Luteolin Nanoparticle in Chemoprevention: In Vitro and In Vivo Anticancer Activity


Abstract

Cancer prevention (chemoprevention) by using naturally occurring dietary agents has gained immense interest because of the broad safety window of these compounds. However, many of these compounds are hydrophobic and poorly soluble in water. They frequently display low bioavailability, poor systemic delivery, and low efficacy. To circumvent this problem, we explored a novel approach toward chemoprevention using nanotechnology to deliver luteolin, a natural compound present in green vegetables. We formulated water-soluble polymer-encapsulated Nano-Luteolin from hydrophobic luteolin, and studied its anticancer activity against lung cancer and head and neck cancer. In vitro studies demonstrated that, like luteolin, Nano-Luteolin inhibited the growth of lung cancer cells (H292 cell line) and squamous cell carcinoma of head and neck (SCCHN) cells (Tu212 cell line). In Tu212 cells, the IC50 value of Nano-Luteolin was 4.13 μmol/L, and that of luteolin was 6.96 μmol/L. In H292 cells, the IC50 of luteolin was 15.56 μmol/L, and Nano-Luteolin was 14.96 μmol/L. In vivo studies using a tumor xenograft mouse model demonstrated that Nano-Luteolin has a significant inhibitory effect on the tumor growth of SCCHN in comparison to luteolin. Our results suggest that nanoparticle delivery of naturally occurring dietary agents like luteolin has many advantages and may have potential application in chemoprevention in clinical settings. Cancer Prev Res; 7(1): 65–73. ©2014 AACR.

Introduction

Cancer remains one of the deadliest diseases causing a large number of deaths worldwide. In 2008, about 7.6 million people died of cancer-related causes globally, and it is estimated that by 2030, there will be 13.1 million cancer deaths (1).

Chemoprevention is a way of controlling cancer in which the occurrence of the disease can be completely prevented, slowed down, or reversed by administering one or more naturally occurring compounds or synthetic agents. Even after the treatment of cancer by surgical removal of tumor, or chemotherapeutic drug, radiation therapy or both, there is a high probability of cancer recurrence. Chemoprevention can prevent the risk of cancer recurrence among cancer patients, and it can also reduce the risk of cancer in the general population. Prevention offers the most cost-effective long-term strategy for the control of cancer. Chemoprevention by using naturally occurring nontoxic molecules has emerged as a unique strategy for cancer management (2). Recently, naturally occurring dietary agents present in vegetables, fruits, spices, and herbs have generated immense interest for their potential application in chemoprevention and therapy, and in fact many of these compounds are currently under early phase clinical trials, and available over the counter in most pharmacies (3–8). The advantage of dietary agents in comparison to the currently used chemotherapeutic agents is their higher level of safety (3–8). An ideal chemopreventive compound is expected to be nontoxic, orally active, highly effective, less expensive, and easily available.

The flavonoid luteolin, 3',4',5,7-tetrahydroxyflavone, is a natural antioxidant that usually occurs in its glycosylated form in many green vegetables such as artichoke, broccoli, cabbage, celery, cauliflower, green pepper, and spinach (3, 9). Luteolin exhibits a wide range of pharmacological properties ranging from anti-inflammation to anticancer effects. Luteolin has shown anticancer effects against lung cancer, head and neck cancer, prostate, breast, colon, liver, cervical, and skin cancer (10–24). It triggers apoptotic cell death by activating apoptosis pathways and suppressing cell survival pathways. Luteolin has displayed anticancer effects by inducing cell-cycle arrest, senescence, or apoptosis in lung carcinoma cells (10–12), oral squamous cancer cells (13–15), human esophageal adenocarcinoma cells (16),...
human colon cancer cells (17), and human hepatoma cells (18). Luteolin inhibited proliferation and induced apoptosis of prostate cancer (19–21) cells in vitro and in vivo. It increased the efficacy of cisplatin in gastric cancer cells (22). In an animal model, luteolin also inhibited tumor growth against breast cancer cell lines (MCF-7/6 and MDA-MB231-1833; ref. 23). In another study, luteolin significantly reduced the incidence of colon cancer and the number of tumors per rat (24). The results of these studies warrant the evaluation of the chemopreventive potential of luteolin in human subjects.

Although chemoprevention using natural compounds has shown promising results in preclinical settings, its application to humans has met with various challenges, mainly because of inefficient systemic delivery and low bioavailability of these natural compounds (3, 9). To achieve the maximum possible efficacy of a chemopreventive compound, new strategies are required to enhance the bioavailability of potentially useful compounds, and reduce undesired toxicity.

Nanomedicine is an emerging research area and nanotechnology is being implemented and evaluated in several areas of cancer therapeutics and cancer management (25–38). Nanoparticles are known to have many advantages for the delivery of cancer therapeutics, for example, they have longer blood circulation time, higher bioavailability, enhanced permeability and retention (EPR) effect, higher tumor-specific delivery, and higher efficacy (25–38). Studies from our group and other researchers have demonstrated that nanoparticle-mediated delivery could be a promising approach to enhance the bioavailability of chemopreventive agents (such as EGCG, curcumin, luteolin), increase efficacy, and reduce undesired toxicity (38–40).

The flavonoid luteolin has immense potential for its application in cancer prevention and therapy (3, 8, 9). However, luteolin is poorly soluble in water, making its intravenous or intraperitoneal administration very difficult. In this study, we have formulated a polymer-encapsulated luteolin nanoparticle (Nano-Luteolin), which is water soluble, and studied its anticancer properties against squamous cell carcinoma of head and neck (SCCHN, Tu212) and non–small cell lung cancer (NSCLC, H292) cells. In vitro studies have shown that like luteolin, Nano-Luteolin can also inhibit the growth of H292 and Tu212 cells. In vivo studies using tumor xenograft mouse models have demonstrated that Nano-Luteolin has considerable inhibitory effect on tumor growth of SCCHN.

Materials and Methods

Nanoformulation

Polylactic acid (PLA)-polyethylene glycol ether (PEG)-OMe (1 g in 10 mL MeOH) and luteolin (100 mg in 60 mL MeOH) solutions were mixed together. This mixture of PLA-PEG-OMe and luteolin was added dropwise to 200 mL of 1% (w/v) polyvinyl alcohol solution with constant stirring. Stirring was continued for 20 hours. Unencapsulated luteolin precipitated in the solution. The solution was centrifuged at 6,000 rpm, the precipitate got accumulated at the bottom, and the supernatant was filtered using a Millipore Millex-HN syringe-driven filter unit with cut-off 0.20 μm to remove the remaining unencapsulated luteolin. The filtrate was purified using an Amicon ultra-15 centrifugal filter with cut-off 30,000 to obtain pure polymer-encapsulated luteolin nanoparticle (Nano-Luteolin) solution. Freshly prepared Nano-luteolin solution was lyophilized to obtain yellowish powder, and reconstituted for biological studies. Luteolin content in the nanoparticle was calculated by measuring the absorbance of luteolin solution using a Shimadzu UV-2401 PC UV-vis spectrophotometer at 355 nm (41–43). Nanoparticle was dissolved in solvent DMF, and then the nanoparticle lost its structural sanctity (42). The DMF was removed under reduced pressure, and the residue was dissolved in methanol. Then the UV absorbance of the solution was measured to determine the luteolin concentration (41–43). The luteolin content in nanoparticle is 1.4% (w/w) and the encapsulation efficiency is 9% (41–43). The hydrodynamic diameter was obtained using Malvern Zetasizer Nanoseries Nano-ZS90. A Zeiss LSM510 Meta confocal microscope was used for imaging.

Cell lines

SCCHN cell line Tu212 was obtained from Dr. G.L. Clayman (University of Texas M.D. Anderson Cancer Center, Houston, TX), as described in our previous publication (44). This cell line was cultured in DMEM/F12 (1:1) with 10% heat inactivated FBS and maintained in a humidified incubator at 37°C, 5% CO2. The human origin of this cell line was confirmed by genotyping with 9 commonly used STR markers by Research Animal Diagnostic Laboratory (Columbia, MO) in 2009. The human NSCLC cell line H292 was provided by Dr. Shi-Yong Sun who obtained it from Dr. R. Lotan (MD Anderson Cancer Center, Houston, TX) in 2003. H292 cells can be maintained in RPMI1640 medium supplemented with 10% heat-inactivated FBS in a humidified incubator at 37°C, 5% CO2. This cell line has not been authenticated (45).

Reagents

Luteolin (Sigma-Aldrich) was dissolved in DMSO as a stock solution for in vitro studies. The reagent was further diluted in cell culture medium immediately before use. The final concentration of DMSO was less than 0.1%.

Cell viability assay

Cell viability was measured using a sulforhodamine B (SRB) assay (46). A total of 3,000 cells were seeded in a 96-well plate. After 16 hours, cells were treated with Nano-Luteolin or PLA-PEG polymer solutions at various concentrations, and incubated for 72 hours. After 72 hours of culture, cells were fixed with 10% trichloroacetic acid. Plates were stained with 0.4% SRB for 10 minutes and bound SRB was dissolved in 10 mmol/L Tris base (pH 10.5). Cell growth was assessed by optical density (OD) determination at 492 nm using a microplate reader. The percentage of survival was then calculated based on the absorbance values.
relative to the control samples. The no treatment group was considered as 100% cell growth and used as a control, and the treatment group was compared with this control.

**Colony formation assay**
The efficacy of luteolin against Tu212 and H292 cells was tested using a colony formation assay. A total of 400 cells were seeded in 6-well plate tissue culture dishes and treated with luteolin, Nano-Luteolin, or polymer for 72 hours. The concentrations of luteolin in the nanoparticle (Nano-Luteolin) were 5 and 10 µmol/L. Then the media was replaced by fresh media. The cells were maintained under standard cell culture conditions at 37°C and 5% CO₂ in a humid environment. Colonies that formed in 2 weeks were fixed with 10% buffered formalin, stained with 2% gentian violet (w/v methanol solution), washed with water, and air-dried.

**Growth curves**
Growth curves were plotted using average tumor size within each experimental group at the set time points.

**Immunohistochemistry**
Immunohistochemistry analysis for Ki-67 staining on tumor sections was performed using the R.T.U.I. Vectastain kit following the standard manufacturer’s protocol (Vector Laboratories). Tissue sections were incubated with mouse anti-human Ki-67 (prediluted; Invitrogen) for 1 hour at room temperature. The slides were stained with 3, 3′-diaminobenzidine (Sigma Chemical) and counterstained with hematoxylin (Vector Laboratories). TUNEL assay was performed by immunofluorescence using the same specimens as above following the procedure provided by the manufacturer (Promega). The slides were counterstained with DAPI (Invitrogen). Five areas were randomly selected from each slide for analysis. For Ki-67 staining, the intensity of positive cells was measured by counting the absolute number of pixels.

**Statistical analysis**
Statistical significance was assessed using Student T test for SRB assay. P < 0.05 was considered significant in all analyses. For the in vitro antitumor efficacy assay, a log-linear mixed model with random intercept was used to compare the significance of the mean tumor volumes among each group.

**Results**

**Formulation of nanoparticle**
To facilitate the effective delivery of luteolin and obtain associated benefits, we used a diblock copolymer consisting of PLA and PEG to formulate the Nano-Luteolin. An emulsion solvent evaporation method was used to formulate the water-soluble Nano-Luteolin (Experimental Section; Fig. 1). The properties of polymer-encapsulated Nano-Luteolin were characterized by dynamic light scattering (DLS) and transmission electron microscopy (TEM) to give the size of each preparation (Figs. 2A–D). UV-vis spectroscopic analysis of both luteolin and Nano-Luteolin showed the absorbance maxima from the phenyl rings of luteolin at about 261 and 355 nm (Fig. 2E and F). DLS and TEM studies revealed that the mean size of the nanoparticles was about 115 nm.

**In vitro antitumor efficacy study**
To evaluate the anticancer potential of Nano-Luteolin, we performed SRB assays (46) to determine live cell density based on the measurement of cellular protein content. We treated head and neck (Tu212) and lung (H292) cancer cells with luteolin, Nano-Luteolin, or the polymer, and performed SRB assays to compare their efficacy in cell growth inhibition. The SRB assay showed that in both cell lines, Nano-Luteolin exhibited cell growth inhibition similar to that of luteolin (Fig. 3A). We used CalcuSyn software to determine the IC₅₀ values. In Tu212 cells, the IC₅₀ value of Nano-Luteolin was 4.13 µmol/L, and that of luteolin was 6.96 µmol/L. In H292 cells, the IC₅₀ of Nano-Luteolin was 14.96 µmol/L and that of luteolin was 15.56 µmol/L.

Next, we performed a colony formation assay to directly compare the anticancer efficacy of polymer-encapsulated Nano-Luteolin with that of luteolin in Tu212 and H292 cells (Fig. 3B). This study showed that in Tu212 cells, at a concentration of 5 µmol/L, Nano-Luteolin inhibited colony formation more effectively than luteolin; and more colonies formed SRB assays to compare their efficacy in cell growth inhibition. The SRB assay showed that in both cell lines, Nano-Luteolin exhibited cell growth inhibition similar to that of luteolin (Fig. 3A). We used CalcuSyn software to determine the IC₅₀ values. In Tu212 cells, the IC₅₀ value of Nano-Luteolin was 4.13 µmol/L, and that of luteolin was 6.96 µmol/L. In H292 cells, the IC₅₀ of Nano-Luteolin was 14.96 µmol/L and that of luteolin was 15.56 µmol/L.

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were observed following luteolin treatment than nanoparticle (Nano-luteolin) treatment. At a concentration of 10 μmol/L luteolin, both Nano-Luteolin and luteolin displayed a strong cell growth inhibitory effect, and the number of colonies was similar in both cases. In H292 cells, at a concentration of 5 μmol/L, both Nano-Luteolin and luteolin showed a similar effect in inhibition of colony formation, with a similar number of colonies observed. At a concentration of 10 μmol/L, Nano-Luteolin inhibited colony formation more effectively than luteolin; and the number of colonies was greater in luteolin-treated cells than in Nano-Luteolin–treated cells. At a concentration of 15 μmol/L, both Nano-Luteolin and luteolin completely eradicated cancer cells and no colonies were observed in either case (data not shown).

To investigate the cellular uptake of Nano-Luteolin, we formulated polymeric nanoparticles that encapsulated both luteolin and sulforhodamine B acid chloride. As a control, Tu212 cells were incubated with the nanoparticle at 4°C for 15 minutes and the nuclei were stained with DAPI; no internalization of nanoparticle was observed. We then increased the temperature to 37°C and incubated the Tu212 cells with the nanoparticle for 15 minutes, 1 hour, and 3 hours. Confocal images showed that the nanoparticles were taken up by Tu212 cells; the cellular uptake of nanoparticle increased with incubation time (Fig. 4). This shows the ability of the nanoparticle to be internalized into cells in a temperature and time-dependent manner. Tu212 cells were also incubated with free sulforhodamine B acid chloride dye for 15 minutes and 3 hours. A negligible amount of free dye was taken up by Tu212 cells even at 37°C.

**In vivo antitumor study**

We next evaluated the efficacy of Nano-Luteolin in a xenograft mouse model of head and neck cancer developed by subcutaneous injection of Tu212 cells in the flank of athymic nude mice. We divided mice into 4 different groups...
(n = 7 per group): (i) control group treated with PBS, (ii) polymer-treated group, (iii) luteolin-treated group (3.3 mg/kg luteolin); and (iv) Nano-Luteolin–treated group (3.3 mg/kg luteolin equivalent). Each mouse was intraperitoneally administered their assigned compound every alternate day for 7 days before inoculation of 2.5 × 10^6 Tu212 cells by subcutaneous injection into the right flank. The compounds were intraperitoneally administered every alternate day for 30 days. When the tumors grew to a size of 1,700 mm^3 and became ulcerous according to the IACUC guidelines, the mice were sacrificed. A log-linear mixed model with random intercept was used to compare the mean tumor volume between the treatment and control groups. The difference in tumor volume during the whole measurement period reached a significant level between the Nano-Luteolin group and luteolin group (P = 0.0398). Compared with the control group, treatment with nanoparticles resulted in reasonable inhibition of tumor growth, but the difference was not significant (P = 0.1193). Tumor volumes in the polymer (P = 0.5978) and luteolin-treated (P = 0.8719) groups were not significantly different from the control group. These results indicate that the efficacy of Nano-Luteolin is greater than that of luteolin. Indeed, our data showed that at 22 days postinoculation, the tumor volume in control mice was 886 mm^3, compared with 641 mm^3 in the Nano-Luteolin treatment group (Fig. 5A and B). The tumor volumes in the luteolin and polymer groups were 898 and 914 mm^3, respectively. This study shows that the nanoparticle-treated group had a clear inhibitory effect on tumor growth over time when compared with control group (Fig. 5A and B). Furthermore, no weight loss was observed for Nano-Luteolin–treated animals.

**Ki-67 expression and apoptosis in xenograft tumors**

Immunohistochemical analysis of Ki-67 staining revealed a greater inhibition of proliferating cells in the Nano-Luteolin–treated mice than the control group (Fig. 5C). Although there was no statistically significant difference in mean Ki-67 expression between the treated and untreated groups (P = 0.3), we observed a clear trend within the groups. There was no significant difference in the numbers of apoptotic cells among groups (data not shown).

**Discussion**

Nanochemoprevention is a novel concept in which nanotechnology-based regimens are developed for the prevention of cancer. Using nanotechnology, we have prepared water-soluble Nano-Luteolin from hydrophobic luteolin. Nanoparticles can enter into the cell by various mechanisms,
including direct diffusion through the plasma membrane of the cell, and entry through receptor-mediated endocytosis (48–51). The receptor can be a nanoparticle-specific membrane protein, or it can simply be any lipid, protein, or carbohydrate to which the nanoparticle binds, and then undergoes endocytosis (48–51).

We used PLA-PEG polymer because it is safe, biocompatible, and biodegradable, and is already approved by the United States Food and Drug Administration. PLA-PEG–based polymeric nanoparticles have been well studied for the delivery of various drugs and, they are found to be stable after storage (38, 52-63). In fact, a PLA-PEG–based...
polymeric nanoparticle Genexol is approved for treatment of cancer in Korea, and it is undergoing clinical trials in United States for breast cancer, ovarian cancer, non–small cell lung cancer, pancreatic cancer, bladder cancer, ureter cancer, and locally advanced squamous cell head and neck carcinoma (64). PLA is a hydrophobic polymer and insoluble in water, whereas the PEG is hydrophilic and water soluble. Thus, PLA forms the hydrophobic inner core of the nanoparticle, whereas PEG constitutes the hydrophilic outer surface of the polymeric nanoparticle. Hydrophobic luteolin can position itself inside the inner core of the nanoparticle.

To study the in vitro efficacy of Nano-Luteolin, we initially compared the efficacy of luteolin, Nano-Luteolin, and the polymer in cell growth inhibition of head and neck cancer (Tu212) and lung cancer (H292) cells, as assessed by SRB assay. This study showed that in both cell lines, Nano-Luteolin exhibited cell growth inhibition similar to that of luteolin. This prompted us to perform colony formation assays to compare the anticancer efficacy of polymer-encapsulated Nano-Luteolin with that of luteolin in Tu212 and H292 cells. In this study, we observed that the polymer encapsulation of luteolin and its release from polymeric nanoparticle had an effect on its anticancer activity. For example, in Tu212 cells, at a concentration of 5 μmol/L, Nano-Luteolin inhibited colony formation more effectively than luteolin. Similarly, in H292 cells at a concentration of 10 μmol/L, Nano-Luteolin inhibited colony formation more effectively than luteolin.

We also investigated the cellular uptake of polymeric nanoparticles that encapsulated both luteolin and sulforhodamine B acid chloride. This study confirmed the ability of the nanoparticle to be internalized into cells in a temperature and time dependent fashion.

Finally, we evaluated the efficacy of Nano-Luteolin using a xenograft mouse model of head and neck cancer. Our study showed that in mice treated with the water-soluble Nano-Luteolin with PEG surface coating, there was a marked inhibition of tumor growth over time when compared with that in the luteolin group. The PEG group on the nanoparticle surface is known to decrease the nonspecific biofouling of nanoparticles in vivo, minimize nanoparticle uptake by the RES, increase the circulation time of nanoparticle, and decrease the premature clearance of nanoparticles by the mononuclear phagocytic system (36–38, 52–63). Moreover, because of the EPR effect, nanoparticles can enter into the tumor through the leaky vasculature.

Figure 5. Antitumor effect of Nano-Luteolin in an animal model. A, representative mouse from each group. B, tumor growth of Tu212 xenograft was inhibited in the Nano-Luteolin-treated group compared with the control and luteolin. For Tu212 tumors, the difference in tumor volume during the whole measurement period reached a significant level between the Nano-Luteolin and luteolin group (P = 0.0398). Other comparisons were insignificant (P > 0.05). C, paraffin-embedded tissue sections from different treatment groups were immunostained with anti-Ki-67 for cell proliferation.
Most likely because of a combination of these advantages, Nano-Luteolin is more effective in tumor growth inhibition than free luteolin. In fact, the recent study (65) also suggested that nanoencapsulated combinations of ACS (aspirin, curcumin, and free sulforaphane) showed higher efficacy even in lower doses compared with the combinations of free drugs in a chemically induced pancreatic neoplasia model.

In this study, the luteolin content inside the polymeric nanoparticle is about 1.4% by weight, resulting in the administration of a low dose of luteolin (3.3 mg/kg body weight). We believe that if we increase the amount of luteolin encapsulation, or if we can administer a higher dose of luteolin through Nano-Luteolin, which in turn will further increase the in vivo efficacy of the nanoparticles. To increase luteolin encapsulation, we are investigating the use of various polymers such as PHB-P-PEG, PLGA-PEG, and PEO-PPO to formulate luteolin nanoparticles. Moreover, an appropriate targeting ligand can be conjugated to the nanoparticle surface to target a specific tumor-overexpressing receptor. We will investigate this approach through in vivo experiments using appropriate animal models, and explore the use of luteolin nanoparticles as a potential candidate for chemoprevention as well as cancer therapy in clinical settings.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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Debatosh Majumdar, Kyung-Ho Jung, Hongzheng Zhang, et al.


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