REVIEW

Injected nanocrystals for targeted drug delivery

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Received 29 October 2015; received in revised form 4 November 2015; accepted 16 November 2015

KEY WORDS
Nanocrystals; Targeted drug delivery; Biodistribution; Ligand; Stimuli response; Encapsulation

Abstract
Nanocrystals are pure drug crystals with sizes in the nanometer range. Due to the advantages of high drug loading, platform stability, and ease of scaling-up, nanocrystals have been widely used to deliver poorly water-soluble drugs. Nanocrystals in the blood stream can be recognized and sequestered as exogenous materials by mononuclear phagocytic system (MPS) cells, leading to passive accumulation in MPS-rich organs, such as liver, spleen and lung. Particle size, morphology and surface modification affect the biodistribution of nanocrystals. Ligand conjugation and stimuli-responsive polymers can also be used to target nanocrystals to specific pathogenic sites. In this review, the progress on injected nanocrystals for targeted drug delivery is discussed following a brief introduction to nanocrystal preparation methods, \textit{i.e.}, top-down and bottom-up technologies.

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1. Introduction

More than 40% of drug candidates in the drug development process exhibit poor solubility, leading to poor and variable bioavailability. The non-specific distribution of most drugs throughout the body results in side effects, further limiting their clinical use. Targeting strategies based on nanocarriers are important solutions for these problems. Nanocarriers, i.e., liposomes, nanoparticles, micelles and nanoemulsions, have been widely used to selectively deliver poorly soluble drugs to pathological tissues, organs or cells. However, the intrinsic drawbacks, such as platform instability, limited drug loading, high manufacturing cost, scale-up difficulties, and quality control difficulties, contribute to the limited acceptance of these nanocarriers in clinical. Only a couple of nanocarrier-based preparations are successfully marketed, e.g., Doxil®️, DaunoXome®️️ and Abraxane®️.

Development of nanocrystals emerged amid various shortcomings of existing delivery techniques for targeted therapy. Nanocrystals are drug crystals with particle size ranging from dozens to a few hundreds of nanometers, while in some cases, pure drug crystals may be physically stabilized by surfactants and/or polymers. Absence of any carrier chemicals offer a theoretic drug distribution of most drugs throughout the body. 

2. Preparation of nanocrystals

2.1. Top-down techniques

High-energy mechanical forces are involved in the top-down approaches, which can be provided either by media milling (MM) (NanoCrystals®️️) or high-pressure homogenization (HPH) (IDD-P®️️, DissoCubes®️️ and Nanopure®️️) to comminute large crystals. The biggest advantage in top-down process is that it is a universal technique to prepare crystalline nanoparticles and is flexible in production scale. Thus, the process has been widely adopted to prepare commercial nanocrystals. Almost all commercial products were produced by NanoCrystals®️️ except for Triglide®️️ by IDD-P®️️. The disadvantage of this technology includes high energy and time consumption. 

2.1.1. Media milling (NanoCrystals®️️)

A milling chamber, motor, recirculating chamber, coolant and milling media are the major components of the media mill (Fig. 1). In the process, the milling chamber is fed with a crude slurry containing drug, water and stabilizers, and agitated by the motor. Generally, the slurry occupies 2%–30% (w/v) volume of the milling chamber, while the milling media occupy 10%–50% (w/v) of the slurry. During agitation, the milling media roll over inside the chamber, generating high energy forces by shearing and impacting with drugs to reduce the particle size. The operation can be performed either in batch (discontinuous mode) or recirculation mode (continuous mode), depending on the scale. Recirculation is advantageous to reduce milling time and decrease particle size. The milling media can be retained in the chamber by media separators if recirculation mode is performed. Thermogenesis is severe due to the high energy generated during milling and long-term operation, leading to stability concerns. Therefore, the coolant is a necessity to control the temperature during the milling process.

2.1.2. High pressure homogenization (IDD-P®️️, DissoCubes®️️ and Nanopure®️️)

During the process of HPH, drug suspensions are introduced into a high pressure homogenizer and forced to pass through a very narrow homogenization pathway in a sudden burst under high pressure. Fracture of drug particles is achieved by cavitation, high-shear forces and collisions among particles. The process is generally composed of three steps: (1) dispersion of crude drug powders in pure solution or in solution containing stabilizer, (2) reduction of particle size by high-speed shearing or homogenization under low pressures, (3) high pressure homogenization to achieve the desirable particle size and size distribution. Based on the instruments and solution used, HPH can be further divided into three patented technologies: microfluidizer for IDD-P®️️ technology, piston gap homogenizer for DissoCubes®️️ (water) and Nanopure®️️ (non-aqueous media).
2.2. Bottom-up techniques

The bottom-up process grows nanocrystals from solution, which includes two crucial steps: nucleation and consequent crystal growth. In comparison, nucleation is especially important to achieve small and uniform nanocrystals. Higher nucleation rate increases the number of nuclei formed from the supersaturated solution, leading to decreased supersaturation. Less growth of each nucleus in the end can be anticipated as a consequence. Also, if a large number of nuclei are produced concurrently in the nucleation stage, a narrow particle size distribution is obtained. Therefore, it is essential to promote rapid and homogeneous nucleation in the bottom-up process.

Nucleation can be triggered by either mixing with antisolvent or removal of solvent. The mixing of drug solution and antisolvent is generally achieved with conventional mixing equipment, i.e. magnetic stirring and agitator blade. In order to promote the nucleation, sonication can be introduced to provide cavitation effects. This method is called sonoprecipitation. Some highly efficient mixing equipments have also been used to prepare nanocrystals, including confined impinging jet reactor, multiple inlet vortex mixer, and static mixer. With these instruments, intense micro-mixing between the two fluids is fulfilled in the order of milliseconds. A homogeneous solution with high supersaturation may be achieved even before the onset of nucleation, favoring small nanocrystals with narrow size distribution. Spray-drying and freeze-drying are common ways to remove solvent. Recently, spray-freezing into liquid and controlled crystallization during freeze-drying techniques also has been developed to prepare nanocrystals by removal of solvent.

Supercritical fluid (SCF) can be used to prepare nanocrystals by taking advantage of the unique physical properties of SCF, with combined diffusivity like gas and solubilization like liquid. In addition, quick and easy removal of SCF without excessive drying can greatly increase the milling efficiency, while the coolant can control the temperature of the materials. The milling time required to generate nanocrystals depends on the properties of the drugs, the milling media and the extent of particle size reduction, varying from hours to days.
facilitate the precipitation of nanoparticles. Supercritical carbon dioxide (SCO2) is the most favored SCF due to the mild critical point (31 °C and 73.8 bar) and low environmental impact. Depending on the solubility of a compound in SCO2, nanocrystal preparation can be achieved by rapid expansion of SCO2 from drug solution40, or by precipitation using SCO2 as the antisolvent41.

3. Targeted delivery by nanocrystals

3.1. In vivo distribution of nanocrystals

Due to being sequestered and transported by MPS cells, i.v. injected nanocrystals distribute more in MPS cell-abundant organs, such as liver, spleen and lung, than the solution counterpart4,14,15. Nevirapine nanocrystals are more easily taken up in vitro by macrophages than the solution formulation, showing 2.76-fold higher nevirapine concentration in macrophages at the end of a two-hour culture. Therefore, gamma scintigraphy confirmed that nevirapine nanocrystals accumulated more in MPS-rich organs including spleen, liver and thymus, as well as exhibited prolonged residence at the target sites in comparison to pure drug solution44. Similarly, the relative targeting efficacy (rt) values of liver, lung and spleen for amoitone B nanocrystals (275 nm) are 3.32, 2.50 and 1.42, respectively, compared to the solution (Table 1). The nanocrystals remained in liver and lung for a longer time, benefiting therapy in liver and lung38,46. Indeed, hydroxycamptothecin nanocrystals (168 nm) were highly accumulated in liver, spleen and lung27. The area under curve (AUC) of hydroxycamptothecin nanocrystals in liver, spleen and lung respectively are 410-, 46- and 40- fold higher than that obtained with a solution formulation (Table 1).

Particle size may play a significant role in the biodistribution of nanocrystals. Oridonin nanocrystals were prepared by HPH, with mean particle size of 103 nm and 897 nm achieved by adjusting the nanocrystals. Oridonin nanocrystals were prepared by HPH, with mean particle size reduction53. It is thus hypothesized that the smaller nanocrystals dissolve relatively quickly in blood, minimizing phagocytosis by the MPS cells and presenting similar in vivo behavior to the solution7. On the contrary, larger particles are more likely to be phagocytosed by the MPS, resulting in greater distribution to liver, spleen and lung8,49. The size effects on biodistribution are still controversial. Asulacrine nanocrystals, 133 nm, were prepared by HPH. Although having enhanced dissolution and saturation solubility, the nanocrystals still showed a significantly greater accumulation in liver, lung and kidney with altered pharmacokinetics, as compared to the solution54. AZ68 amorphous nanosuspensions, 100–150 nm, showed enhanced oral bioavailability over the crystalline nanocrystals, 300–400 nm, due to enhanced solubility and dissolution rate. However, no significant difference was found in the pharmacokinetic parameters when comparisons were made between the formulations after i.v. administration37. Nanocrystals are usually adopted by insoluble drugs. Given the insoluble properties (usually <0.1 mg/mL), especially for anticancer drugs56, combined with high i.v. dose, injected nanocrystals are not expected to dissolve rapidly due to lack of local mixing and insufficient initial volume for distribution4.

Particle morphology also influences the biodistribution of nanocrystals. Spherical and rod-like 10-hydroxycamptothecin nanocrystals (500 nm) were prepared with similar hydrodynamic sizes and surface charges7. The rod-like nanocrystals showed significantly higher uptake by KB cells than the spherical ones. Therefore a shape-dependent cytotoxicity was observed. In addition, in vivo studies showed obviously superior antitumor efficacy was achieved by the rod-like nanocrystals over the spherical one and free drug solution, and no statistically significant weight loss was observed. Similarly, the needle-shaped camptothecin nanocrystals (250 nm) accumulated more in the lung, because the high aspect ratio may hinder the escape from local entrapment39.

Surface modification of nanocrystals may change their biodistribution behaviors. Serum albumin, PEG and dextran was physically adsorbed on the surface of nevirapine nanocrystals by simply incubating the bare nanocrystals in the modifier solution38. Surface modification with PEG reduced the uptake of nanocrystals by primary macrophages. On the contrary, surface modification with serum albumin and dextran showed 1.39 and 1.22 fold higher cellular drug
concentration at the end of 2 h than that of bare nanocrystals. As a consequence, surface modification with serum albumin and dextran decreased the accumulation of bare nanocrystals in blood, while increased accumulation in liver, spleen and lung, both due to fast uptake by macrophages. Furthermore, the nevirapine nanocrystals were able to cross blood-brain barrier in less than 30 min and maintained adequate levels up to 24 h after modification with serum albumin. None of the other nanocrystals formulations, modified or not, showed significant levels in brain. Polycations, including IgG, protamine and poloxamer to coat the bare paclitaxel (PTX) nanocrystals by physical adsorption 59, DOTAP-coated nanocrystals (DOTAP-NCs) showed faster biodistribution properties of i.v. injected nanocrystals and factors affecting biodistribution.

| Drug    | Stabilizer | Size (nm) | Animal model | Reference preparation | Biodistribution (Cmax) | Ref. |
|---------|------------|-----------|--------------|------------------------|------------------------|------|
|         |            |           |              |                        | Blood | Heart | Liver | Spleen | Lung | Kidney | Tumor | Thymus |
| Am-B    | PC/F68     | 275       | Mice         | Solution               | 2.07 | 0.77 | 3.32 | 1.42 | 2.50 | 0.82 |
| HCPT    | None       | 168       | H22 bearing mice | Solution               | 8.78 | 7.01 | 410.49 | 46.05 | 40.63 | 42.03 | 5.72 |

Effects of particle size on the biodistribution

| Drug    | Stabilizer | Size (nm) | Animal model | Reference preparation | Biodistribution (Cmax) | Ref. |
|---------|------------|-----------|--------------|------------------------|------------------------|------|
| ORI     | F68/PC     | 103       | Mice         | Solution               | 1.05 | 1.09 | 0.97 | 0.88 | 1.09 | 1.05 |
| RD      | F68/PVP/HPMC | 184     | Mice         | Solution               | 0.40 | 0.89 | 1.33 | 2.65 | 1.08 | 1.43 |

Effects of surface modification on the biodistribution

| Drug    | Stabilizer | Size (nm) | Animal model | Reference preparation | Biodistribution (Cmax) | Ref. |
|---------|------------|-----------|--------------|------------------------|------------------------|------|
| NVP     | None       | 458       | Rats         | Solution               | 1.75 | 1.16 | 1.77 | 2.56 | 0.62 | 0.75 |
| Serum   | 495        |           |              | Solution               | 1.02 | 0.60 | 2.60 | 3.74 | 4.75 | 0.57 |
| PEG     | 520        | nanocrystals |            | Solution               | 0.58 | 0.52 | 1.47 | 1.46 | 7.66 | 0.76 |
| Dextran | 520        | nanocrystals |            | Solution               | 1.14 | 0.86 | 2.51 | 2.80 | 2.27 | 0.54 |
|         |            | Bare      |              | Solution               | 0.65 | 0.74 | 1.42 | 1.09 | 3.66 | 0.72 |

Effects of ligand conjugation on biodistribution

| Drug    | Stabilizer | Size (nm) | Animal model | Reference preparation | Biodistribution (Cmax) | Ref. |
|---------|------------|-----------|--------------|------------------------|------------------------|------|
| PIK-75  | PC/F68     | 182       | SKOV-3       | Solution               | 0.77 | 13.76 | 0.91 | 0.72 | 4.69 |
| DTX     | PC/DSPE-PEG | 204     | B16 bearing mice | Solution               | 0.97 | 17.86 | 9.80 | 3.23 | 0.93 |

3.2. Ligand targeted delivery

To facilitate targeting to cancer cells, the strategy of using various ligands that bind specifically to a receptor expressed by malignant cells is attractive. Attaching ligands to the surface of nanocrystals can thus deliver the drug specifically to the cancer cell via receptor-mediated endocytosis with minimal accumulation at nonspecific sites. Note that modification with “stealth” molecules like PEG and poloxamer to avoid quick clearance by macrophages is still essential.

Folate-based targeting systems present an effective means of selectively delivering therapeutic agents to tumors, because the folate receptor is overexpressed on many human cancer cells, folate has low immunogenicity, its ease of modification, good tissue penetration and rapid clearance from receptor-negative tissues. Folate-modified PIK-75 (a phosphatidylinositol 3-kinase inhibitor) nanocrystals were prepared by HPH with Pluronic F68-folate.
P-glycoprotein (P-gp)63. Polymers that undergo physiochemical
traits improved the toxicity to multidrug resistant cells by inhibiting
ele glycol 1000 succinate (TPGS) from the paclitaxel nanocrystals.
Responsive copolymers may pave the way for the design of ROS-
be benefi

3.3. Stimuli-responsive drug delivery

Generally, stabilizer adsorbed onto the surface of nanocrystals can
prevent aggregation by providing steric and/or electronic repulsions.
An optimal surfactant thus should have high affinity to the surface
of nanocrystals. But in some cases, shedding of the stabilizer in response to a local endogenous stimulus may in fact
be beneficial. For instance, shedding of d-α-tocopheryl polyethylene
glycol 1000 succinate (TPGS) from the paclitaxel nanocrystals
improved the toxicity to multidrug resistant cells (B16 cells), and was
attributed to folate-induced internalization by the target cells. In
contrast, both nanocrystals showed similar in vivo distribution in B16
tumor-bearing mice including the tumor sites (Table 1). Instead of
being chemically anchored, the ligands are reversibly adsorbed onto the
surface of nanoparticles through stabilizers. Although equilibrium can be
reached between adsorbance and desorption in solution, stabilizers
can be detached from nanocrystals upon mild heating or dilution61,
inevitably resulting in loss of the stabilizing agent as well as any
appended ligands by in vivo dilution. Furthermore, the binding between
ligands and receptors on the surfaces of the target sites may be
preferential over the absorbance between stabilizers and nanocrystals,
leading to the binding of ligands alone to the receptors62.

4. Encapsulation of nanocrystals

As discussed above, stabilizers are generally reversibly adsorbed onto
the surfaces of drug nanocrystals, being easily shed from the
nanocrystals by dilution or heating. The desorption of stabilizers may
cause stability concerns or even affect the in vivo performance of
nanocrystals. An improvement for this issue is to encapsulate
nanocrystals in cages.

The layer-by-layer (LbL) assemble technique is an effective way to
stabilize particles, based on the iterative adsorption of oppositely
gored polymers on a surface23. Compared with the one-layer
physisorption of stabilizers, the iterative coating may provide a firm
shell to stabilize nanocrystals. Tamoxifen (TMF) and paclitaxel (PTX)
nanocrystals (between 100 nm and 200 nm) can be stabilized by the
LbL assembly technique with positively charged poly(allylamine
hydrochloride) (PAH), poly(dimethyl)diallylammonium chloride
(PDDA), and negatively charged sodium poly(styrene sulfonate)
(PSS), respectively64. LbL coating did not significantly alter the particle
sizes and morphologies of nanocrystals, while drug release can be
easily controlled by changing the coating thickness or composition.
Furthermore, with polyamino-containing PAH as the outer layer, the
specific targeting ligands such as mAb 2CS can be conjugated to
LbL-stabilized PTX nanocrystals, leading to increased cytotoxicity to
MCF-7 and BT-20 cells.

Cross-linking of stabilizers adsorbed onto the surface of nanocrystals is
another option to avoid shedding of stabilizers. Chitosan was used as a
stabilizer to prepare PTX nanocrystals by media milling, followed by
immobilization onto the surface of the nanocrystals through cross-
linking with tripolyphosphate25. Furthermore, folate was introduced to the
surface of the cross-linked chitosan/drug nanocrystals by conjuga-
tion through N-(3-dimethylaminopropyl)-N-ethylcarbodiimide hydro-
chloride (EDC). The cross-linked chitosan, acting as a diffusion barrier,
decreased the release of PTX, while conjugation further decreased the
release due to the reinforced hydrophobicity by folate. Cross-linking by
click chemistry can also be used to encapsulate nanocrystals.
Amphiphilic copolymer was synthesized by ring-opening copolymer-
ization with mPEG as a hydrophilic segment to provide steric
stabilizing effects and alkyln containing poly(δ-valerolactone) as
hydrophobic segment to adsorb on to PTX nanocrystals. The
adsorbed copolymer can be crosslinked by diazido-containing mole-
cules through click chemistry around nanocrystals, forming a non-
sheddable polymeric “nanocage”. The nanocages were found to act as
sterically stabilizing barriers to prevent aggregation and provided a
means for enhanced retention of targeting agents on nanocrystals.
Although all of the abovementioned cross-linked nanocrystals show
potential in improved stability and targetability, biodistribution and
 cellular uptake studies have not been reported.

5. Summary and future perspective

Compared with traditional nanocarriers, the advantages of nano-
crystals in physical stability, high drug loading and relative ease of
production bring attractive alternatives for delivery of poorly soluble drugs. Both top-down and bottom-up techniques have been developed for preparing nanocrystals. The bottom-up techniques may be more suitable to prepare nanocrystals for i.v. injection than the top-down techniques, considering the potential contamination from milling media.

Due to quick ingestion by macrophages, the i.v. injected nanocrystals can be passively delivered to MPS rich organs, such as liver, spleen and lung. Particle size, morphology and surface modification may greatly influence the in vivo distribution of nanocrystals. Although ligands facilitate targeting to cancer cells, physically adsorbed ligands on the surface of nanocrystals may be shed by dilution in vivo, losing the targeting function. However, shedding of stabilizers in response to pH or oxygen may be advantageous for targeted delivery to some specific pathogenic sites like tumors or sites of inflammation. Furthermore, stabilizers can be immobilized on the surface of nanocrystals by crosslinking, which may enhance not only the stability of nanocrystals but also retention of targeting agents.

However, both the in vitro cellular uptake and the in vivo fate of nanocrystals have not been fully explored due to the limitation of current detection technologies. The cellular uptake and in vivo distribution of nanocrystals is generally detected by measuring the amount of drug molecule present. It is difficult to discriminate if the results are due to the nanocrystals themselves or the dissolved molecules. Hybrid nanocrystals, by physically integrating fluorescent dyes inside the crystal71, may be a good way to resolve this issue. Only with complete understanding of the factors that affect the performance of nanocrystals can an optimal formulation be designed. In addition, with breakthroughs in the development of novel methods and devices, we believe that i.v. injected nanocrystals will occur in the near future.

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