ABSTRACT

Objective: To overcome low physiological solubility, poor bioavailability, the short plasma half-life of andrographolide (AG), a delivery system based on poly (D, L-lactide-co-glycolide) (PLGA) nanoparticles (NPs) were developed to increase the efficiency of AG against visceral leishmaniasis (VL).

Methods: Andrographolide-PLGA nanoparticles (AGnp) were prepared with Pgp efflux inhibitor vitamin E TPGS (D-a-tocopheryl polyethylene glycol 1000 succinate) by emulsion solvent evaporation method and characterized. Antileishmanial activity was evaluated using in vitro and in vivo VL infection model.

Results: The particle size of AGnp was found to be 171±1.5 nm with an encapsulation efficiency of 81%. The AGnp reduced AG cellular toxicity, retained its in vitro antileishmanial activity and lead to a reduction (99.9%) of parasite burden in the Leishmania donovani infected spleen and liver. AGnp was more active in infected mice liver at low dose than in spleen. Therapeutic indexes (TI) were 6.9-fold greater in AG and 68-fold in AGnp compared to amphotericin B (AmB) when evaluated in L. donovani infected spleen.

Conclusion: Incorporation of AG in PLGA nanoparticles, provided controlled and improved in vivo performance against VL.

Keywords: Andrographolide, PLGA nanoparticles, In vitro activity, In vivo antileishmanial activity, Macrophage, Therapeutic index

INTRODUCTION

Leishmaniasis is a neglected tropical disease, indigenous to tropical and subtropical areas and affects about 12 million people around the world. However, it's also becoming more common in developed countries, because of the increasing immunosuppressed population [1]. The current therapy against this parasite infection is not adequate and has the following limitations: toxicity, high cost, non-effectiveness, resistance or hospitalization requirement. The first line chemotherapy treatments are based on injectable pentavalent antimonials (Pentostam® and Glucantime®), which are highly toxic and drug resistance has already proved to be an issue [2].

AmB deoxycholate (Fungizone®) normally considered as second-line drug, which has become the first line therapy in Bihar, India. Following the loss of effectiveness of antimonial drugs, it requires careful and slow intravenous administration due to its high toxicity [3]. Liposomal AmB formulations (Ambisome®) have been developed in order to improve toxicological and pharmacokinetic properties. Virtually, these lipidic formulations reduced toxicity exhibited a better half-life and a higher efficacy in the leishmaniasis treatment. Unfortunately, their high cost and relapse in immunocompetent patients are the major limitations for their large-scale use especially in under developing countries [4].

Oral antineoplastic agent, miltefosine (MIL) was introduced as the first effective oral treatment for VL, and as an alternative treatment for HIV patients [5]. Teratogenic potential and resistance development are the major limitations of MIL in women of child-bearing age [5, 6]. A parenteral formulation of aminoglycoside antibiotic paromomycin (PMM), showed 94% efficacy in clinical trials and introduced for VL in India [7]. A strategy of co-administration of available antileishmanial drugs was carried out by the drugs for Neglected Diseases initiative to provide safety and efficacy for the treatment of VL [8].

It is roughly estimated that of the discovered 17,000 species of plants, nearly 3,000 species are used in the medicinal field. The use of plant extracts and phytochemicals, both with known antimicrobial properties, can be of great significance in therapeutic treatments [9]. Numerous plant derived products from different structural classes have been investigated as antileishmanial candidates including various alkaloids, terpenoids, flavonoids and quinonoid. AG, a labdane diterpene was isolated from the leaves of Indian medicinal plant Andrographis paniculata, exert significant antiproliferative effects on the life cycle of L. donovani, the causative agent of VL [10, 11]. However, this compound has drawbacks, such as low aqueous solubility, poor bioavailability, and short plasma half-life, making their potential development as chemotherapeutic agent prohibitive.

By using Nano Drug Delivery System (NDDS), one can reduce their cytotoxicity side effects, site-directed drug delivery, and aqueous solubility properties, hence contributing to their bioavailability. Leishmania parasites are dimorphic, alternating between promastigote and amastigote form during their life-cycle. In macrophage cells of mammals, Leishmania cells reside and multiply [12]. Fibroblasts play an important role during the chronic phase of parasitic infection due to their inability to sustain parasite killing and may provide a safe target for the parasites in clinically latent diseases [13]. Indeed, phagolysosomal localization of the parasites, prevent drugs from readily diffusing into the target and hence represents a major problem in the development of effective antileishmanial agent. Therefore, the use of NDDS, capable of delivering antileishmanial compounds to infected cells should improve the therapeutic efficacy (therapeutic index) of these drugs and at the same time, reduce the toxicity by altering the pharmacokinetic and bio distribution profile of the drug.

Many NDDS have already been used for antileishmanial compounds [14]. In general, these systems tend to increase drug efficacy while decreasing toxicity, resulting in an improved therapeutic index (TI) [15]. The biggest improvement, the cost-efficacy benefit, is believed to come from nano drug carriers. Recently, polylactide NPs containing basic acid were more effective than microemulsions in an in vivo hamster model of VL [16]. Other example includes AmB-loaded in poly (ε-caprolactone) NPs [17] or in mannose-anchored, PLGA NPs for the efficient delivery of AmB to macrophages [18].

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Received: 18 Aug 2016 Revised and Accepted: 05 Oct 2016
The aim of this study was to develop and characterize a controlled drug delivery system for the treatment of VL, using an in vitro active AG [10, 11]. Therefore, hydrophobic AG was encapsulated in the biodegradable polymer PLGA in order to increase its solubility, reduce cytotoxicity and enhance TL. The physicochemical characterization, the biological evaluation and its delivery system of this new antileishmanial drug were investigated. The AG load PLGA NPs were not able to reduce cellular drug toxicity, retaining it's in vitro antileishmanial activity and improving efficacy by 8 to 10 fold when compared with free AG on L. donovani infected BALB/c mice, in the spleen.

**MATERIALS AND METHODS**

**Animal and ethics statement**

Six-week-old BALB/c mice of either sex, weighing 20–25 g and of approximately the same age were used for the study and they were obtained from a biological supply vendor (Rta Ghosh and Co., Kolkata, India). The experimental protocols were approved by the Jadavpur University Animal Ethics Committee (Id # 11/Pharm./384/11), and procedures followed were in accordance with the Committee for the Purpose of Control and Supervision of Experiments on Animals (CPCSEA) of Government of India and followed the standards as described in the *Guide for the Care and Use of Laboratory Animals*. Animals were housed five per cage for acclimatization one week before experiments at the animal house facility of Jadavpur University. Mice were fed with a standard diet and water ad libitum. Mice were exposed to a normal day and night cycle.

**Experimental materials: medicines and chemical reagents**

PLGA (melt: glycolide = 50:50, molecular weight: 40,000-75000 Da), TPGS, C15H26O10 (CH2 CH2 O) 23, AG, PMM, AmB, MIL, fluorescein 5(6)-isothiocyanate (FITC), medium 199, RPMI 1640, dialysis tubing D9652 (MW cut of 12400) and fetal calf serum (FCS) were purchased from Sigma-Aldrich (USA). Sodium stibogluconate (SSG) was a generous gift from Albert David Ltd. (Kolkata, India). All other chemicals and reagents were reagent grade or higher.

**Equipment and instruments**

Standard glassware of Borosil® were used for experimental purpose. A 700 MW sonicator, model vibra cell vex 750 (Sonics, USA); A 700 MW sonicator, model vibra cell vex 750 (Sonics, USA); a precision balance 0.00001 g; Mettler Toledo ALS4 (Mettler, USA); an ultracentrifuge, Hitachi CS 120 GXHL (Hitachi Koki, Japan) were used in the preparative processes. Chemical analysis was carried out by dual pump HPLC model (UPHPLC, Dionex UltiMate 3000, Thermo Scientific); Zetavisor nano ZS (Malvern, UK); atomic force microscope microscope; AFM: Veeco Nanoscope IIIa, England); and atomic force microscopy (AFM: Veeco Nanoscope IIIa, England). AGnp suspension was a generous gift from Albert David Ltd. (Kolkata, India). All other chemicals and reagents were reagent grade or higher.

**Preparation of PLGA NPs containing AG**

The encapsulation of AG in PLGA NPs was obtained by emulsion solvent evaporation method as described previously by Roy et al. [10]. Briefly, 100 mg PLGA and 5 mg of AG were dissolved in 6 ml chloroform. This suspension was centrifuged at 30000 r. p. m. for 20 min. The drug-loaded NPs were dispersed in phosphate buffered saline (PBS) (0.1 M, pH 7.4 or pH 5.5) and were then placed in an orbital shaker, shaking at 300 r. p. m. at 37 °C. At designated time intervals, the suspension was centrifuged at 30000 r. p. m. for 20 min. The pellet was resuspended in the corresponding fresh buffer to continue the drug release, and the supernatant was used for drug quantification. The quantity of AG was determined by the same HPLC procedure as mentioned above. The error bars were obtained from the triplicate samples.

**Preparation of fluorescein-loaded PLGA NPs (FITCnp)**

FITC was used as a model drug and was encapsulated into PLGA NPs by emulsion solvent evaporation method described above. FITC was dissolved in dimethylformamide (DMF) at 100 mg/ml and 0.1 ml of solution was added into 10 mg of polymer in 2 ml of chloroform, and rest of the process was performed as described above.

**Drug encapsulation efficiency and drug loading**

AG nanof ormulations were evaluated in terms of encapsulation efficiency (EE), according to equation (1).

\[
EE (\%) = \left( \frac{\text{Mass of AG originally taken} - \text{Mass of AG in supernatant}}{\text{Mass of AG originally taken}} \right) \times 100 (1)
\]

Estimation of AG in all cases was carried out by a reverse phase HPLC system. The mobile phase was acetonitrile (0.1% v/v) and phosphoric acid in water (40:60 v/v) at a flow rate of 1 ml/min. The analysis was carried out by using 250 X 4.6 mm C18 column. A peak area (y) vs. concentration (x) graph for AG was first prepared, y = 30145, x = 68911, R^2 = 0.9930, retention time was 4.5 min. This was used to detect AG concentration throughout. Mass of AG in solution before and after nanoparticulation in the supernatant was determined by HPLC experiments for calculation of entrapment efficiencies [11].

**In vitro drug release assay**

The drug-loaded NPs were dispersed in phosphate buffered saline (PBS) (0.1 M, pH 7.4 or pH 5.5) and were then placed in an orbital shaker, shaking at 300 r. p. m. at 37 °C. At designated time intervals, the suspension was centrifuged at 30000 r. p. m. for 20 min. The pellet was resuspended in the corresponding fresh buffer to continue the drug release, and the supernatant was used for drug quantification. The quantity of AG was determined by the same HPLC procedure as mentioned above. The error bars were obtained from the triplicate samples.

**Cell culture**

The mice peritoneal monocyte cells were grown at 37 °C with 5% CO2 in RPMI 1640 medium, complemented with 10% heat-inactivated fetal bovine serum, 2 mmol L-glutamine, 100 U/ml penicillin and 100 µg/ml streptomycin. For macrophage differentiation, mice monocyte cells were incubated in the presence of 20 mg/ml phorbol-12-myristate-13-acetate (PMA, Sigma-Alrich) for 18 h at 37 °C and left another 24 h with fresh medium containing no PMA to induce maturation.

**Cellular uptake of FITC-loaded NPs**

In order to study nanoparticle uptake in macrophage cells, the desired cell concentration (3 X 10^6 cells/well) was seeded with FITCnp (0.5 mg/ml). After incubation of specific times in CO2 incubator at 37 °C, cells were washed twice with PBS to eliminate unbound NPs, centrifuged (1000 r. p. m., 5 min) after trypsinization, then suspended in 0.5 ml of PBS and observed in FITC channel under fluorescence microscope.
Parasite and culture conditions

*L. donovani* AG83 (MHOM/IN/83/AG83) was VL isolate obtained as a gift from Indian Institute of Chemical Biology, Council of Scientific and Industrial Research, Kolkata, India. *L. donovani* AG83 promastigotes were grown at 25 °C in medium 199 supplemented with 10% heat-inactivated fetal bovine serum, 2 mmol L-glutamine, 20 mmol HEPES, 100 U/ml penicillin and 100 µg/ml streptomycin. *L. donovani* axenic amastigotes were derived from promastigotes by culturing them in MMA/20, pH 5.5 (medium for axenic amastigotes) culture medium as described previously [10]. Amastigotes were maintained in culture, at 37 °C in an atmosphere of 5% CO2 by sub-passage (105 parasites/ml), every 5 d.

Evaluation of drug susceptibility on intracellular *L. donovani* amastigotes

The growth of the AG83 wild-type amastigotes on the mouse macrophages was evaluated as described [11]. Briefly, adherent cells grown in 24-well plates at 37 °C with 5% CO2 were incubated with stationary-phase promastigotes for 4 h at 37 °C at a 1:5 cell:parasite ratio. After the parasite internalization period, cells were washed at least twice with fresh media to remove non-phagocytosed parasites and kept with variable concentrations of free AmB, SSQ, PNM, MIL, AG or AGnp for 72 h. The amastigote number in macrophages was assessed after staining with Giemsa. 100 cells on the glass disks were counted by inverted microscope. Three independent experiments in triplicate for each concentration were performed for the efficacy of drugs and NPs. Results were presented as the ratio between the infection proportions of treated and untreated macrophage cells. Drug concentration necessary to decrease the number of intracellular amastigotes to 50%, inhibitory concentration 50% (IC50) was determined by linear regression analysis.

Cytotoxicity assay and selectivity index

Macrophages cells were cultured in RPMI-1640 supplemented with 10% FCS, 20 mmol L-glutamate, 16 mmol NaHCO3, penicillin (50 U/ml) and streptomycin (50 µg/ml). The assay was performed in 24-well tissue culture plates in the presence of standards of macrophages. The wells were seeded with test solutions, and the viable macrophages were counted microscopically.

A key part of drug discovery and development is the characterization and optimization of the safety and efficacy of drug candidates and to identify those that have an appropriately balanced safety-efficacy profile for a given indication. The selectivity index (SI) which is typically considered as the highest exposure to the drug that results in no toxicity to the exposure that produces the desired efficacy, is an important parameter in efforts to achieve this balance. In the present study, the degree of selectivity of the drug or its formulation is expressed as SI = cytotoxicity (CC50%) of a drug or its formulation in a macrophage cell line/IC50 of the same drug or its formulation, where CC50 is the concentration required to kill 50% of the host cell population and IC50 is the concentration required to kill 50% of the parasites inside the host cell. When the SI value is ≥10, that drug or formulation will present promising activity, that is higher than its CC50 [19].

**In vivo studies**

For infection of mice, stationary phase promastigotes of AG83 wild-type were collected, washed and suspended with sterile PBS. A volume of 200 µl of sterile PBS containing 107 parasites was injected through tail-vein, which will lead to a systemic distribution of parasite throughout the body. The mice from all infected groups were treated after 45 d of infection by intraperitoneal injection of 200 µl membrane sterilized drug solutions or nanoformulation. Dosing schedule was either one dose/day for 5 consecutive days or a gift from Indian Institute of Chemical Biology, Council of Scientific and Industrial Research, Kolkata, India.

**Results**

Experimental results were expressed as mean±standard deviation. Student’s t-test was used to calculate the statistical difference of mean values. Differences were considered significant at a level when p<0.01. For toxicity studies, an unpaired t-test was used to compare groups. A p value<0.05 was considered to be statistically significant.

**RESULTS**

The physicochemical characteristics of the formulated nanoparticles such as particle size, polydispersity, ζ-potential and drug encapsulation efficiency are summarized in table 1. Among the various physicochemical properties of NPs, the drug loading particle size and surface property may be the most important parameters that determine theirs in vitro and in vivo performance [15]. The NPs were prepared from the PLGA by emulsification solvent diffusion method. The optimized amount of 0.04% (w/v) of TPGS used as an emulsifier exhibited negative surface charge (-35.8 mV) indicating near stable dispersion of NPs with a narrow size distribution (171.4±11.5 nm) identical to unloaded PLGA NPs (168.5±10.3 nm) (table 1).

The polydispersity index characterizes the nanoparticulate system in terms of size homogeneity by a value of the relative variance of sizes in a NP population [21]. The characterization of the unloaded and AG loaded NPs by TEM and AFM (fig. 1 and 2, respectively) showed a monodispersed size distribution and good re-dispersibility suggesting that their surface is stabilized by the deposition of TPGS, which prevent aggregation. Before release study, AGnp showed no change or perforation at the surface (fig. 2A). Whereas AGnp showed cleavage perforation at the surface (fig. 2B) after 600 h release study.

**Table 1: Size, polydispersity index and ζ-potential characterization of nano-formulations**

| Nanof ormulations | Size (nm) | Polydispersity Index | ζ-potential (mV) | Encapsulation efficiency (%) |
|-------------------|-----------|----------------------|-----------------|--------------------------|
| Empty PLGA NP s    | 168.5±5  | 0.24±0.03            | 38.3±1.7        | NA                       |
| AGnp              | 171.4±11.5* | 0.23±0.02         | -               | 81.1±3.4               |

*Results are expressed as mean±SEM, (n=4). *p<0.001, statistically significant difference when compared with empty NPs. NA: Not Applicable.

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Furthermore, storage stability studies revealed that the physical structure of the NPs is stable up to 3 mo at 4 °C [11]. The release profile of AGnps under physiological (7.4) pH and acidic (5.5) pH (similar to the phagolysosome) are shown in fig. 3.

It was found that a significant initial burst release profile was obtained for both conditions during the first half day. Especially, in the case of pH 5.5, AGnps released approximately 50% of its content over the first day of the study, while under the physiological pH the same quantity was released after 1 w. After the initial burst release, there was a phase of constant AG release. The AG release from PLGA NPs reached a plateau after 150 h. We have investigated the in vitro antileishmanial activity of standard antileishmanial drug; AmB, SSG, PMM and MIL along with free AG and AGnp against intracellular wild-type L. donovani amastigote cells and compared their CC50 in macrophage cells (table 2).

Table 2: Antileishmanial activity profile of standard antileishmanial drugs, AG and AGnp against intracellular L. donovani wild-type amastigote cell line

| Drug   | Cellular AG83 evaluation model | CC50 µM (Macrophage cells) |
|--------|-------------------------------|----------------------------|
|        | Wild-type                     | SI                         |
| AmB    | 0.14±0.05*                    | 93                        |
| SSG (SbV)b | 1.5±0.20                   | 17                        |
| PMM    | 7±2*                          | 34                        |
| MIL    | 0.3±0.04*                     | 97                        |
| AG     | 13±20*                        | 7.1                       |
| AGnp   | 26±2*                         | 73                        |

Results are expressed as mean±SD, (n=4). Assays are described in Materials and Methods. Values for antimonials agents are in µg SbV/ml, SI. Selectivity Index was CC50/IC50, *p<0.01, significant difference compared with SSG, **p<0.05, no significant difference compared with SSG.

Table 3:

| Drug  | Murine model | CC50 µM (Macrophage cells) |
|-------|--------------|----------------------------|
| AmB   | 0.34±0.04    | 97                        |
| SSG   | 1.5±0.20     | 34                        |
| PMM   | 7±2          | 97                        |
| MIL   | 0.3±0.01     | 7.1                       |
| AGnp  | 26±2         | 73                        |

Results are expressed as mean±SD, (n=4). Assays are described in Materials and Methods. Values for antimonials agents are in µg SbV/ml, SI. Selectivity Index was CC50/IC50, *p<0.01, significant difference compared with SSG, **p<0.05, no significant difference compared with SSG.

Using a homogenization solvent evaporation technique, FITC-loaded PLGA NPs were obtained with 173±10.7 nm and -36±1.8 mV, characteristics identical to AGnp, and those were used to evaluate cellular uptake of FITCnps by macrophage cells. Fluorescence microscopy was applied to confirm the internalization of the FITC-loaded PLGA NPs by macrophages (fig. 4).

Macrophage cells under investigation exhibited increasing FITC fluorescence intensity from 15 min to 60 min. In the present study, the effect of AG and AGnp were evaluated using the acute murine model of VL by treating the mice at 6 w post infection with AG, AGnp and AmB or SSG as the positive control (table 3 and 4).
AGnp have demonstrated significant advantages compared to free AG in reducing cellular toxicity (CC50) and increasing SI. These polydispersity index values being less than 0.3 (table 1), indicating proven effective in reducing the toxicity of the drug [13, 15]. The AmB and MIL followed by AGnp were most selective for wild AG83 strains when evaluated in vivo.

Results are expressed as mean±SEM, (n=5), ip: intraperitoneal, *p<0.001, significant difference compared with SSG, **p<0.5, no significant difference compared with SSG.

| % Suppression of amastigote burden | Drug | Dose, ip mg/kg/week | Dosing (number of week) |
|-----------------------------------|------|----------------------|-------------------------|
|                                   | SSG (SBw) | 40                    | 4                       |
|                                   | AG       | 2                    | 2                       |
|                                   | AG       | 2                    | 4                       |
|                                   | AGnp     | 2                    | 2                       |
|                                   | AGnp     | 2                    | 4                       |

Table 4: Antileishmanial activity profile of standard antileishmanial drugs, AG and AGnp on the parasite burden of L. donovani wild-type amastigote cell line in mice

| ED50 mg/kg | Antileishmanial drug and nanoformulation | Route of administration (consecutive dose) | AG83 evaluation model | LD50 (mg/kg)* |
|-----------|----------------------------------------|------------------------------------------|----------------------|--------------|
|           | AmB                                    | 5 x ip                                   | 0.3±0.06*            | 90           |
|           | SSG (SBw)*                             | 5 x ip                                   | 9.5±2.21             | 8.9          |
|           | AG                                     | 5 x ip                                   | 17±4.32**            | 618          |
|           | AGnp                                   | 5 x ip                                   | 3.6±0.77**           | 6111         |

Results are expressed as mean±SEM, (n=5), *Determination of 50% suppression of parasite burden in spleen of mice by drugs (ED50) are described in Materials and Methods and defined as the dose that produces a quantal effect in 50% of the population that takes it, **Determination of 50% death of mice by drugs (LD50) are described in Materials and Methods. Therapeutic Index (TI) is a quantitative measurement of the relative safety of drugs, which is the ratio of LD50/ED50. Values for sodium stibogluconate are in mg SBG/kg as given in Materials and Methods, *p<0.001, significant difference compared to stibogluconate, **p<0.5, no significant difference compared to stibogluconate.

Weekly intraperitoneal administration of all the treatments showed a significant (p<0.001) lower parasite burden in the visceral organs, spleen and liver when compared with the mice in control groups that received either PBS/DMF or empty PLGA NPs (table 4).

**DISCUSSION**

The multidisciplinary field of nanotechnology is bringing the science of the almost incomprehensibly small device closer and closer to reality. Nanotechnology offers the ability to build large numbers of products that are incredibly powerful by today's standards [22].

VL can be caused either by L. donovani (in Asia and Africa) or L. infantum (in southern Europe). In this study, L. donovani was selected for the development of the new antileishmanial nanof ormulation, since it has been the objective of our research. For the therapeutic application of an antileishmanial agent, high selectivity compared to its host cell is the primary requirement. Selectivity is expressed in terms of selectivity index (SI). To be a safe drug, SI should be greater than 10 [19]. It appears from table 2 that AmB and MIL followed by AGnp were most selective for wild AG83 strains when evaluated in vitro in intracellular amastigotes. The AGnp have demonstrated significant advantages compared to free AG in reducing cellular toxicity (CC50) and increasing SI. These results are in accordance with other in vitro and in vivo studies, in which the encapsulation of a compound into a nanocarrier was proven effective in reducing the toxicity of the drug [13, 15]. The polydispersity index values being less than 0.3 (table 1), indicating that the NPs were of relatively uniform size. The encapsulation of AG into the NPs, resulted in a statistically significant (p<0.01) decrease in the negative surface charge (table 1) indicating in vitro stable dispersion of NPs. In general, it is thought that NP suspension with large positive or negative ζ-potential values (± ±30 mV) are less likely to suffer from aggregation phenomena due to electrical repulsion. Upon the in vivo administration, the physiological condition will mask the almost neutral surface charges of the nanof ormulations, contributing to the equilibrium of the system. Drug loading of the nanof ormulations was optimized to control the size of NPs. Due to the fact that the amount of encapsulated drug is crucial in a drug delivery system, high drug loading rate is desirable to reach therapeutic necessities. Optimized AGnp was prepared with a drug loading of 8% (w/w) and an encapsulation efficiency of 81.1±3.4. The high encapsulation efficiency obtained is a consequence of hydrophobic nature of the AG. The treatment with the AGnp was significantly more effective than free AG in reducing parasite burden in spleen and liver, at an equivalent drug dose of 2 mg/kg/week either for 2 w or 4 w for wild-type L. donovani. Most strikingly, AGnp at 2 mg/kg/week dose for 4 w showed 99.9% lowering of parasite burden in both spleen and liver infected with wild-type L. donovani. Therapeutic applicability of any chemotherapeutic agent depends on its safety which is quantitatively expressed as a therapeutic index (TI). TI is the ratio of LD50/ED50. Values for sodium stibogluconate are in mg SBG/kg as given in Materials and Methods, *p<0.001, significant difference compared to stibogluconate, **p<0.5, no significant difference compared to stibogluconate.

**RESULTS**

Weekly intraperitoneal administration of all the treatments showed a significant (p<0.001) lower parasite burden in the visceral organs, spleen and liver when compared with the mice in control groups that received either PBS/DMF or empty PLGA NPs (table 4).

**CONCLUSION**

In conclusion, the in vivo activity data exhibited by AGnp provides evidence that intraperitoneal administrations to mice very efficiently reduced parasite burden in the visceral organs of acute infected BALB/c mice. A facile approach to preparing biodegradable, biocompatible, and FDA approved PLGA NPs with high drug load and encapsulation efficiency of AG using the homogenization solvent evaporation method is described. Fluorescence microscopic observation provides compelling evidence for complete internalization of FITC-PLGA NPs in macrophages, which are the host of Leishmania amastigotes. Interestingly, AG-loaded NPs turned out to be the most effective and selective in killing intracellular L. donovani amastigotes in macrophage cells model than first and second line antileishmanial drugs. In vitro results translate well into the in vivo model of visceral leishmaniasis, whereas phagocytic macrophage cells are the major constituent of visceral organs. Indeed, AG-loaded PLGA NPs were very efficient in reducing parasite burden in the visceral organs of acute infected BALB/c mice. Acute
and subacute toxicity profile of AGnp were much less than the free AG, and first and second antileishmanial drugs. In summary, we showed that AGnp has great advantages as a delivery system for AG, providing controlled, effective and safe delivery for treatment of visceral leishmaniasis.

ACKNOWLEDGMENT

This study was supported by funding from Indian Council of Medical Research (ICMR) (Grant No. AMR/48/2011-ECD-I), New Delhi, India. Mr. Pallab Ghosh and Dr. Subhasish Mondal were awarded Senior Research Fellowship and Research Associateship respectively from ICMR to carry out this research work. We would like to thank Dr. Shyamol Roy of Indian Institute of Chemical Biology, Kolkata, India for his aid to procure Leishmania AG83 strain.

CONFLICT OF INTERESTS

We declare that we have no conflict of interest.

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How to cite this article

- Pallab Ghosh, Subhasish Mondal, Tanmoy Bera. Preparation and characterization of andrographolide nanoparticles for visceral leishmaniasis chemotherapy: in vitro and in vivo evaluations. Int J Pharm Pharm Sci 2016;8(12):102-107.