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Article type: Original Article

Received: 23 November 2023

Accepted: 22 January 2024

Published online: 13 February 2024

eISSN: 2544-1361

Eur J Clin Exp Med

doi: 10.15584/ejcem.2024.2.8

Encapsulation of genistein in glycidylated G3 polyamidoamine dendrimers enables diffusion of genistein through biological membranes and anti-nematode activity of the encapsulate

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ABSTRACT

Introduction and aim. Poorly soluble isoflavonoid genistein is known as an anti-nematode agent and also it decreases the risk of certain types of cancer. The biological activity of genistein is limited mostly by its low solubility. Therefore many attempts to increase genistein solubility in water were reported. We applied a polyamidoamine dendrimer, modified its surface by glycidylation, and used this macromolecule as a guest for genistein.

Material and methods. Polyamidoamine dendrimer 3rd generation was substituted with 64 glycidol residues to obtain a macromolecule host for genistein. The stoichiometry of this host-guest complex was determined. The complex was tested for skin model permeability, toxicity on fibroblast (BJ) and keratinocyte (HaCaT) cell lines *in vitro* and anthelmintic activity on the *Caenorhabditis elegans* nematode.

Results. The partition coefficient of genistein between octanol and water was determined ($K_{O/W}$). The 1:1 host-guest complex was isolated and used as drug delivery system for genistein delivery. PAMAM G3 glycidyled dendrimer containing genistein indicated an anthelmintic activity at 50 μ M concentration.

Conclusion. The solubility of genistein in water increases 640 times in presence of an equimolar concentration of the dendrimer. One molecule of host dendrimer encapsulates 3 molecules of genistein. The encapsulate is an efficient anti-nematode formulation.

Keywords. *C. elegans*, fibroblast BJ toxicity, genistein, keratinocyte HaCaT toxicity, PAMAM dendrimer

Introduction

Genistein (5,7-dihydroxy-3-(4'-hydroxyphenyl)chromen-4-one) is a trihydroxyisoflavone (Fig. 1) which is considered as a phytoestrogen of rather low bioavailability due to its hydrophobic character.¹ Soy based diets deliver isoflavonoids (IFLs) into the digestion system. Among them, genistein (GEN) and its 7-O-glucosides are absorbed in the small intestine (10%) within the first 2 hours and then in the large intestine (90%) within 4-6 hours, where gut bacteria release GEN. Detailed studies (absorption, distribution, metabolism, and excretion) of IFLs after soy intake were performed based on urinary and plasma levels of IFLs.¹ Biological activity of IFLs in humans is rather low. Generally IFLs are suggested to protect against many chronic diseases (including coronary heart diseases, subclinical atherosclerosis, type 2 diabetes), and decrease the risk of certain types of cancer such as breast and prostate cancers.

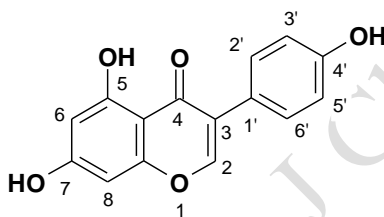


Fig 1. Formula of GEN with atom numbering

On the other hand, IFLs including GEN are anti-nematode agents. IFLs were demonstrated to impede soybean cyst nematode (SCN) by influencing sex ratios and the number of female eggs. GEN was shown to strongly influence the physiological index of SCN in a dosage and time dependent way.² When SCNs were exposed to 0.37 mM GEN (100 µg/mL) aqueous solution (with 1% DMSO), a 50% reduction of SCN mobility (measured by reversal frequency assay), ca 35% reduction of oxygen consumption, and severe body leaking after 24 hours treatment were observed.

Another nematode model organism, a transgenic A β -expression *Caenorhabditis elegans* strain CL4176 was used to determine the ability of IFLs to alleviate A β expression-induced paralysis in *C. elegans*, which correlated with a reduced level of hydrogen peroxide and β amyloid.³ This relationship was observed only for glycitein, not for GEN. The authors concluded that the neuroprotective effect of phytoestrogens is due to their anti-oxidative activities.

Inspired by the potential health beneficial effects of GEN intake and reported high membrane permeability of GEN across Caco-2 cell monolayers and effective efflux of GEN,⁴ Shen et al. designed a Drug Delivery System for GEN delivery.⁵ GEN was entrapped in micelles prepared from Soluplus® and α -Tocopheryl polyethylene glycol 1000 succinate (TPGS) in order to improve GEN solubility and thus oral bioavailability of GEN. Micelles 185 nm in size were loaded with GEN up to almost 4% DL and then tested *in vitro* for

GEN delivery. Thus, GEN was dispersed in the mixed micelles (M) to an apparent concentration of 1.5 mg/mL, while GEN solubility in water is much lower (1.3 µg/L).⁶ GEN was released from GEN-M dissolved in methanol in dialytic conditions into saline buffer with surfactants with 4-fold higher efficiency than GEN alone. The apical-basolateral permeability through Caco-2 cell monolayer was slightly higher for GEN-M than that for GEN, which resulted in decrease in efflux ratio from 0.84 for GEN into 0.73. Finally, the pharmacokinetic studies on rats revealed the 4-fold increase of GEN levels in plasma with a maximum at 0.7 hour for GEN-M in comparison with 1.0 hour T_{max} for GEN alone. Many other DDSs for GEN delivery were discovered, which slightly improved solubility and permeability of GEN, and the subject was recently reviewed.⁷

Aim

We have designed the DDS for GEN delivery based on a modified polyamidoamine (PAMAM) dendrimer generation 3. The native dendrimer was used before to encapsulate riboflavin and 8-methoxypsoralene for transdermal delivery.^{8,9} However, recently, we modified the G3 dendrimer by glycidylation in order to eradicate primary amine groups of native G3.¹⁰ Those G3^{gl} dendrimers were very well soluble in water and efficiently internalized into normal human fibroblasts and two cancer lines within 1 hour.

Material and methods

Materials

Genistein (>98% purity) was purchased from Merck KGaA (Darmstadt, Germany). Third generation polyamidoamine dendrimer (G3) was synthesized according to Tomalia's protocol and then modified by conversion of primary amine groups into bis-2,3-dihydroxypropylamine groups as was described before to yield G3^{gl} (molecular weight 11645 Da).^{10,11} HaCaT keratinocytes were purchased from CLS Cell Lines Service GmbH (Eppelheim, Germany) and BJ normal human fibroblasts from American Type Culture Collection (Manassas, VA 20108, MA, USA). Dulbecco's Modified Eagle Medium supplemented with sodium pyruvate, L-glutamine, high glucose (DMEM) was provided by Biological Industries (Cromwell, CO, USA), and fetal bovine serum by Gibco (Waltham, MA, USA). Penicillin and streptomycin solution, phosphate-buffered saline (PBS) with and without magnesium and calcium ions were provided by Thermo Fisher Scientific Inc. (Waltham, MA, USA). Trypsin-EDTA solution, 0.4% trypan blue solution, dimethylsulfoxide (DMSO) for molecular biology, 5-fluoro-2'-deoxyuridine (FUdR) and other chemicals and buffers were purchased from Merck KGaA (Darmstadt, Germany). Alamar Blue test was purchased from Sigma, (Life Technologies, Bleiswijk, The Netherlands). Cell culture dishes and materials were from Nunc (Roskilde, Denmark), Corning Inc. (New York, NY, USA) or Googlab Scientific (Rokocin, Poland). Reagents used to culture of *C. elegans* nematode were supplied by Sigma-Aldrich (Saint Louis, MO, USA) or Carl Roth GmbH & Co., KG (Karlsruhe, Germany).

Methods

The 1-D ^1H and ^{13}C NMR spectra and 2-D ^1H - ^1H correlations spectroscopy (COSY), ^1H - ^{13}C heteronuclear single quantum correlation (HSQC), and heteronuclear multiple bond correlation (HMBC) spectra were recorded in DMSO- d_6 using Bruker 300 MHz instrument (Rheinstetten, Germany) at College of Natural Sciences, University of Rzeszow.

UV-Vis spectra were recorded with Hitachi U-1900 spectrometer (Tokyo, Japan).

The permeation GEN and GEN@G3^{gl} was studied using Franz diffusion assembly (Thermo Scientific (UK) model DC 600) equipped with 6 cm³ acceptor compartments. Polyvinylidene fluoride (PVDF, 0.125 mm thickness) or prepared rabbit skin (RS, 0.55 mm thickness) model membranes were used for permeation studies.

Partition of GEN between octanol and water containing host G3^{gl}

Analytical protocols used in partition experiments and transdermal diffusion experiments (vide infra) required determination of extinction coefficients in various solvents. The UV-vis spectra were taken in water, ethanol, octanol, and in 70% aqueous phosphate buffered pH 7.4 and 30% ethanol (receiving solution in diffusion tests) are shown at Figure 2.

Solubility of GEN in octanol was determined by suspending 5.1 mg GEN in 5 mL octanol, stirring the mixture at 25 °C for 12 hours, filtration off the undissolved octanol, and determination of GEN concentration using previously determined extinction coefficient at 336 nm, $\epsilon_{336} = 3.52 \times 10^3 \text{ mol}^{-1} \times \text{dm}^3 \times \text{cm}^{-1}$. Finally, the 3.77 M concentration of GEN in octanol saturated solution was elucidated.

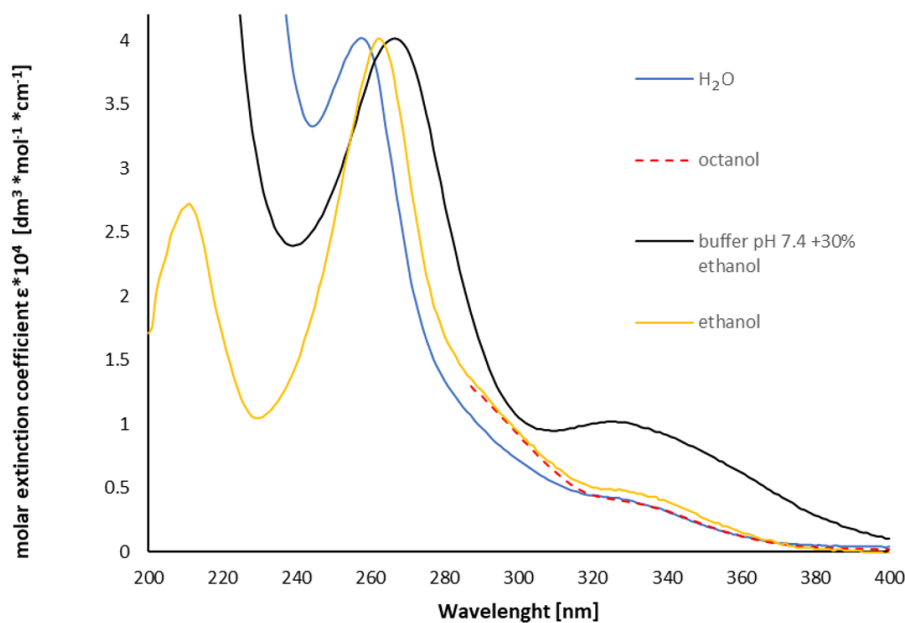


Fig. 2. The UV-Vis spectra of GEN in various solvents. Only part of GEN spectrum in octanol is shown (dashed line) due to high absorption of octanol below 290 nm

In o/w partition experiments, 60 mM solutions of GEN in octanol was prepared. Several partition experiments were performed by equilibration of 10 ml GEN in octanol against 10 ml of water, 0.21 mM G3^{gl} (aq), 0.63 mM G3^{gl} (aq), 0.63 mM G3^{gl} (aq), 1.91 mM G3^{gl} (aq), and 5.70 mM G3^{gl} (aq) with vigorous magnetic stirring at 25°C for 48 hours. Then, the aqueous and octanol phases were separated and concentration of GEN in octanol ($\lambda=336$ nm, $\epsilon_{336}=3.52\times 10^3$ mol⁻¹ \times dm³ \times cm⁻¹) and in water ($\lambda=255$ nm, $\epsilon_{255}=3.82\times 10^4$ mol⁻¹ \times dm³ \times cm⁻¹) were determined spectrophotometrically. Thus the partition coefficients $\log K_{ow}=\log(c_o/c_w)$ were obtained in function of concentration of G3^{gl}. The results are presented graphically in the Figure 3.

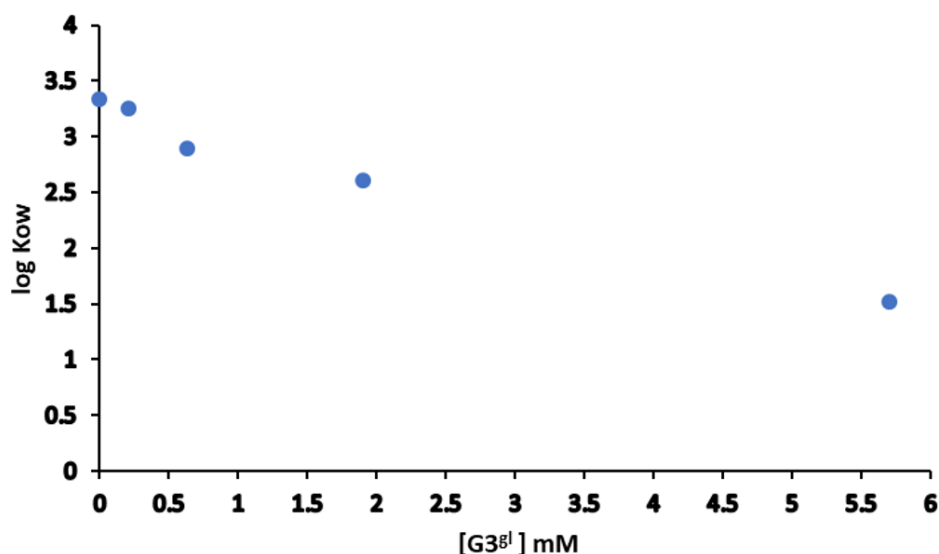


Fig. 3. The values of octanol/water partition coefficient in function of concentration of the host dendrimer G3^{gl} in the water phase

Transdermal permeation of GEN and GEN@G3^{gl} encapsulate

To analyze the ability of GEN to diffuse through skin models, synthetic polyvinylidene fluoride (PVDF) and prepared rabbit skin (RS) were studied using hydroxyethylcellulose-based hydrogel as delivery form and a mixture of phosphate-buffered water pH 7.4 (70 %) and ethanol (30 %) as receiving solutions. The ability of GEN (guest) to release from the dendrimer (host) and from hydrogel followed by permeation of skin model was monitored spectrophotometrically at 266 nm (λ_{max} , $\epsilon_{266}=4.0\times 10^4$ mol⁻¹ \times dm³ \times m⁻¹). The delivery gels were prepared as follows: 1:1 G3^{gl} : GEN solution was prepared by dissolving 0.7386 g G3^{gl} in 4.0 ml water, 17.1 mg GEN in 1.5 mL ethanol and mixing the solutions. The mixture was stirred at 50°C for 2 hours and then cooled to room temperature. The final concentrations of GEN and G3^{gl} were both 11.5 mM. In the meantime, the hydrogel was prepared by addition of 0.75 g hydroxyethylcellulose to phosphate-

buffered water (25 mL). After homogenization, 0.5 mL of 11.5 mM GEN or G3^{gl}: GEN solution was added to freshly prepared gel and homogenized rapidly to obtain the delivery system. Typically 0.32 g of delivery sample was mounted topically on membrane of a Franz chamber filled with 6 ml receiving solution below the membrane (PVDF or RS). The initial amount of GEN in the mounted sample was between 16 and 20 µg (ca 75 nmoles) and equimolar amounts of G3^{gl}. The receiving solution (6 mL) was removed in 2 hr time intervals and replaced with new portions. The concentration of GEN in receiving solution was quantified by measurements of absorption at 266 nm. The results are presented as cumulative percentage of released GEN in time for PVDF and RS vs time (vide infra).

Cell cultures

BJ human normal skin fibroblasts, doubling time 1.9 day, and HaCaT human immortalized keratinocytes, doubling time 24 hours, were propagated in a DMEM medium supplemented with 10% FBS, and 100 U/ml penicillin, 100 µg/ml streptomycin. Cells were cultured at 37°C in 5% CO₂ atmosphere and 95% humidity, with growth medium changed every 2–3 days and passaged at 60–80% confluence, using 0.25% trypsin-0.03% ethylenediaminetetraacetic acid in PBS (calcium- and magnesium-free). Cell morphology was checked under the Nikon Eclipse TE2000 inverted microscope (Tokyo, Japan) equipped with phase contrast. The number and viability of cells were estimated by the trypan blue exclusion test, with Automatic Cell Counter TC10™ (Bio-Rad Laboratories, Hercules, CA, USA).

Cytotoxicity of GEN, G3^{gl} and GEN@G3^{gl} encapsulate

Alamar Blue assay

BJ or HaCaT cells were seeded in flat-bottom 96-well culture plates at a density of 1×10^4 cells/well (200 µL cell suspension/well) and allowed to attach for 24 hours. After culture medium removal, GEN, G3^{gl} and GEN@G3^{gl} in the concentration range 1–100 µM were added (100 µL/well) and incubated for 24 hours. Then, tested drugs solutions (GEN, G3^{gl} and GEN@G3^{gl}) were aspirated and 60 µM resazurin solution was added (100 µL/well). The plates GEN@G3^{gl} were incubated at 37°C for 2 hours. After that, the fluorescence was measured at $\lambda=570$ nm with a microplate reader (Thermo Fisher Scientific, Waltham, MA, USA). The control sample were cells (BJ and HaCaT separately) grown in DMEM medium without addition of tested samples, for which viability was assumed to be 100%. An experiment was performed in three independent assays in triplicate.

Toxicity against Caenorhabditis elegans

The *C. elegans* nematode wild-type culture (strain N2, variety Bristol) was used to estimate the *in vivo* activity of the G3^{gl} and GEN@G3^{gl} as described earlier.¹² After the transfer of nematodes to a 96-well plate (about 20 individuals in 50 µL), the solutions of the studied compounds in a complete medium were added

(50 $\mu\text{L}/\text{well}$). The maximal DMSO final concentration was equal to 0.2% and had no significant influence on nematode viability. Five replicates were made for each concentration. The plate was incubated at 21 $^{\circ}\text{C}$ for seven days. During this time, live and dead worms were counted under an inverted microscope (Delta Optical IB-100).

Statistical analysis

To estimate the differences between treated samples and non-treated controls for the cell culture assays, a nonparametric Kruskal–Wallis test was performed because the data did not show signs of a normal distribution. To analyze differences in nematode viability between the control and the nematodes incubated with dendrimer and encapsulate, the Kaplan-Meier estimator was used. Statistically significant differences against the control were determined with Gehan's Wilcoxon test. The $p < 0.05$ was considered statistically significant. Analyses were performed with Statistica 13.3 software (StatSoft, Tulsa, OK, USA).

Results and discussion

Stoichiometry of host-guest encapsulates

Genistein (GEN) was characterized by the 1-D ^1H , ^{13}C , and heteronuclear HSQC, and HMBC NMR spectroscopy. 2-D NMR measurements enabled us to unambiguously assign the ^1H and ^{13}C resonances (Fig. 4).

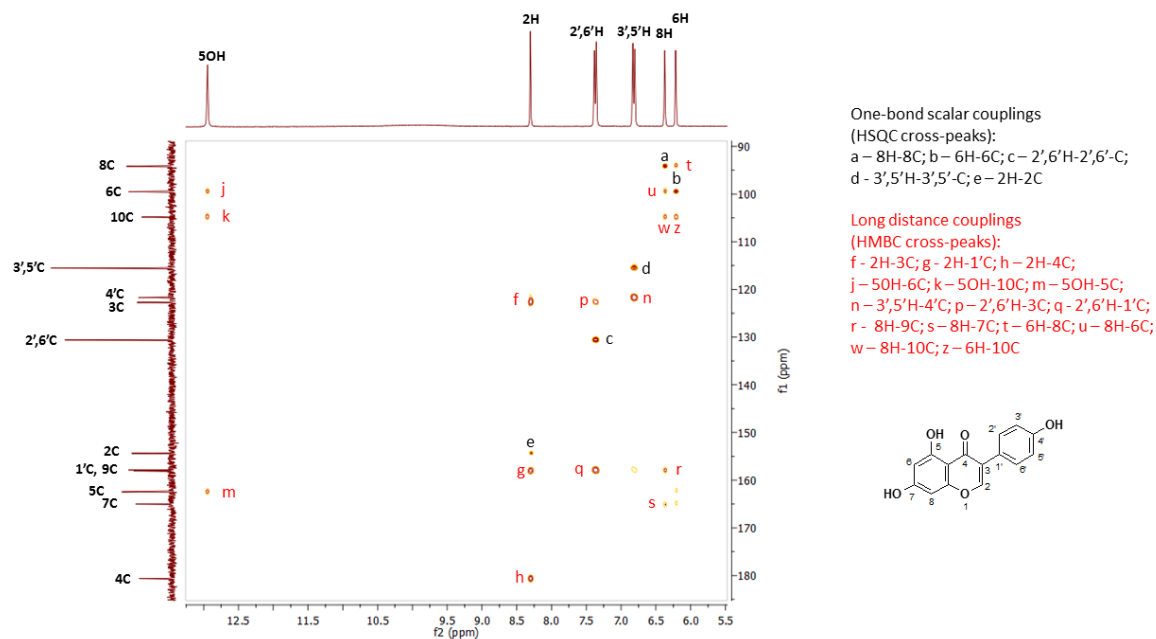


Fig. 4. The 2-D HSQC/HMBC combined map and 1-D spectra of GEN in DMSO- d_6 with spectral assignments. For atom numbering, the semi-structural formula of GEN is shown

Then the G3st dendrimer in D₂O was titrated with GEN in order to determine the ability of the host to encapsulate the guest. The starting spectrum of G3st in D₂O (9 mM) is presented at Figure 5A. To this, a solution GEN in DMSO-d₆ (125 mM) was added stepwise until no precipitate was formed. The ¹H NMR spectra of the solutions are presented at Figure 5, traces B-D. We found that the maximum concentration of GEN in the mixture was 31 mM (Fig. 5D); above this, the GEN (or GEN@G3st encapsulate) precipitated upon addition to the aqueous solution. Thus, we concluded that solubility of GEN in water increased from 4.8 μM to 31×10³ μM concentration in presence of G3st host, i.e. four orders of magnitude. Furthermore, the molar stoichiometry of the GEN@G3st encapsulate was finally at least 3.5:1 GEN:G3st (Fig. 5D).

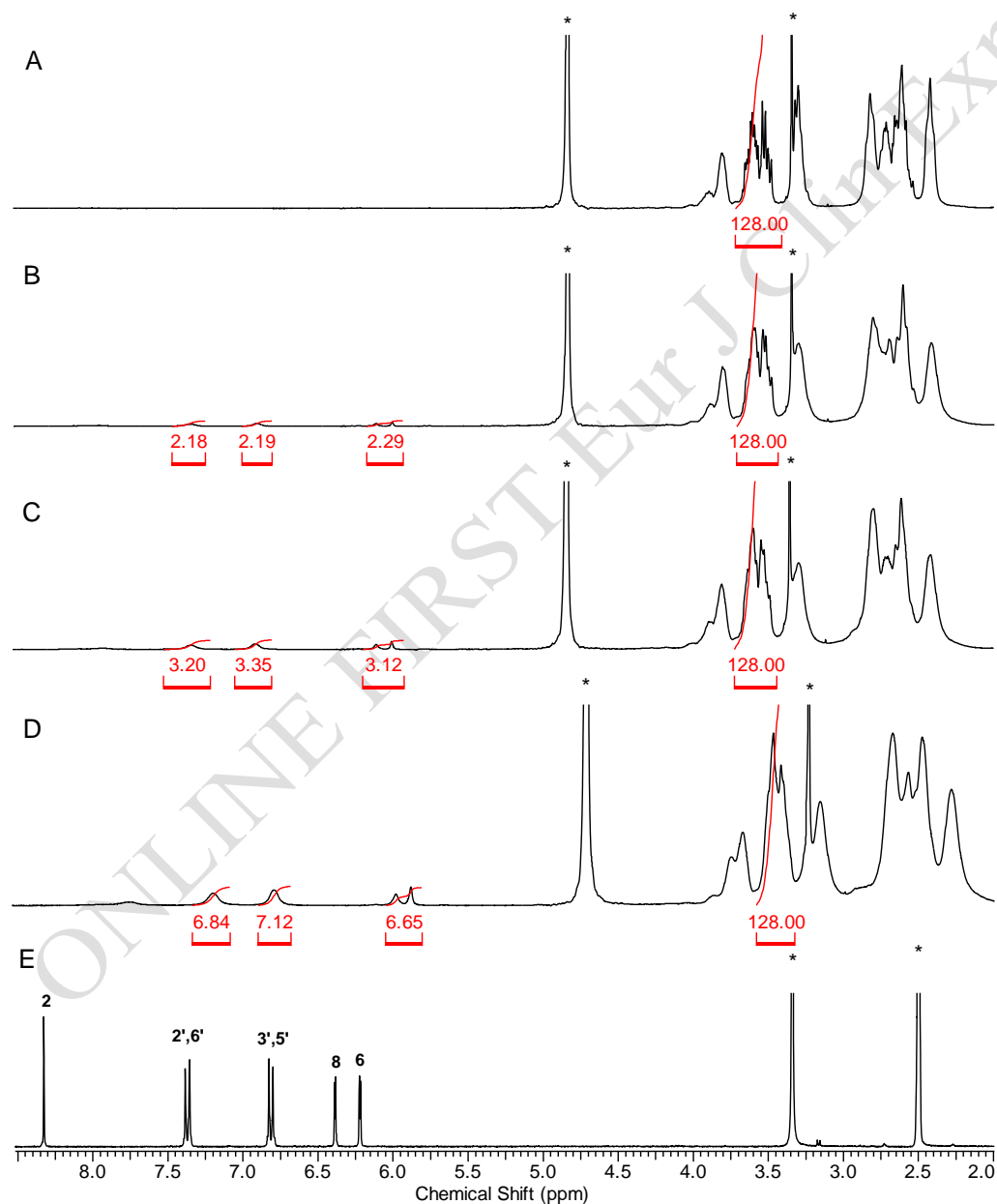


Fig. 5. ^1H NMR titration of G3^{gl} (in D_2O) with GEN (in DMSO-d_6). A – spectrum of G3^{gl} in D_2O (ca 9 mM concentration); B – D: spectra of solution containing G3^{gl} and 1.1, 1.6, and 3.4 equivalents of GEN; E – spectrum of GEN in DMSO-d_6 . The residual resonances of HDO, DMSO-d_5 , and methanol are labeled with asterisks. The [128H] integral intensity signal of 2,3-dihydroxypropyl substituents (64 residues) centered at 3.5 ppm were used as an internal reference

Skin permeation

GEN is known to be highly hydrophobic. We measured the $K_{\text{O/W}}$ parameter using standard procedure of partition between octanol and water.¹³ We obtained $\log K_{\text{O/W}}=3.34$, which was close to the value of 3.04 determined before.¹³ Then we determined the $\log K_{\text{O/W}}$ in presence of various concentrations of the G3^{gl} host in the water phase (Fig. 3). We found that $K_{\text{O/W}}$ decreased almost two orders of magnitude in presence of 5.7 mM G3^{gl} in water phase, namely from 2157 to 33.7 (corresponding to $\log K_{\text{O/W}}$ 3.34. and 1.53, respectively). We have assumed that the highly hydrophobic G3^{gl} host was absent in the octanol phase, which is reasonable considering that $\log K_{\text{O/W}}=-2.24$ in case of PAMAM G3 dendrimer,¹⁴ indicating that solubility of that hydrophilic dendrimer in water is 5754 times higher than in octanol. From partition experiments, we conclude that $\text{GEN@G3}^{\text{gl}}$ encapsulate loses the guest GEN molecule, which is promising in terms of biological conditions which might be met when $\text{GEN@G3}^{\text{gl}}$ in water is delivered into tissue.

Considering the determined stoichiometry achievable in aqueous environment (at least 3 GEN per 1 G3^{gl} host) we obtained the encapsulate 1:1 GEN: G3^{gl} and tested this as DDS in skin permeation experiments, as well as toxicity against human cell lines and *C. elegans*.

Skin permeation of GEN was tested using hydroxyethylcellulose hydrogel as a donor, polyvinylidene fluoride (PVDF) and freshly prepared rabbit skin (RS) membranes as skin models, and phosphate buffered water/ethanol receiving solutions. The amount of transferred GEN from donor into receiver was determined spectrophotometrically within 48 hours (Fig. 6 and 7). The cumulative amount of GEN permeated through PVDF indicated 3-fold enhancement of GEN release from encapsulate $\text{GEN@G3}^{\text{gl}}$ donor in comparison with GEN alone in donor. The time of 10% GEN transfer, $\tau_{0.1}$ was used as comparative parameter. Thus the estimated $\tau_{0.1}$ was 3.2 ± 0.2 hour in case of $\text{GEN@G3}^{\text{gl}}$, while 6.5 ± 0.2 hour in case of GEN alone (Fig. 6). The values of $\tau_{0.1}$ for $\text{GEN@G3}^{\text{gl}}$ were shorter than those obtained in similar delivery system for 8-methoxypsoralen in PAMAM G3 and G4 dendrimers, which were 6.5 and 9.0 hours,⁹ respectively as well as riboflavin in PAMAM G3,5 dendrimer, which was determined as 6.5 hours.⁸ The release of GEN from both hydrogel and from $\text{GEN@G3}^{\text{gl}}$ in hydrogel was relatively fast; the control experiment after 24 hours indicated that permeation was completed within the first 12 hours.

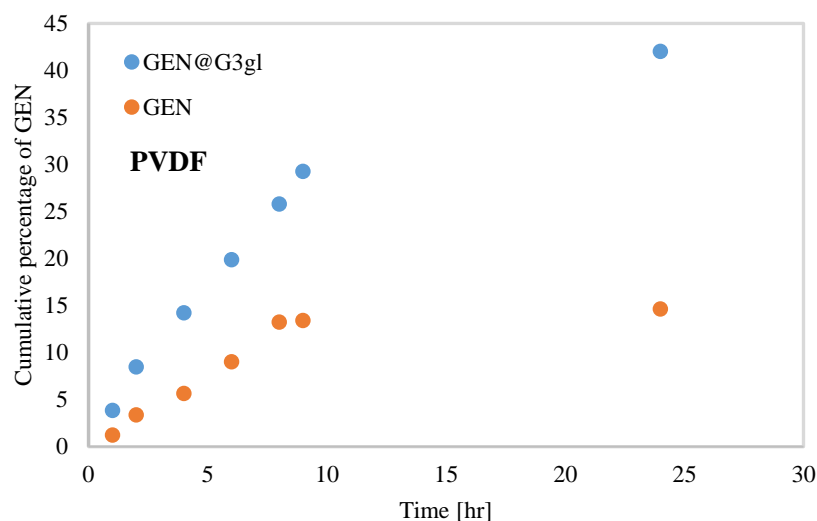


Fig. 6. The permeation of GEN from hydrogel containing GEN and GEN@G3^{gl} encapsulate through PVDF. Standard deviation for 5 times repeated experiments was not higher than 1.5%

In case of permeation through rabbit skin, the release of GEN from hydrogel and GEN@G3^{gl} was stopped after 32 hours of experiments (Fig. 7). No statistically relevant enhancement of GEN release from GEN@G3^{gl} versus GEN alone in the hydrogel donor was found, although the release of GEN from encapsulate was ca 1% faster than from GEN in hydrogel within first 30 hours. Because no 10% of transfer was achieved in either case, the time of 3% transfer was chosen for comparison with other results, $\tau_{3\%}$. Thus the $\tau_{3\%}=7.5\pm 0.2$ hour was determined for GEN release from GEN@G3^{gl}, while it was 12.0 ± 0.2 hour for GEN alone. For comparison $\tau_{3\%}=1.5\pm 0.1$ hours was determined for riboflavin release from riboflavin – PAMAM G3 encapsulate in o/w emulsion through porcine skin membrane and 7.4 ± 0.1 hour for 8-methoxypsoralen in PAMAM G3 in an analogous experiment.^{8,9} Generally, only a slight increase of rabbit skin permeation was observed in case of GEN@G3^{gl} encapsulate in comparison with GEN alone. Presumably the reason is highly hydrophobic conditions within the skin, promoting GEN release already in the rabbit skin tissue. The kinetics of GEN permeation is thus limited by diffusion of GEN through RS.

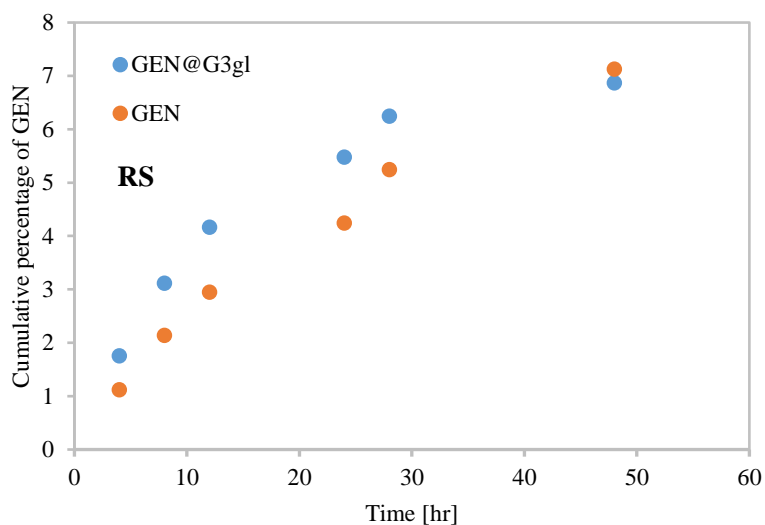


Fig. 7. The permeation of GEN from hydrogel containing GEN and GEN@G3^{gl} encapsulate through rabbit skin. Standard deviation for 5 times repeated experiments was not higher than 0.3%

Kitagawa et al. used w/o microemulsions prepared from isopropyl myristate (oil phase), 150 mM NaCl(aq), ethanol and Tween 80 surfactant to enhance the solubility of GEN and other isoflavones.¹⁵ Using various microemulsions, they were able to enhance the GEN dispersion 1300–2000 times. The microemulsions were then used as GEN delivery system to accumulate GEN in guinea pig dorsal skin and Yukatan micropig skin. The amount of accumulated GEN increased 25–59 times in comparison with GEN in a NaCl(aq) delivery experiment. Accumulated GEN in skin significantly inhibited lipid peroxidation *in vitro* dose-dependently. Furthermore, pretreatment of guinea pig dorsal skin with GEN containing microemulsions prevented UV irradiation-induced erythema formation. As described here, solubilization effects for GEN using G3^{gl} is more efficient than the aforementioned microemulsion dispersion.

***In vitro* toxicity of GEN, G3^{gl} and GEN@G3^{gl}**

In order to estimate the biological properties of GEN, G3^{gl} and GEN@G3^{gl} encapsulates, we performed the toxicity Alamar Blue assay on BJ normal human fibroblasts and immortalized human keratinocytes (HaCaT cell line). We determined that neither GEN, nor G3^{gl} or GEN@G3^{gl} exerted any toxic effect in range of 1–100 μ M concentration (Fig. 8).

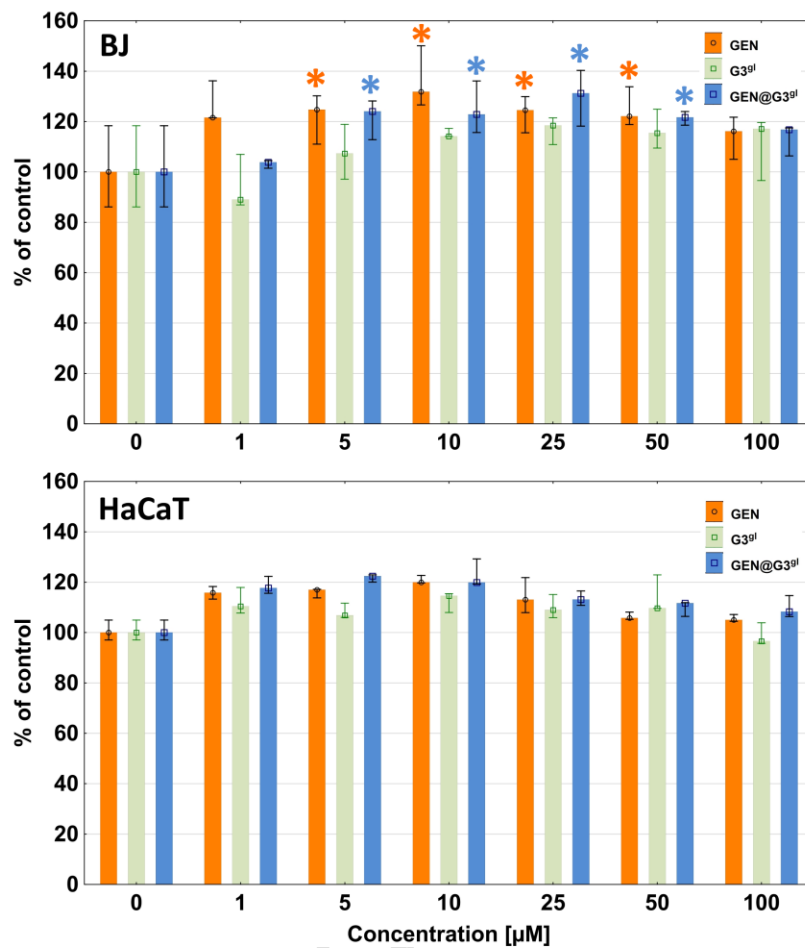


Fig. 8. Biological activity of GEN, G3^{gl}, and GEN@G3^{gl} against normal human BJ fibroblasts and immortalized HaCaT keratinocytes after 24 hours incubation. Results are presented as medians (percentage of non-treated control). Whiskers indicate the lower (25%) and upper (75%) quartile ranges. * $p \leq 0.05$, Kruskal–Wallis test (against non-treated control)

Moreover, a slight increase of cell viability over the entire range of used concentrations (1–100 μM) was noted, which could be related to the trophic effect of the substances used. Obtained results were consistent with others, where GEN did not influence on HaCaT cell viability up to 100 μM concentration after 24 h incubation (MTT assay or Sulforhodamine B (SRB) assay).^{16,17} Also Pawlicka et al. indicated that genistein was not toxic up to 150 μM concentration against BJ fibroblasts, and observed that genistein at lower concentrations (10–100 μM) stimulated fibroblast growth (MTT assay, 24 h incubation).¹⁸

It is worth mentioning that increases of cell viability under the influence of GEN@G3^{gl} was probably an effect of presence of GEN in encapsulate, since viability after incubation with GEN and GEN@G3^{gl} was always higher than G3^{gl} alone at appropriate concentrations (Fig. 8).

In vivo toxicity against *C. elegans*

Due to previously reported anti-nematode activity of GEN, we have tested the GEN@G3^{gl} biological effect on *C. elegans* in comparison with G3^{gl}.^{2,3} We found that after 7 days incubation, glycidylated G3 PAMAM dendrimer did not influence on *C. elegans* lifetime (Fig. 9).

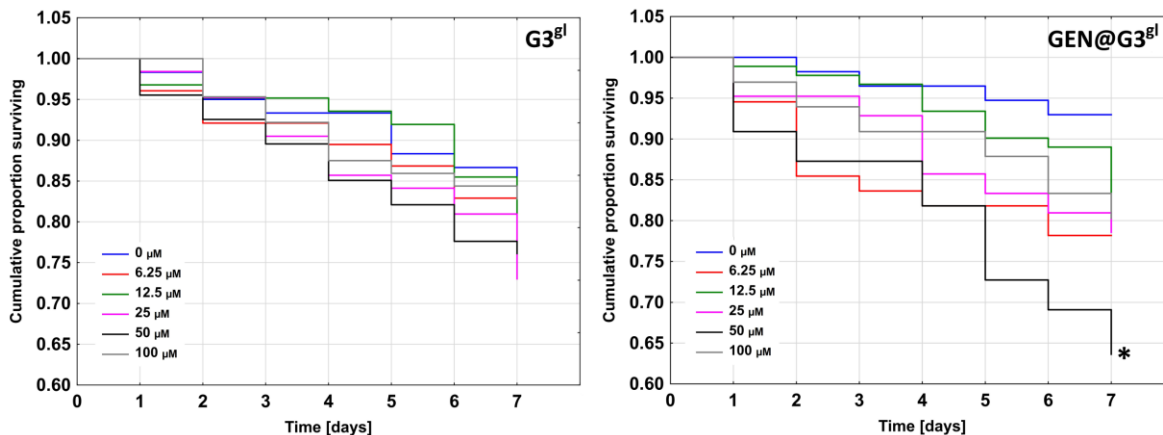


Fig. 9. The Kaplan–Meier survival curves of *C. elegans* after 7 days of incubation with G3^{gl} and GEN@G3^{gl}. Results are presented as cumulative proportion surviving. Statistically significant differences against DMSO-treated control (0.2%) obtained by Gehan’s Wilcoxon test are marked with asterisks * ($p \leq 0.05$) in the colors corresponding to the tested concentrations

A similar pattern was observed for GEN@G3^{gl} up to 25 μM concentration. At 50 μM concentration, viability of nematodes decreased significantly, achieving a value of 63% after 7 days incubation. It was interesting that 100 μM concentration of both G3^{gl} and GEN@G3^{gl} had a slighter effect than 50 μM concentration. In summary, at a 50 μM concentration, the genistein delivered as GEN@G3^{gl} encapsulate induced an anthelmintic effect.

Conclusion

Third generation polyamidoamine dendrimers modified by exhausting glycidylation, act as a solubilizer for the highly hydrophobic isoflavonoid genistein. The host dendrimer macromolecule is able to encapsulate more than 3 molecules of guest genistein. Water solubility of genistein increased about 27 times in presence of the host. The 1:1 genistein : dendrimer encapsulate promotes skin permeation of genistein. It was non-toxic against normal BJ fibroblast and immortalized HaCaT keratinocyte human cells. The 1:1 genistein : dendrimer encapsulate indicated anthelmintic action at 50 μM concentration against *C. elegans*.

Declarations

Funding

The cost of experimental work was covered by Statutory Activity Fund of Medical College at Rzeszow University.

Author contributions

Conceptualization, A.F-R. and S.W.; Methodology, S.W. and Ł.U.; Software, Ł.U.; Validation, S.W., Ł.U. and A.F-P.; Formal Analysis, S.W.; Investigation, J.D., A.F-R, M.Z-D, and S.W.; Resources, Ł.U.; Data Curation, Ł.U.; Writing – Original Draft Preparation, Ł.U., S.W., and A.F-R; Writing – Review & Editing, S.W.; Visualization, S.W. and Ł.U.; Supervision, S.W.; Project Administration, S.W.; Funding Acquisition, S.W.

Conflicts of interest

Authors declare no conflict of interest.

Data availability

Raw data are available from corresponding author on reader demand.

Ethics approval

There are no ethic approvals needed for experimental work presented.

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