Roles of p53 and Caspases in Induction of Apoptosis in MCF-7 Breast Cancer Cells Treated with a Methanolic Extract of Nigella Sativa Seeds

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Abstract

Background: Nigella Sativa (NS) is an herb from the Ranunculaceae family that exhibits numerous medicinal properties and has been used as an important constituent of many complementary and alternative medicines (CAMs). The ability of NS to kill cancer cells such as PC3, HeLa and hepatoma cells is well established. However, our understanding of the mode of death caused by NS remains nebulous. The objective of this study was to gain further insight into the mode and mechanism of death caused by NS in breast cancer MCF-7 cells. Materials and Methods: Human breast cancer cells (MCF-7) were treated with a methanolic extract of NS, and a dose- and time-dependent study was performed. The IC₅₀ was calculated using a Cell Titer Blue® viability assay assay, and evidence for DNA fragmentation was obtained by fluorescence microscopy TUNEL assay. Gene expression was also profiled for a number of apoptosis-related genes (Caspase-3, -8, -9 and p53 genes) through qPCR. Results: The IC₅₀ of MCF-7 cells was 62.8µL/mL. When MCF-7 cells were exposed to 50 µL/mL and 100 µL/mL NS for 24h, 48h and 72h, microscopic examination (TUNEL assay) revealed a dose- and time-dependent increase in apoptosis. Similarly, the expression of the Caspase-3, -8, -9 and p53 genes increased significantly according to the dose and time. Conclusions: NS induced apoptosis in MCF-7 cells through both the p53 and caspase pathways. NS could potentially represent an alternative source of medicine for breast cancer therapy.

Keywords: Nigella sativa seeds - MCF-7 cells - anticancer, apoptosis - p53 - caspases-3, 8, 9

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Introduction

Nigella sativa (NS), a dicotyledon of the Ranunculaceae family, is an amazing herb and a promising medicinal plant with a rich historical and a religious background (Goreja, 2003). NS is commonly known as “black cumin seed” and has been used in many Middle Eastern countries for thousands of years as a spice, food preservative and curative remedy for numerous disorders (Chopra et al., 1956; Nadakarni, 1976; Yesilada et al., 1995). In the past two decades, considerable effort has contributed to the scientific validation of the medicinal properties of NS and its use as a medicine for the treatment of asthma (El-Tahir et al., 1993), bronchitis, headache, rheumatism, fever, influenza and eczema as well as for the treatment of dyslipidemia, hyperglycemia and related abnormalities (Zaoui et al., 2002). In addition, the anti-inflammatory (Houghton et al., 1995; Mutabagani and El-Mahdy, 1997), anti-diabetic (Al-Hader et al., 1993; El-Shabrawy and Nada, 1996), anthelmintic (Mahmoud et al., 2002), analgesic (Khanma et al., 1993), antibacterial (El-Kamali et al., 1998; Mouhajir et al., 1999) and anticanancer properties of NS have been tested and validated (Nair et al., 1991; Salomi et al., 1992; El-Daly., 1998).

Methanolic crude extract of NS seed exhibits antitumor effects in vitro on carcinoma, lymphoma and sarcoma (Salomi et al., 1991; Salomi et al., 1992). Methanolic extract of NS has been reported to possess in vitro cytotoxicity in the PC3 cell line, whereas the chloroform fraction of NS was found to induce apoptosis in HeLa cells and SiHa cells (Shafi et al., 2008; Shafi et al., 2009). Two purified components of the NS seed, thymoquinone (TQ) and dithymoquinone (DTQ), have been established to exhibit cytotoxic activities in some parental and multidrug-resistant human tumor cell lines. TQ triggers apoptotic cell death in human colorectal cancer cells, and apoptosis is associated with the up-regulation of p53 and p21WAF1 and a significant down-regulation of the anti-apoptotic Bcl-2 protein (Gali-Muhtaşib et al., 2004). In addition to these direct anti-tumor effects, black seed preparations may exhibit potential in cancer chemoprevention as well as in reducing the toxicity of standard antineoplastic drugs (Nair et al., 1991; Salomi et al., 1991).

Although the effect of NS on different biological processes has been established, there are comparatively few studies on its anticanencer property against breast...
cancer. This study was therefore designed to determine whether NS induces apoptosis in the MCF-7 breast cancer cell line and, if so, which pathway(s) is/are involved the programmed cell death: the mitochondrial (caspases) pathway, the nuclear (p53) pathway or both.

Materials and Methods

_Nigella sativa_ seeds were purchased from local markets and authenticated at department of Botany, King Saud University, Riyadh. The seeds were washed with distilled water and dried in the air. Dried seeds were powdered, and 500 grams of grounded seeds were soaked in 1 L of high-performance liquid chromatography (HPLC)-grade methanol in a sterile bottle and kept for 24 hours at room temperature with stirring with a sterile rod twice. Extraction was performed three times as described above. The extract was then filtered using sterile filter paper. The solvent from the extract was removed under reduced pressure. Approximately 8 mL of extract was obtained after concentration. The extract was aliquoted into 1-ml vials and stored at -20°C until used for experiments (Hasan et al., 2007).

Maintenance of MCF-7 cells

The MCF-7 breast cancer cell line was a kind gift from Dr. M. A. Akbarshah at the Mahatma Gandhi-Doerenkamp Center (MGDC) for Alternatives to Use of Animals in Life Science Education, Bharathidasan University, India. Maintenance and culture procedures were exactly similar to that of reported in our earlier study (Alshatwi et al., 2013). Briefly, The cell line was maintained and propagated in 90% Dulbecco’s Modified Eagle’s Medium (HyClone, Thermo Scientific, MA, USA) containing 10% fetal bovine serum (HyClone, Thermo Scientific) and 1% penicillin/streptomycin (HyClone, Thermo Scientific). Cells were cultured as an adherent monolayer (i.e., cultured at 70% to 80% confluence) and maintained at 37°C in a humidified atmosphere of 5% CO₂. Cells were harvested after brief trypsinization. All chemicals used were of research grade.

Cell viability assays

Cell viability was assayed where and as required, using a trypsin blue exclusion test with slight modifications (El Sharkawi et al., 2014). To assess the toxicity of different concentrations of NS on MCF-7 cells, the Cell Titer Blue® viability assay (Promega Madison, WI) was performed. The assay was performed by following the manufacturer’s instructions. Briefly, MCF-7 cells (2×10⁶ cells/well) were plated in 96-well plates and treated with a range of doses (0, 25, 50, 75, 100 and 125 µL/mL NS) for 24h. Subsequently, 40 µL of the Cell Titer Blue solution was directly added to the wells and incubated at 37°C for 6h. The fluorescence was recorded with a 560 nm/590 nm (excitation/emission) filter set using a Bio-Tek microplate fluorescence reader (FLX800™), and the IC₅₀ was calculated. Samples were run in quadruplets for each concentration of NS in three independent experiments.

For a dose- and time-dependent study, MCF-7 cells were treated with either 50 µL/mL or 100 µg/mL NS for 24, 48 and 72h for the terminal deoxynucleotidyl transferase-mediated dUTP nick end-labeling (TUNEL) assay. The cells were incubated with the same NS concentrations for 24 and 48h for real-time quantitative PCR analysis.

Terminal deoxynucleotidyl transferase dUTP nick end-labeling (TUNEL) assay

The DeadEnd® TUNEL assay kit (Promega, Madison, WI) was used to study apoptosis in a time- and dose-dependent manner. The manufacturer’s instructions were followed with slight modifications. Briefly, MCF-7 cells (1.5X10⁶ cells/well) were cultured in 6-well plates to study apoptosis in adherent cells. Cells were treated with 50 µL/mL and 100 µL/mL NS for 24, 48 and 72h. After the incubation period, the culture medium was aspirated, and the cell layers were trypsinized. The trypsinized cells were reattached on 0.01% polylysine-coated slides, fixed with 4% methanol-free formaldehyde solution, and stained according to the DeadEnd fluorometric TUNEL system protocol (Zhang et al., 2014). The stained cells were observed using a Carl-Zeiss (Axiovert) epifluorescence microscope using a triple band-pass filter. To determine the percentage of cells undergoing apoptosis, 1000 cells were counted in each experiment (Shafi et al, 2009).

Real-time quantitative PCR analysis

Reverse transcription-polymerase chain reaction (RT-PCR; Applied Biosystems 7500 Fast, Foster City, CA) was used to analyze the expression of apoptotic genes by using a real-time SYBR Green/ROX gene expression assay kit (QIAGen, Germany). The FastLane® Cell cDNA kit (QIAGEN, Germany) was used to prepare cDNA directly from cultured cells., and the mRNA levels of Caspase-3, Caspase-8, Caspase-9 and tp53 as well as the reference gene, GAPDH, were assayed using gene-specific SYBR Green-based QuantiTect® Primer assays (QIAGEN, Germany). Quantitative real-time RT-PCR was performed in a reaction volume of 25 µL according to the manufacturer’s instructions. Briefly, 12.5 µL of master mix, 2.5 µL of primer assay (10x) and 10 µL of template cDNA (100 µg) were added to each well. After a brief centrifugation, the PCR plate was subjected to 35 cycles of the following conditions: (i) PCR activation at 95°C for 5 min; (ii) denaturation at 95°C for 5 sec; (iii) annealing/ extension at 60°C for 10 sec. All samples and controls were run in triplicates on an ABI 7500 Fast Real-time PCR system. The quantitative RT-PCR data were analyzed by a comparative threshold (Ct) method, and the fold inductions of samples were compared with the untreated samples. GAPDH was used as an internal reference gene to normalize the expression of the apoptotic genes. The Ct cycle was used to determine the expression level in control cells and MCF-7 cells treated with NS for 24 and 48h. The gene expression level was then calculated as described by Yuan et al. (2006). The results were expressed as the ratio of the reference gene to the target gene using the following formula: ΔCt=Ct (apoptotic genes)-Ct (GAPDH). To determine the relative expression levels, the
following formula was used: \( \Delta \Delta C_t = \Delta C_t \) (Treated) - \( \Delta C_t \) (Control). Thus, the expression levels were expressed as n-fold differences relative to the calibrator. The value was used to plot the expression of apoptotic genes using the expression \( 2^{-\Delta \Delta C_t} \).

### Results

**Effect of NS on MCF-7 breast cancer cell proliferation and apoptosis**

To explore the anticancer effect of NS on MCF-7 human breast cancer cells, several *in vitro* experiments were conducted.

**Determination of NS toxicity on MCF-7 cells**

The cytotoxic effect of 0 to 125 µL/mL NS on MCF-7 cells was examined. A dose-dependent reduction in color was observed after 24h of treatment with NS, and 87.71% of the cells were dead at the highest concentration of NS tested (125 µL/mL). The IC\(_{50}\) of NS for MCF-7 cells was determined to be 62.83 µL/mL (Figure 1).

**Quantification of apoptosis by a TUNEL assay**

To determine whether the inhibition of cell proliferation by NS was due to the induction of apoptosis, a TUNEL assay was used. Figures 2, 3, 4 and 5 summarize the effect of NS on MCF-7 cells. A dose- and time-dependent increase in the induction of apoptosis was observed when MCF-7 cells were treated with NS.

At 24h, 43.65% and 58.32% of the cells treated with 50 µL/mL and 100 µL/mL, respectively, underwent apoptosis when normalized with control. Similarly, 57.42% and 73.11% of the treated cells for 48 hours and 68.27% and 76.81% of the treated cells for 72h were apoptotic when treated with 50 µL/mL and 100 µL/mL, respectively (Figure 5).

![Figure 1. A graphical Representation of Viability at Different Doses of NS.](image1)

![Figure 2. Comparative Representation of TUNEL-Positive (Apoptotic) Cells.](image2)

![Figure 3. Microscopic TUNEL Assay for 24 hrs.](image3)

![Figure 4. Microscopic TUNEL Assay for 48 hrs.](image4)
Quantification of mRNA levels of apoptotic-related genes

To investigate the molecular mechanism of NS-induced apoptosis in MCF-7 cells, the expression levels of several apoptosis-related genes were examined. Figures 6 and 7 summarize the gene expression changes of Caspase-3, -8, and -9 and p53. NS increased the transcripts of Caspase-3, -8, and -9, and p53 by several fold. The expression levels of these genes in MCF-7 cells treated with 50 µL/mL NS for 24 h increased by 5.15-, 2.10-, 2.3-, and 2.81-fold, respectively, compared with the levels in untreated control cells (Figure 6). Similarly, the expression levels of Caspase-3, -8, and -9 and p53 in MCF-7 cells treated with 100 µL/mL NS for 24 h increased by 7.00, 3.62, 8.78, and 4.72-fold, respectively, compared with levels in untreated control cells (Figure 6). In a time-dependent manner, the expression levels of the apoptosis-related genes in MCF-7 cells treated with 50 or 100 µL/mL NS for 48 h increased when compared with the levels in untreated control cells (Figure 6). However, the expression levels of Caspase-3, -8, and -9 and p53 in MCF-7 cells treated with 100 µL/mL NS for 48 h markedly increased by 17.37, 4.82, 10.06 and 6.48-fold compared with control untreated cells (Figure 6). Together, these data suggest that the expression of caspases and p53 was induced by NS in a dose- and time-dependent manner.

Discussion

The mechanism of action of many anticancer drugs is based on their ability to induce apoptosis (Motomura et al., 2008; Florea and Busselberg, 2011). However, unfavorable side effects and the resistance to many anticancer agents have become serious problems (Sonis et al., 2011). Thus, there is a growing interest in the use of plant-based compounds or dietetic products to develop safe and more effective therapeutic agents for cancer treatment (Kma, 2013; Mangal et al., 2013). In due course our group already has demonstrated the anti-preoperative potential of organic extracts from root bark of Juglans Regia against MDA-MB-231 human breast cancer cells (Hasan et al., 2011). In addition of that, our group also demonstrated that methanolic extract of fenugreek whole plant (without root) has potential to induce apoptosis in MCF-7 human breast cancer cells through the involvement of Fas receptor and Caspase-8 (Alshatwi et al., 2013). In present study we are focusing on the anti cancer and apoptosis inducing ability of NS seed extract in MCF-7 human breast cancer cells. NS seeds have been well known for their medicinal properties for thousands of years (Goreja, 2003). No side effects or health hazards have been reported for the use of NS as a medicine (elsewhere). In the past decade, considerable research effort has been focused on elucidating the anti-tumor and cytotoxic effects of NS so that the medicinal property of NS against cancer could be validated scientifically. NS reportedly exhibits cytotoxic activity against hepatoma cells (Thabrew et al., 2005), PC3 prostate cancer cells (Shafi et al., 2008) and HeLa cervical cancer cells (Shafi et al., 2009) and SiHa cervix cancer cells (Hasan et al., 2013). Alkaloids from NS seeds (thymoquinone and thymohydroquinone) exhibit anti-tumor properties in many tumor models and in vivo (Ivankovic et al., 2006).

There are many mechanisms through which apoptosis can be enhanced in cells. Agents suppressing the proliferation of malignant cells by enhancing apoptosis may constitute a useful mechanistic approach to both cancer chemoprevention and chemotherapy. Most dietetic products with anticancer activity act as strong antioxidants and/or modify the activity of one or more protein kinases involved in cell cycle control; protein kinase A, protein kinase B, protein kinase C, JNK-1, CDK-2, and CDK-4 are either activated or deactivated by these antioxidants. This effect may be mediated through the activation of some tumor suppressor genes, such as p21WAF1/CIP1 and p27KIP1, in a p53-independent pathway (Thabrew et al., 2005). In our earlier studies, we observed that HeLa cervical cancer cells underwent apoptosis mediated by the
p53 and caspase pathways (Shaﬁ et al., 2009).

Therefore, we hypothesized that apoptosis could be the mode of cell death in MCF-7 breast cancer cell through either the nuclear (p53) or mitochondrial (Caspase) pathway or a combination of both pathways. To test this hypothesis, we sought to determine the role of NS in inhibiting cell growth and modulating the expression of caspases-3, -8, and -9 and p53. The data presented in this paper demonstrate a time- and dose-dependent inhibition by NS of MCF-7 human breast cancer cell proliferation. Recently, we observed that NS treatment resulted in an 88.3% inhibition of proliferation of SiHa human cervical cancer cells at a concentration of 125 µL/mL of methanolic extract at 24 h and a 50% inhibition of proliferation at a concentration of 93.2 µL/mL (Hasan et al., 2013).

The sensitivity of cells to any of these stimuli may vary depending on factors such as the expression of pro- and anti-apoptotic proteins. The mitochondrial apoptotic pathways and death receptor pathways are the two major pathways that have been characterized in mammalian cells. The mitochondria have a central role in regulating the caspase cascade and apoptosis (Hengartner, 2000). Caspases have a central role in the apoptotic process in that they trigger a cascade of apoptotic pathways. The release of cytochrome-c from mitochondria leads to the activation of procaspase-9 and then caspase-3 (Hengartner, 2000). The activation of caspase-3 is an important downstream step in the apoptotic pathway (Hengartner, 2000). In addition, the effector caspase, caspase-3, and the initiator caspases, caspase-8 and -9, are the main executors of apoptosis (Earnshaw et al., 1999). Caspase-8 is in the death receptor pathway, whereas caspase-9 is in the mitochondrial pathway, and both pathways share caspase-3 (Czabotar et al., 2014).

In a downstream pathway of apoptosis, once caspase-8 is activated, it directly processes the downstream effectors, caspase-3, -6, and -7. In an alternative pathway, caspase-8 activates crosstalk between the death receptor pathway and the mitochondrial pathway by the cleavage of Bid to Bid, a pro-apoptotic member of the Bcl2 family. The activation of caspase-8 has a central role in Fas-mediated apoptosis. Moreover, the cleavage of Bid has been shown to be associated with caspase-8 activation (Pommier et al., 2004). Taken together, the data presented in this study suggest that apoptosis induced by NS treatment may be involved in the mitochondrial pathways, as demonstrated by the increased expression levels of caspase-3, -8, and -9 after NS treatment. In addition, this study suggests the involvement of the extrinsic death pathway in MCF-7 breast cancer cell after treatment with NS, as demonstrated by increased expression levels of caspase-8. These data are in agreement with our recent published work in which NS exposure increased the expression of caspase-3, -8, and -9 several fold. This effect of NS can be attributed to the active compounds present in NS. The anticancer activity of thymoquinone (TQ), an active ingredient isolated from Nigella sativa, has been studied. TQ signiﬁcantly inhibited proliferation, induced apoptosis and activated caspase-3, -7 and -9 in the colon cancer cell line HCT116 (Kundu et al., 2014).

p53, the most commonly mutated gene associated with cancer, helps to regulate the cell cycle and has a key role in ensuring that damaged cells are destroyed by apoptosis. The data presented in this study indicate that the expression levels of p53 and caspase-3, -8 and -9 were markedly increased after NS treatment in a concentration-dependent manner. These data suggest that NS induced apoptosis by regulating pro-apoptotic genes.

The possibility that p53-mediated apoptosis may be associated with the activation of caspase-3, -8 and -9 is suggested by the ability of p53 to activate both the extrinsic and intrinsic apoptotic pathways (Salim et al., 2013). p53 enhances cancer cell apoptosis and prevents cell replication by stopping the cell cycle at G1 or interphase (Fridman and Lowe, 2003). By inducing the release of mitochondrial cytochrome-c, p53 might be able to activate the effector caspases, including caspase-3. Caspase-3, -8, and -9 may be the apoptotic effector machinery engaged by p53 to mediate teratogen-induced apoptotic pathways (Takaoka et al., 2003; Pekar et al., 2007).

In conclusion, to our knowledge, the results presented in this study show for the first time that NS exerts its anticancer effects by blocking the proliferation of MCF-7 cells and inducing apoptosis in part by modulating the expression levels of caspase-3, -8, and -9 and p53. NS induces, at least in part, p53 and caspase-mediated apoptosis in MCF-7 cells. Therefore, the present study demonstrates that NS signiﬁcantly inhibits the growth of MCF-7 human breast cancer cells in vitro and provides the underlying mechanism for the anticancer activity. NS could potentially represent an alternative source of medicine for Breast cancer therapy. The role of both p53 and caspases may represent the synergistic effect of different components of NS seeds. This study supports the development of dietetic plant product-based drugs for the treatment of breast cancer. Further research is required to characterize and analyze different components of NS seeds before developing a promising chemotherapeutic agent for breast cancer treatment from NS.

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References


