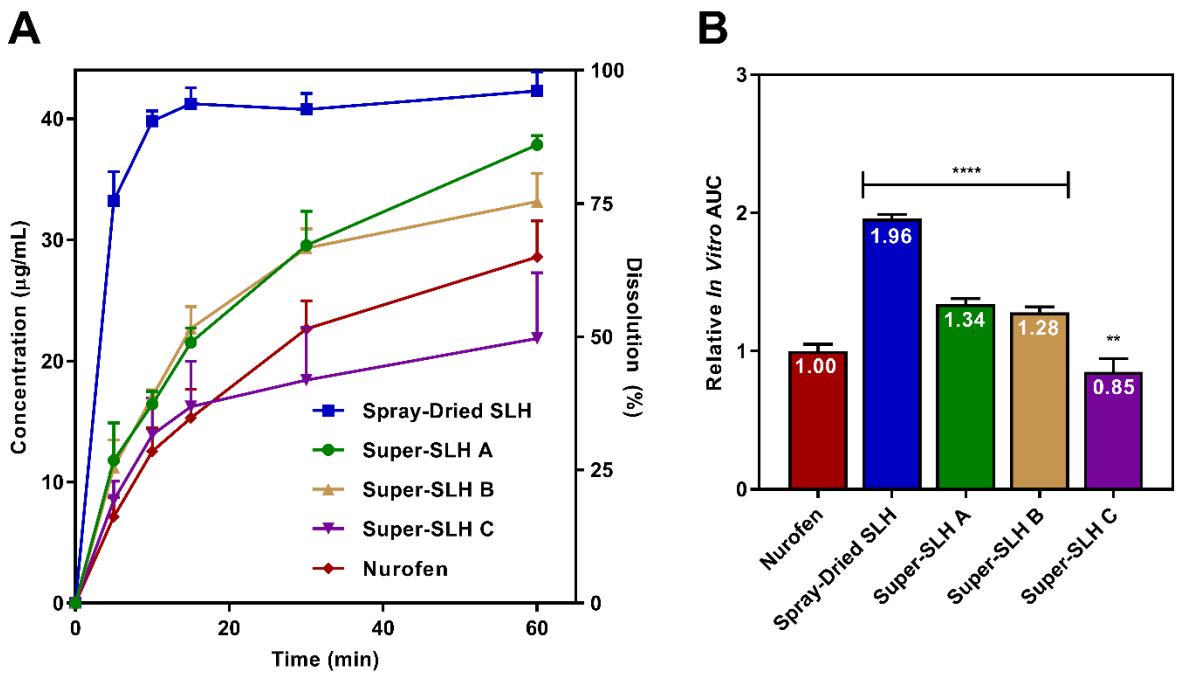

Figure 2

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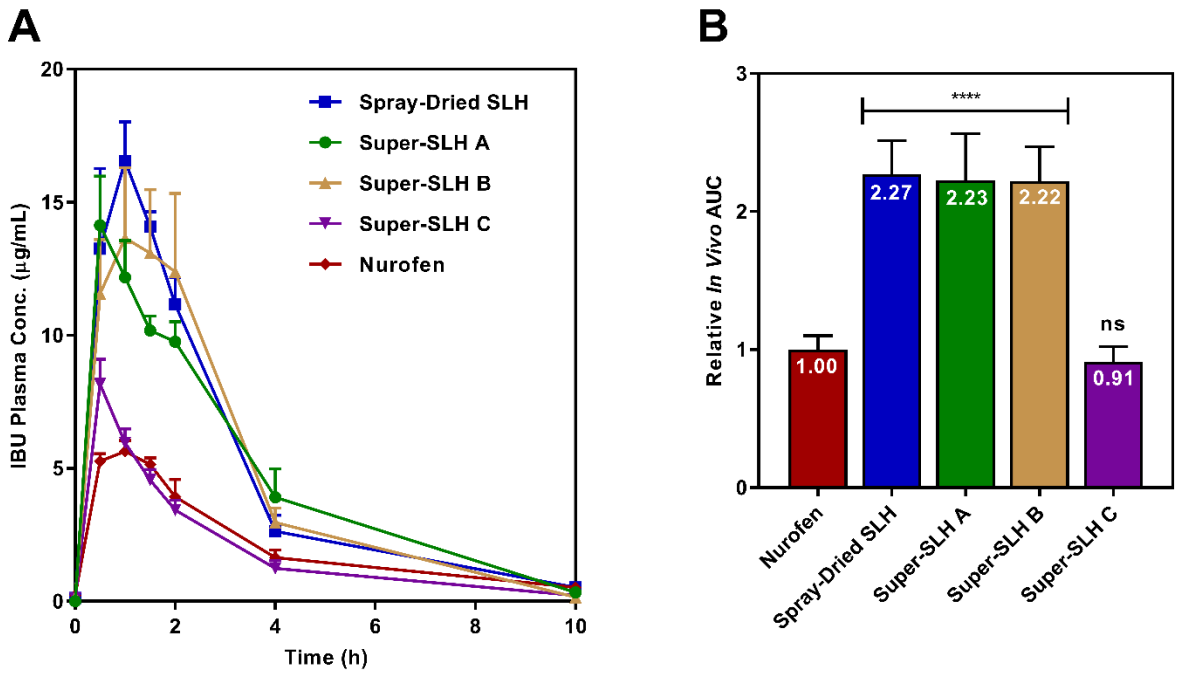

Figure 3

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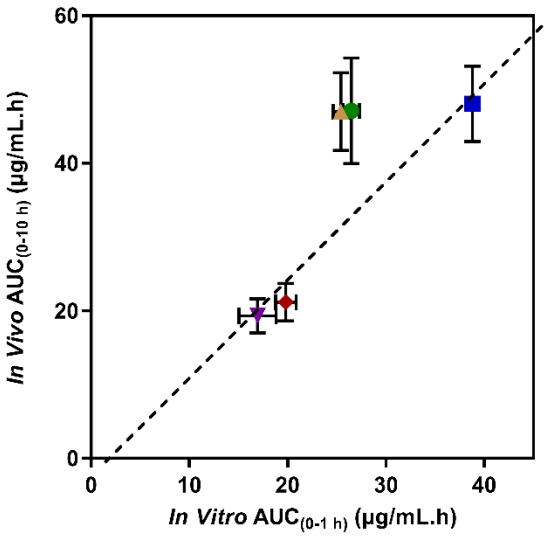

Figure 4

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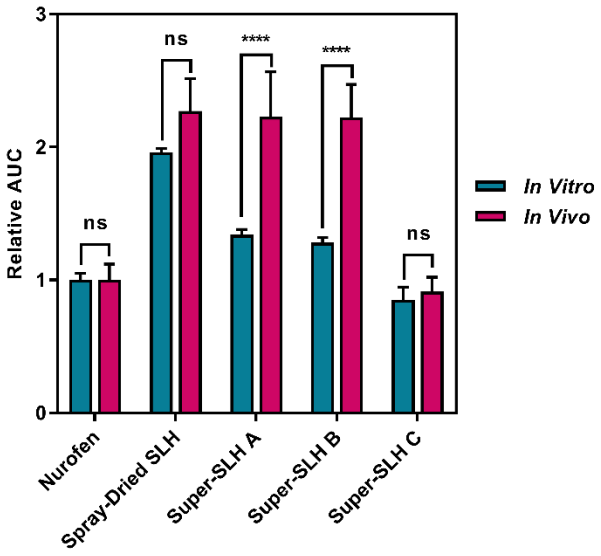

Figure 5

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