The Red Wine Polyphenol Resveratrol Displays Bilevel Inhibition on Aromatase in Breast Cancer Cells

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Estrogen plays a crucial role in the development of breast cancer, and the inhibition of estrogen synthesis has been an important target for the prevention and treatment of this disease. The rate-limiting reaction of the hormone biosynthesis is catalyzed by cytochrome P450 (CYP) 19 enzyme or aromatase. It has been of genuine interest to uncover an aromatase-inhibitory compound from a dietary source. Resveratrol is a polyphenolic compound that can be isolated from grape peel. Because of its structural resemblance to estrogen, resveratrol's agonistic and antagonistic properties on estrogen receptor have been examined and demonstrated. In the present study, the effect of resveratrol on the expression and enzyme activity of aromatase was investigated. By assaying on MCF-7 cells stably transected with CYP19 (MCF-7aro cells), resveratrol inhibited the aromatase activity with an IC50 value of 25μM. Kinetic analysis indicated that both competitive and noncompetitive inhibition might be involved. The administration of 10 nmol/l testosterone—a substrate of aromatase—produced a 50% increase in the MCF-7aro cell number. This cell proliferation specifically induced by testosterone was significantly reduced by 10μM resveratrol. In addition, 50μM resveratrol significantly reduced the CYP19-encoding mRNA abundance in SK-BR-3 cells. The transcriptional control of CYP19 gene is tissue specific, and promoter regions I.3 and II have previously been shown to be responsible for CYP19 expression in breast cancer cells. Luciferase reporter gene assays revealed that resveratrol could repress the transcriptional control dictated by the promoter regulation. The present study illustrated that pharmacological dosage of resveratrol inhibited aromatase at both the enzyme and mRNA levels.

Key Words: resveratrol; aromatase; breast cancer cell proliferation.

Epidemiological studies have shown that the use of exogenous estrogen (Collaborative Group on Hormonal Factors in Breast Cancer, 1997; IARC, 1999; Pike and Spicer, 1993) or augmented endogenous estrogen concentration (Adlercreutz et al., 1994; Toniolo et al., 1995) is associated with increased breast cancer risk. The causal relationship between estrogen exposure and breast cancer has been reviewed by Colditz (1999).

The cancer-inducing mechanisms of estrogen in the breast can be multifaceted and may participate in either the initiation or the promotion stage. Estrogen can be metabolized into various catechol estrogens, and estrogen-2-hydrolyase and estrogen-4-hydrolyase are cytochrome P450 (CYP) enzymes that hydroxylate estrogen at the C-2 and C-4 positions, respectively (Liehr, 2000). These hydroxylated metabolites can further be converted into quinone and semiquinone structures, which have been shown to be carcinogenic in animal models (Li and Li, 1987; Liehr et al., 1986). In addition, free radicals generated by some of these metabolites may cause oxidative DNA damage (Zhu and Conney, 1998). These genotoxic effects of estrogen have been demonstrated in MCF-7 cells (Yared et al., 2002) and rat mammary tissues (Zhang et al., 2001).

The notion that estrogen promotes breast cancer is reinforced in a transgenic mouse model that develops spontaneous mammary tumors. Treatment of estrogen accelerates the development of neoplastic lesions and carcinomas in these mice (Yoshidome et al., 2000). Estrogen-induced cell proliferation has been a major focus in breast cancer research. The pertinent mechanisms lie in the regulation of cell cycle (Dickson et al., 1987; Tsai and O’Malley, 1994), Bcl-2 family protein expression (Leung and Wang, 1999), and the interaction with plasma membrane receptors (Watson et al., 1999).

Estrogen is synthesized from cholesterol in several steps, and CYP19 (aromatase) catalyzes the final rate-limiting reaction. Aromatase is encoded by a single-copy gene (Means et al., 1989; Toda et al., 1990). The promoter utilization for CYP19 regulation varies in different tissues, which provides the basis for tissue-specific expression (Harada et al., 2003). Polymorphisms in the CYP19 gene have been associated with breast cancer risk (Lee et al., 2003). Many aromatase inhibitors have recently been developed, and some of them are promising agents for breast cancer prevention and therapy (Cuzick, 2003).

Resveratrol is a nonflavonoid phytoestrogen and can be isolated from grape peel. Previous epidemiological studies
have shown that resveratrol intake is inversely associated with breast cancer risk (Levi et al., 2005; Simopoulos, 2004). Because the CYP19-inhibitory property was previously demonstrated in red wine extract (Eng et al., 2001, 2002), we would like to evaluate whether resveratrol was one of the active ingredients for the inhibition in the present study. Two breast cancer cell lines, MCF-7aro and SK-BR-3, were used, respectively, for enzyme kinetic measurement and mRNA expression analyses.

**MATERIALS AND METHODS**

**Chemicals**

Resveratrol (Cat. No. R-5010) was obtained from Sigma Chemicals (St Louis, MO). All chemicals, if not stated, were purchased from Sigma Chemicals.

**Cell Culture**

The breast cancer cell line SK-BR-3 was a generous gift from Dr Richard K. W. Choy (Department of Obstetrics and Gynaecology, the Chinese University of Hong Kong, Kowloon, Hong Kong), and the parental breast cancer MCF-7 cell line, from which the stable transfected cell lines were derived, were obtained from American Tissue Culture Collection (Rockville, MD). The MCF-7 cells were stably transfected with human CYP19 (MCF-7aro), which were used for an “in-cell” aromatase assay as previously described (Zhou et al., 1990).

The stably transfected MCF-7 cells were maintained in Eagle’s minimum essential medium (Invitrogen, Grand Island, NY) supplemented with 10% fetal bovine serum (FBS) (Invitrogen Life Technology, Rockville, MD) and the selection antibiotic 500 μg/ml G418 (USB Corporation, Cleveland, OH). SK-BR-3 cells were cultured in McCoy’s 5A medium (Sigma Chemicals) with 10% fetal bovine serum (FBS) (Invitrogen Life Technology, Rockville, MD) and the selection antibiotic G418. SK-BR-3 cells were cultured and treated as described above. After 24 h of treatment, total RNA was extracted from the cells using TRIzol reagent (Invitrogen, Carlsbad, CA). The concentration and purity of the isolated RNA were determined by the absorbance reading observed at 260 and 280 nm. Three micrograms of total RNA, oligo-dT, and M-MLV Reverse Transcriptase (USB Corporation) were used for the first strand synthesis. Target fragments were quantified by real-time PCR and an Opticon 2 system (MJ Research, Waltham, MA). CYP19 copy number was determined by absolute quantification. A standard curve was constructed by 10-fold serial dilutions from 10 to 10^6 copies amplified from pGEMT-CYP19 or pGEMT-β-actin. Sample copy number was read from the standard curve. An SYBR green PCR Master Mix Reagent kit was obtained from Applied Biosystems (Foster City, CA), and PCR reactions were set up as described in the manual. A typical reaction contained 200 μmol/l of forward and reverse primer and 2 μl of cDNA, and the final reaction volume was 20 μl. The reaction was initiated by preheating at 50°C for 2 min, followed by 95°C for 10 min. Subsequently, 45 amplification cycles were then carried out with a 15-s denaturation at 95°C and 1 min annealing and extension at 58°C. Copies of β-actin RNA were also determined and used for normalization. The forward and reverse primers designed for CYP19 were 5’-ATC TCT GGA GAG GAA ACA CTC ATTA-3’ and 5’-CTG CCT TCA TAA AGA AGGG-3’. Those for β-actin were 5’-CCTAAGGAACTGCGTGGG-3’ and 5’-AGG CGT ACA GGG ATC GCA-3’, respectively. Dissociation curve and gel image analysis did not reveal nonspecific amplifications generated from these primers.

**Measurement of Cell Viability**

Previous studies (Grube et al., 2001; Sun et al., 1997; Wang et al., 2005) have shown that MCF-7aro cell proliferation is specifically induced by testosterone through aromatase-mediated estrogen synthesis. By comparing the positive and negative testosterone treatments, the contribution of aromatase on cell proliferation and the inhibition of cell proliferation through counter-acting aromatase can be estimated.

Cell number was assessed by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) staining as described by Mosmann (1983). Briefly, MCF-7aro cells were seeded in 96-well plates and maintained in EMEM supplemented with 10% charcoal dextran-treated serum (Hyclone, Logan, UT). The cells were allowed 24 h for attachment and treated with testosterone and/or resveratrol for 48 h. At the end of the treatment, 50 μl of 1 mg/ml of MTT was added to the cells and incubated at 37°C for 4 h. Cell viability was assessed with respect to the absorbance at 544 nm.

**Luciferase Gene Reporter Assay**

**Construction of CYP19 promoter–driven reporter plasmid.** As reviewed by Simpson et al. (1994), human aromatase is encoded by a single-copy gene with 10 exons. The expression of CYP19 is tissue specific and also regulated by alternate promoter usage. A nascent mRNA of aromatase comprises a protein-coding region coming from exons II to X and an untranslated subfracton coming from exon I located upstream of the coding region. There are different subfractons on the first exon that are controlled by various tissue-specific promoters. These subfractons of exon I are spliced onto a common acceptor site in exon II to form the nascent mRNA. The promoter usage, thus, dictates the expression of this gene.

A gene fragment (−446/+118) from human CYP19 upstream to exon II was amplified from genomic DNA isolated from SK-BR-3 cells. This fragment contained promoters I.3 and II that were specifically associated with expression in breast cancer cells (Zhou and Chen, 1999; Zhou et al., 1996). Primers were designed with the incorporation of KpnII and Xhol restriction sites.
The Lineweaver-Burk plots.

**Dual luciferase assays.** SK-BR-3 cells were plated in 24-well dishes at $1 \times 10^5$ per well. After 24 h, transient transfection was performed using 1 μl Lipofectamine and 2 μl Plus reagent (Invitrogen Life Technologies) per well. Reporter plasmids (0.25 μg, containing DNA fragments derived from aromatase promoter I,3 and II regions) were transfected into cells in serum-free medium. The renilla luciferase vector pRL-CMV (Promega Corp) was cotransfected as an internal correction for transfection efficiency. After a 5-h incubation, cells were cultured in phenol red–free PRMI 1640 supplemented with 5% charcoal dextran–treated FBS. After 1 day, the medium was removed, and the cells were treated with resveratrol for 24 h. The cells were lysed, and the activities of the luciferases were determined using Dual-Luciferase Assay Kit (Promega Corp). The luciferase bioluminescence was quantified by using a FLUOstar Galaxy plate reader. The transactivation activities of the CYP19 promoter represented by firefly luciferase light units were then normalized with that of renilla luciferase.

**Western Analysis**

Cells were washed once with PBS (pH 7.4) and harvested into a 1.5-ml microtube with 0.5 ml of lysis buffer (PBS, 1% NP40, 0.5% sodium deoxycholate, 0.1% SDS). The lysis buffer contained protease inhibitors (40 mg/1 phenylmethylsulphonyl fluoride, 0.5 mg/l aprotinin, 0.5 mg/l leupeptin, 1.1 mmol/l EDTA, and 0.7 mg/l pepstatin). The harvested cells were then lysed with a cell disruptor (Branson Ultrasound Corp., Danbury, CT) on ice for 30 s. The protein concentration of cell lysate was determined by Dc protein assay (BioRad, Richmond, CA). Fifty micrograms of lysate protein was separated on 10% SDS-PAGE and transferred onto an Immobilon PVDF membrane (Millipore, Bedford, MA). Primary antibody raised against aromatase (Abcam plc, Cambridge, United Kingdom) and β-actin (Sigma Chemicals), and secondary antibodies conjugated with horseradish peroxidase (HRP) (Santa Cruz Biotechnology, Santa Cruz, CA) were used for protein detection. An ECL Detection Kit (Amersham, Arlington Heights, IL) provided the chemiluminescence substrate for HRP, and the targeted protein was visualized by autoradiography.

**Statistical Methods**

A Prism 3.0 (GraphPad Software, Inc., San Diego, CA) software package was utilized for statistical analysis. The results were analyzed by one-way ANOVA followed by Bonferroni’s multiple comparison test if significant differences ($p < 0.05$) were observed. A t test was employed for comparison of the means between resveratrol-treated and control cultures in Figure 3. Another software package SigmaPlot (SPSS Inc., Chicago, IL) was used for graphing the Lineweaver-Burk plots.

**RESULTS**

**Enzyme Inhibition Assay Performed on MCF-7aro Cells**

A previous study (Wang et al., 2005) has indicated that MCF-7aro cells have an aromatase activity 200 times higher than that assayed in the control cells and can be substituted for recombinant enzyme assay. In the present study, resveratrol displayed an inhibitory effect with an IC$_{50}$ value about 25 μM in the MCF-7aro cell system (Fig. 1).

**Enzyme Kinetic Assay**

Four concentrations, i.e., 0, 10, 25, and 100 μM, of resveratrol were selected for testing the enzyme kinetic response. The Lineweaver-Burk plot revealed that the presence of resveratrol increase the values of $K_m$ and slope accompanying a reduction in $V_{max}$. The plot showed that resveratrol had a mixed type of inhibition on CYP19. In a subplot of slope values against various resveratrol concentrations, a $K_i$ value of 25 μM was determined (Fig. 2).

**Specific Inhibition on Testosterone-Induced Proliferation in MCF-7aro Cells**

Resveratrol was able to reduce the testosterone-induced proliferation of MCF-7aro cells through the inhibition of aromatase (Fig. 3). The administration of 10nM testosterone increased the cell number by 50% as shown at 0μM of resveratrol. Ten micromoles of resveratrol could significantly ($p < 0.05$) reduce the cell proliferation. At 50μM, resveratrol reduced the testosterone-induced cell viability to the same level as their counterparts without testosterone treatment.

**Resveratrol Reduced Aromatase mRNA Expression in SK-BR-3 Cells**

Because aromatase expression in MCF-7 cells was low, we employed the breast cancer cell line SK-BR-3 for the assessment of mRNA expression levels. Quantitative RT-PCR indicated that the mRNA abundance of aromatase was reduced by resveratrol. Cultures treated with 50μM resveratrol revealed a 55% drop in aromatase expression, and 100μM of the phytocompound could decrease the expression by about 75% (Fig. 4).

**Aromatase Activity in SK-BR-3 Cells Treated with Resveratrol**

Since the mRNA abundance could be suppressed by resveratrol, we measured the aromatase activity as an indication
for reduced expression. After 24 h of treatment, the aromatase activity was found to be significantly reduced by 25 μM resveratrol, and the IC50 value was estimated to be 43 μM (Fig. 5).

Effect of Resveratrol on Promoter Activity of CYP19 in SK-BR-3 Cells

As the mRNA expression is reduced by resveratrol, we subsequently determined the transcriptional control driven by promoter regions I.3 and II. Figure 6A demonstrated that the reporter plasmid was actively transcribed in SK-BR-3 cells. Twenty-five micromoles of resveratrol was able to repress the transactivation of CYP19 promoter activity (Fig. 6B) \((p < 0.05)\). This reporter gene assay result suggested that the decrease in mRNA abundance could be caused by inhibition at the transcriptional level.

Effect of Resveratrol on CYP19 at the Protein Level

Since all experiments indicated that the transcription of CYP19 was reduced by resveratrol, we further examined the

![Graph showing the kinetic analysis of resveratrol inhibition on CYP19.](https://academic.oup.com/toxsci/article-abstract/92/1/71/1642950)

**FIG. 2.** Kinetic analysis of resveratrol inhibition on CYP19. MCF-7aro cells were cultured and assayed for aromatase activity. Four concentrations, 0, 10, 25, and 100 μM, of resveratrol were coadministered to the cells for the enzyme kinetic assay. Values are means ± SEMs, \(n = 3\). Lineweaver-Burk plot showed that resveratrol had a mixed type of inhibition on CYP19 with a \(K_i\) value of 25.4 μM.

![Graph showing the reversal effect of resveratrol on testosterone-induced MCF-7aro cell proliferation.](https://academic.oup.com/toxsci/article-abstract/92/1/71/1642950)

**FIG. 3.** Reversal effect of resveratrol on testosterone-induced MCF-7aro cell proliferation. MCF-7aro cells were seeded in 96-well plates and maintained in EMEM supplemented with 10% charcoal dextran-treated serum. Cell number was quantitated after 48 h under the influence of testosterone administration. Values are means ± SEMs, \(n = 8\). (*) Mean values of testosterone-treated cultures were significantly \((p < 0.05)\) higher than those of the cultures without testosterone treatment. Means labeled with x differ \((p < 0.05)\) from those labeled with y; means labeled with a, b, c, or d are also significantly different.

![Graph showing message RNA expressions of aromatase in SK-BR-3 cells treated with resveratrol.](https://academic.oup.com/toxsci/article-abstract/92/1/71/1642950)

**FIG. 4.** Message RNA expressions of aromatase in SK-BR-3 cells treated with resveratrol. SK-BR-3 cells were seeded in six-well plates and maintained in McCoy’s 5A medium supplemented with 10% charcoal dextran-treated serum. Resveratrol was administered to the cultures for 24 h. The effect of resveratrol on the CYP19 expression was determined by real-time RT-PCR, and the CYP19 expression was normalized to β-actin. Values are means ± SEMs, \(n = 3\), and samples are isolated from independent cultures. *Mean values were significantly \((p < 0.05)\) different from those of the control cultures with no resveratrol treatment.
enzyme expression at the protein level. Figure 7 revealed that aromatase was reduced by resveratrol at the concentration of 25\(\mu\)M or more. The data represented one of two experiments with same result and were consistent with the mRNA and enzyme activity data.

**DISCUSSION**

In this study, we found that resveratrol inhibited aromatase activity in MCF-7aro cells, and the enzyme kinetic result revealed that both competitive and noncompetitive inhibitions were involved. A previous study from our laboratory has illustrated that MCF-7aro cells are a viable model for the screening of aromatase inhibitor from phytochemicals, and the differential growth rates observed in MCF-7aro and MCF-7vec cells under testosterone administration are attributed to aromatase activity (Wang et al., 2005). In the present study, resveratrol could inhibit both aromatase activity and testosterone-induced MCF-7aro cell proliferation. These results indicated that resveratrol was a CYP19 inhibitor at the enzyme level.

Resveratrol also reduced the aromatase mRNA abundance in another breast cancer cell line SK-BR-3. We illustrated that the decreased mRNA expression could occur at the transcription level. The promoter utilization of human aromatase gene is tissue specific, and promoters I.3 and II have been identified to be responsible for the expression in breast cancer cells (Chen et al., 1999). In the present study, we demonstrated that the transactivation activity of the gene fragment containing promoters I.3 and II was inhibited by resveratrol.

Many phytochemicals have also been documented to be aromatase inhibitors. By employing human placental microsomes, Le Bail et al. (2001) found that flavonoids exhibit inhibitory actions on aromatase with \(IC_{50}\) values ranging from 34.6\(\mu\)M to concentrations beyond 50\(\mu\)M. The phytochemical naringenin (Kao et al., 1998), on the other hand, is of greater potency than the flavonoids. Red wine extract can inhibit aromatase in the same placental assay system (Eng et al., 2001), and administration of the extract to transgenic mice overexpressing CYP19 in the mammary tissues abrogates mammary hyperplasia. Subsequently, the same group has identified one of the active ingredients in the extract to be procyanidin B dimers (Eng et al., 2003). Because the major source of procyanidin B is in grape seeds, the concentration may not be significant in red wine. In the present study,
resveratrol was demonstrated to inhibit CYP19 at the expression and enzyme levels and could be a contributor for the CYP19-inhibitory effect of red wine extract. This biological suppression of resveratrol might have advantages over procyandin.

Many factors have been described for the regulation of the transcription of aromatase. Cyclic AMP, phorbol esters, dexamethasone, prostaglandin E2, transforming growth factor β, and γ-interferon are documented compounds that increase the transcriptional activity (Simpson et al., 1997), whereas cyclooxygenase (COX) inhibitors exhibit inhibitory effect on CYP19 expression and enzyme activity (Diaz-Cruz et al., 2005). Since resveratrol can suppress COX-2 expression induced by phorbol ester (Subbaramaiah et al., 1998), we speculated that this could be an inactivation mechanism of CYP19 transcription observed in the present study.

Resveratrol has been proposed to be a potential chemopreventive agent against breast cancer. It can protect against 7,12-dimethylbenz[a]anthracene– or N-methyl-N-nitrosourea-induced mammary tumorigenesis, and the protein expression of some downstream genes of estrogen receptor transactivation are also altered (Bhat et al., 2001). The reduction in CYP1A1 expression and enzyme activity may contribute to the anti-initiation activities of resveratrol (Cioloino and Yeh, 1999; Lee and Safe, 2001). Moreover, resveratrol may interrupt the promotion or progression phase by inhibiting COX-2 (Subbaramaiah et al., 1998). Resveratrol’s agonist/antagonist activity toward estrogen receptor binding may contribute to the antagonism of estradiol-induced MCF-7 cell growth, the expression of transforming growth factor α, and insulin-like growth factor I receptor (Lu and Serrero, 1999). The minimum concentration at which aromatase inhibition was observed in the present study was comparable to these studies.

The physiological relevance of resveratrol concentration in human has not been clearly established. The total resveratrol concentration in human plasma is estimated to be around 40 μM after an ingestion of 1 mg of resveratrol per kg body weight at 1.5 h (Meng et al., 2004). In rats, a dosage of 2 mg/kg administered intragastric (ig) gives 1.2 μM resveratrol in blood.

In a pharmacokinetic study of resveratrol, Sale et al. (2004) have demonstrated that giving 240 mg/kg ig to mice would result in a peak plasma concentration of 32 μM in 2 h. Therefore, the effective CYP19-suppressing concentrations observed in the current study are most likely falling into the pharmacological range.

In summary, we demonstrated that resveratrol inhibited the enzyme activities and reduced the mRNA abundance of CYP19. This study suggested that resveratrol could reduce localized estrogen production in breast cancer cells.

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RESVERATROL INHIBITS CYP19


