Mitochondria, Calcium, and Calpain are Key Mediators of Resveratrol-Induced Apoptosis in Breast Cancer

Dhruv Sareen, Soesiaiwati R. Darjatmoko, Daniel M. Albert, and Arthur S. Polans

ABSTRACT

Resveratrol (RES), a natural plant polyphenol, has gained interest as a nontoxic chemopreventive agent capable of inducing tumor cell death in a variety of cancer types. However, the early molecular mechanisms of RES-induced apoptosis are not well defined. Using the human breast cancer cell lines MDA-MB-231 and MCF-7, we demonstrate that RES is antiproliferative and induces apoptosis in a concentration- and time-dependent manner. Preceding apoptosis, RES instigates a rapid dissipation of mitochondrial membrane potential by directly targeting mitochondria. This is followed by release of cytochrome c and second mitochondria-derived activator of caspase/direct inhibitor of apoptosis-binding protein with low pl (Smac/DIABLO) into the cytoplasm and substantial increase in the activities of caspases-9 and -3 in MDA-MB-231 cells. In addition, live cell microscopy demonstrates that RES causes an early biphasic increase in the concentration of free intracellular calcium ([Ca$^{2+}$]), probably resulting from depletion of the endoplasmic reticulum stores in breast cancer cells. In caspase-3-deficient MCF-7 cells, apoptosis is mediated by the Ca$^{2+}$-activated protease, calpain, leading to the degradation of plasma membrane Ca$^{2+}$-ATPase isoform 1 and fodrin; the degradation is attenuated by buffering [Ca$^{2+}$], and blocked by calpain inhibitors. Mitochondrial permeability transition pore antagonists also blocked calpain activation. In vivo mouse xenograft studies demonstrate that RES treatment inhibits breast cancer growth with no systemic toxicities. Together, these results suggest a critical role for mitochondria not only in the intrinsic apoptotic pathway but also in the Ca$^{2+}$ and calpain-dependent cell death initiated by RES. Thus, RES may prove useful as a nontoxic alternative for breast cancer treatment.

Despite earlier diagnosis and aggressive therapeutics, breast cancer remains a leading cause of death among women. The chance of developing invasive breast cancer during a woman’s lifetime is approximately 1 in 8, and more than 40,000 women die of metastatic disease each year (Jemal et al., 2006). Inherent or acquired tumor drug resistance limits many agents used in the treatment of this disease. In addition, these cytotoxic agents are often associated with severe, dose-limiting, systemic toxicities. Therefore, the need for development of novel nontoxic therapeutic agents active against breast cancer remains an important goal.

Basic and preclinical research on resveratrol (RES [trans-3,4’,5-trihydroxystilbene]), a naturally occurring polyphenol enriched in grapes and red wine, has shown pleiotropic cardioprotective, antiaging, and anticancer activities (Savouret and Queene, 2002; Aggarwal et al., 2004; Bradamante et al., 2004). RES has been shown to inhibit tumor initiation, promotion, and progression in a variety of cell culture systems, including breast cancer cells (Jang et al., 1997; Bhat et al., 2004). It is noteworthy that RES suppresses in vivo tumor growth in xenograft and mutagen-induced animal models of mammary carcinogenesis (Banerjee et al., 2002; Garvin et al., 2006). Preliminary studies in our laboratory suggest that RES is effective in preventing tumor growth in neuroblas-
toma and uveal melanoma murine xenograft models. Nevertheless, the precise mechanisms by which RES confers inhibition of tumor growth in vivo have not been well elucidated. In vitro studies on human cancer cell lines revealed that RES initiates antiproliferative and/or pro-apoptotic actions (Savouret and Quesne, 2002). The pro-apoptotic effect of RES has been attributed to downstream events activated after binding to putative cell surface receptors, including integrin αvβ3 and sulfonylurea receptor isoform 1 (Lin et al., 2006; Hambrock et al., 2007). In addition, RES targets several enzymes involved in carcinogenesis, suggesting that multiple signaling cascades may be activated or inhibited depending on the cellular background (Sareen et al., 2006).

Apoptosis requires the participation of intracellularzymogens that systematically dismantle the cell via two distinct pathways. Activated caspase-8 (extrinsic death-receptor pathway) and activated caspase-9 (intrinsic mitochondrial pathway) both activate the executioner caspase-3, which in turn activates the degradation phase of apoptosis (Ashkenazi and Dixit, 1998; Green and Reed, 1998). There is evidence that RES can induce apoptosis through both mechanisms, although the absence of functional caspase-3 in MCF-7 breast cancer cells indicates that alternative mechanisms may be involved (Delmas et al., 2003; Mohan et al., 2006; Sareen et al., 2006). In a separate intrinsic apoptotic pathway, alterations in Ca2+ homeostasis involving the ER can cause a stress response. In resting cells, the concentration of Ca2+ in the extracellular milieu and in the ER is relatively high (in the millimolar range). In contrast, the cytoplasmic Ca2+ concentration is maintained at ~100 nM by active extrusion from the cell by plasma membrane Ca2+-ATPases (PMCA), plasma membrane Na+/Ca2+ exchangers, and active uptake of cytosolic Ca2+ into the ER and mitochondria by distinct Ca2+-ATPases and transporters, respectively. During elevated levels of cytosolic Ca2+ the mitochondrial membrane potential (ΔΨm) drives Ca2+ uptake into the mitochondria. Under conditions of stress, de-energized mitochondria release Ca2+ back to the cytosol via different mechanisms, opening of the mitochondrial permeability transition pore (mPTP) being one (Orrenius et al., 2003). Loss of Ca2+ homeostatic control either by release from the ER and mitochondria or influx through plasma membrane channels leads to sustained levels of cytosolic Ca2+ and cell death. However, the mechanisms that couple changes in cellular Ca2+ to apoptotic cell death in response to RES have been elusive and, in particular, the apoptosis-related Ca2+ targets have not been identified.

Although the best characterized proteases in apoptosis are caspases, other proteases, including calpains and cathepsins, contribute to apoptosis in the absence of caspase activation (Harwood et al., 2005). The Ca2+-dependent cysteine proteases, m- and μ-calpains, are frequently activated in apoptosis models involving elevated [Ca2+]i. Calpain substrates include membrane receptors and transporters, cytoskeletal proteins, and intracellular enzymes. In particular, there is evidence that proteolysis of plasma membrane Na+/Ca2+ exchanger 3 by calpain plays a prominent role in the delayed and irreversible Ca2+ elevation leading to neuronal demise (Bano et al., 2005). However, the mechanisms of cellular calpain activation during apoptosis are not well understood, and little is known about the involvement of calpains in tumor cell death.

In this study, we sought to investigate the early and pivotal intracellular apoptotic signaling mechanisms in MDA-MB-231 (caspase-3 positive) and MCF-7 (caspase-3 negative) breast cancer cells in response to RES. We demonstrate that RES significantly inhibits tumor growth in a xenograft model of breast cancer. In vitro and in vivo data show that RES induces mitochondrial depolarization and a transient spike in [Ca2+]i, followed by a secondary gradual rise in [Ca2+]i, contributing to an irreversible commitment to undergo the execution phase mediated by caspases and calpains.

Materials and Methods

Materials. The human breast cancer MCF-7 and MDA-MB-231 cell lines were obtained from Dr. Elaine Aralid (University of Wisconsin, Madison, WI). RES purchased from Cayman Chemicals (Ann Arbor, MI) was dissolved in sterile DMSO and further diluted in cell culture media. Mouse monoclonal antibodies were purchased for GAPDH from Biogenesis Inc. (Poole, UK), cytochrome oxidase subunit IV (clone 12C4) from Invitrogen (Carlsbad, CA), cytochrome c (clone TH8.2C12) from BD Pharmingen (San Diego CA), Smac/DIABLO from Cell Signaling Technology (Danvers, MA), α-fodrin (clone AA6) from BIOMOL International LP (Plymouth Meeting, PA), apoptosis-inducing factor (E-1) from Santa Cruz Biotechnology (Santa Cruz, CA). Rabbit polyclonal PMCA1 antibody was obtained from Affinity Bioreagents (Golden, CO). All other common reagents were procured from Sigma Chemical Co. (St. Louis, MO).

Cell Culture. MDA-MB-231 and MCF-7 cells were grown in Dulbecco’s modified Eagle’s medium, supplemented with 10% (v/v) fetal bovine serum, 2 mM l-glutamine, 100 units/ml penicillin G, 100 mg/ml streptomycin sulfate, and 0.25 mg/ml amphotericin B. Cultures were maintained at 37°C in 5% CO2.

Breast Cancer Xenograft Study. Female athymic nu/nu mice, ~6 weeks of age (Harlan Sprague-Dawley, Indianapolis, IN), were housed in a pathogen-free isolation facility. Animal care and treatment protocols were approved by the University of Wisconsin-Madison Institutional Animal Care and Use Committee. Female Sprague-Dawley breast cancer animals were purchased, 5 × 106 cells reseeded in 500 μl of 1:1 culture media and basement membrane matrix (Matrigel; BD Biosciences, San Jose, CA) and injected subcutaneously into the dorsal flanks of 72 mice. After the tumors were established (150 mm3), the animals were randomized into control and treatment groups (n = 36 mice per group). Control group animals were administered 0.1 ml of Neoebe M5 oil alone, and treatment group animals received 50 mg/kg resveratrol in 0.1 ml of Neoebe M5 oil by oral gavage daily for 5 weeks. Twice weekly during the treatment, each animal was weighed and the tumor volume was determined by measuring tumor size in three dimensions using calipers. Toxicity was assessed by survival, activity, and changes in body weight. At the completion of 5 weeks of treatment, the mice were euthanized; tumors, lungs, and livers were fixed in 10% neutral buffered formalin for histopathologic processing. Five-micrometer sections were cut and stained with hematoxylin & eosin for light microscopic analysis.

Tumor Cell Viability. MCF-7 and MDA-MB-231 cells were seeded in 96-well plates for 2 days and incubated with either DMSO or RES for a period of 1 to 7 days. At the end of the treatment, CellTiter-Blue dye was added according to the manufacturer’s instructions (Promega, Madison, WI). Fluorescence was measured at excitation/emission wavelengths of 560/590 nm, using a fluorescence...
Cell Cycle Distribution Analysis. Propidium iodide staining was used to analyze DNA content on a flow cytometer (BD Biosciences FACstation) equipped with cell cycle analysis software, using standard procedures (Sareen et al., 2006).

Determination of Apoptotic Cell Morphology. MCF-7 and MDA-MB-231 cells were seeded into eight-well LabTek II chamber-slides (Nalge Nunc International, Rochester, NY) and treated with 100 μM RES. At the end of the treatment, cells were fixed, washed, and stained with 1 μg/ml Hoechst 33528 (Invitrogen), using standard procedures (Sareen et al., 2006). Cells were viewed under a fluorescence microscope (Carl Zeiss, Oberkochen, Germany) using a 4.6-diamidino-2-phenylindole filter set, and apoptotic cells were counted.

Isolation of Mitochondria. Mitochondria from MCF-7 and MDA-MB-231 cells were isolated using a Potter-Elvehjem homogenizer according to previously published methods (Sareen et al., 2006).

Mitochondrial Transmembrane Potential. Changes in mitochondrial membrane potential from whole cells and isolated mitochondria were analyzed on a Shimadzu RP 5301-PC spectrophotofluorometer (Shimadzu Scientific, Columbia, MD) using the mitochondria-selective dye JC-1 (Cell Technology, Mountain View, CA), as described previously (Sareen et al., 2006).

Cytochrome c and Smac/DIABLO Release. Cytosolic and mitochondrial extracts were analyzed for cytochrome c and Smac/DIABLO content by immunoblotting, as described previously (Pozzo-Guisado et al., 2005; Sareen et al., 2006). Protein concentration of the fractions was determined using the Bio-Rad protein assay kit (Bio-Rad Laboratories, Hercules, CA). Purity of the cytosolic fraction was confirmed by immunostaining with a mitochondria-specific marker, cytochrome oxidase subunit IV. GAPDH, a cytoplasmic protein, served as a control for protein loading.

Determination of Caspase Activation. MCF-7 and MDA-MB-231 cells were seeded on 10-cm culture dishes, treated with vehicle, RES, or additional apoptotic stimuli, and the activities of caspases-2, -3, -8, and -9 determined as described previously (Mohan et al., 2006; Guisado et al., 2005; Sareen et al., 2006). Protein concentration of the mitochondrial extracts were analyzed for cytochrome oxidase subunit IV. GAPDH, a cytoplasmic protein, served as a control for protein loading.

Calpain Activity. Calpain activity in intact cells was monitored using a Shimadzu RP 5301-PC spectrophotofluorometer (Shimadzu Scientific, Columbia, MD) by measuring Ca2+-dependent and calpain specific hydrolysis of the peptide 7-amino bond of the cell-permeable fluorogenic calpain substrate, S-L-LVY-AMC (Sigma) (Potter et al., 1998). Previous studies have demonstrated that this assay is linear with cell number and the activity measured is representative of m- and μ-calpain activities observed with protein substrates (Sasaki et al., 1984; Guttman and Johnson, 1998). In brief, cells from confluent dishes were harvested with 0.25% trypsin-EDTA solution, neutralized with 10% fetal bovine serum containing media, and washed twice with HEPES-buffered Hank's balanced salt solution, pH 7.4, without phenol red. Equal numbers of cells per assay were resuspended in HEPES-buffered Hank's balanced salt solution at 2.5 × 10⁵ cells/ml and prewarmed at 37°C in a 5% CO2 incubator for 10 min. Wherever indicated, the intracellular Ca2+-chelator BAPTA-AM (20 μM), the cell-permeable μ- and m-calpain inhibitors PD 150606 (50 μM; selectively blocks the Ca2+ binding sites), SJA 6017 (50 μM; active site inhibitor), and MDL 28170 (25 μM; active site inhibitor) and the mPTP inhibitor cyclosporin A (CsA; 20 μM) (EMD Biosciences) were pretreated in the cell suspension, mixed, and incubated at 37°C for 30 to 45 min. To assay calpain activity, RES (100 μM final concentration) or DMSO vehicle was added to untreated or pretreated cell suspension (2.5 × 10⁵ cells) 1 min before S-L-LVY-AMC (25 μM) addition. Fluorescence was measured and calpain activity plots obtained at various time points on the spectrophotofluorometer with the excitation/emission wavelengths of 360 nm/400 to 500 nm. The initial rate of substrate cleavage, which is linear, was measured at 5 to 15 min after substrate addition. Trypan blue exclusion was used to ensure that the cells remained viable through the procedure.

Immunoblotting. Cultures were washed twice with PBS and lysed in ice-cold lysis buffer (50 mM Tris-HCl, pH 7.5, 150 mM NaCl, 0.5% Nonidet P-40, 1 mM PMSF, 1 mM NaF, 1 mM dithiothreitol, and 4 mg/ml complete protease inhibitor cocktail). Protein concentration was determined in cell lysates using the Bio-Rad protein assay kit. Aliquots of protein were mixed with SDS sample buffer and Western blot analysis performed using standard protocols (Sareen et al., 2006).

Results

Resveratrol Inhibited Tumor Growth in Athymic Nude Mice. We examined the effect of resveratrol on human breast cancer tumor growth in vivo by ectopic implantation of MDA-MB-231 cells into athymic nude mice. After 5 weeks of oral drug treatment, tumor growth in the RES-fed group,
compared with the control groups that were fed vehicle alone, was inhibited by 51% \((p = 0.003)\) (Table 1). RES treatment had no effect on body weight and diet consumption during the 5 weeks of the experiment. No other signs of systemic toxicity or any adverse health effects as monitored by activity and posture of mice were observed. Furthermore, liver sections from RES-treated mice showed no evidence of abnormal pathology compared with those from controls. In addition, 14% (5/36) of the mice in the MDA-MB-231 RES-treated group showed regression of tumor size relative to the initial tumor volume (data not shown).

**Resveratrol Displayed Dose- and Time-Dependent Proapoptotic and Antiproliferative Effects in Breast Cancer Cells.** To examine the antitumor activity of RES in human breast cancer cells, exponentially dividing MDA-MB-231 and MCF-7 cells were treated with increasing concentrations of RES, and cell viability was measured over time. RES caused marked growth inhibition and significantly decreased the viability of MDA-MB-231 cells (IC\(_{50}\) at 48 h = 128.8 \(\mu\)M) and MCF-7 cells (IC\(_{50}\) at 48 h = 151.8 \(\mu\)M) in a time- and concentration-dependent manner compared with the DMSO-treated control (Fig. 1A). At 100 to 200 \(\mu\)M RES, there was a regression in the number of viable cells (Fig. 1A; compare days 1 and 7). The cytotoxicity caused by RES may be due in part to antiproliferative and proapoptotic effects. Consequently, the effect of RES on cell cycle progression was analyzed by flow cytometry in exponentially dividing cultures of MDA-MB-231 and MCF-7 cells treated with either DMSO or RES, and the percentages of cells in G\(_0/G_1\), S, and G\(_2/M\) phases were calculated (Fig. 1B). RES caused an accumulation of cells in the S phase of the cell cycle for both cell lines [MDA-MB-231 (21% in control versus 70% and 71% with 50 and 100 \(\mu\)M RES, respectively) and MCF-7 (47% in control versus 70% with 50 \(\mu\)M RES)] with a concomitant decrease in the population of cells in the G\(_0/G_1\) phase, indicative of a late S phase or early G\(_2/M\) block. It is noteworthy that at 100 \(\mu\)M RES, the population of MCF-7 cells in G\(_0/G_1\) increased to 54%, whereas cells in G\(_2/M\) decreased to 2%, suggestive of an early S phase block. These data are consistent with previous observations from other groups (Aggarwal et al., 2004; Kim et al., 2004). The block in cell cycle progression, therefore, contributes to RES-induced antiproliferative effects. In addition, there was a significant increase in the sub-G\(_1\) fraction (hypodiploid DNA content) in both cell lines, possibly due to DNA fragmentation, resulting in an increase in RES-induced apoptotic cell death (data not shown). Subsequently, the ability of RES to cause MDA-MB-231 and MCF-7 cell apoptosis was determined by examining nuclear morphological changes with fluorescence microscopy. Cells that exhibited typical morphological features of apoptosis, such as chromatin condensation and pyknotic nuclei, increased in a time-dependent manner when treated with RES. Results are represented as the percentage of apoptotic cells, which increased from 1.3% and 0.9% in control to 52% and 45% in RES-treated MDA-MB-231 and MCF-7 cells, respectively (Fig. 1C), suggesting that RES has a proapoptotic effect in both breast cancer cell lines. The morphological changes indicative of apoptotic cell death were further confirmed by transmission electron microscopy providing evidence that the mitochondria were predominantly affected by RES (data not shown).

**Resveratrol Disrupted Mitochondrial Function in Breast Cancer Cells.** During chemical-induced apoptosis, early and pivotal events occur in the mitochondria that are often, although not always, associated with the collapse in \(\Delta\Psi_{m}\) (Sun et al., 1999). To delineate this mechanism, we measured RES-induced alterations in \(\Delta\Psi_{m}\) by using the mitochondrial selective lipophilic cation JC-1. In MDA-MB-231 and MCF-7 cells, RES exerts a dose-dependent decrease in the ratio of JC-1 red-green fluorescence intensity after 10

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**TABLE 1**

Oral administration of resveratrol suppresses growth of an established MDA-MB-231 breast cancer xenograft in vivo

<table>
<thead>
<tr>
<th>Group</th>
<th>Tumor Size</th>
<th>Standard Error</th>
<th>n</th>
<th>P Value</th>
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</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>630.96</td>
<td>103.86</td>
<td>36</td>
<td>0.003</td>
</tr>
<tr>
<td>50 mg/kg RES</td>
<td>307.62</td>
<td>52.3</td>
<td>36</td>
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MDA-MB-231 cells resuspended in Matrigel were injected subcutaneously into the dorsal flank of C57BL/6J mice, and tumors were allowed to grow. Thirty-six mice per group were fed vehicle (50 mg/kg per day) in vehicle (Neobee M5 oil) or vehicle alone by oral gavage. At the end of 5 weeks of treatment, tumors were recovered and measured. Tumor volume was transformed to the log scale before analysis to obtain approximately normal distribution residuals and analyzed using a one-way analysis of variance test to detect statistical differences in tumor size among the groups. Data represent the average tumor volume in mm\(^3\) assessed by caliper measurement ± S.D. Differences in tumor volume among the vehicle- and RES-treated groups were considered statistically significant at \(p < 0.05\).
Resveratrol causes loss of ΔΨm in intact cells and isolated mitochondria. MDA-MB-231 cells (A) and MCF-7 cells (B) were treated with DMSO (UNT) or 50, 100, and 200 μM RES, 25 μM FCCP, and 10 μM valinomycin for 10 min. Cells in a suspension at 5 × 10^5 cells/ml were rinsed, stained with JC-1 dye, and monitored for changes in the red-green fluorescence ratio (red fluorescence derived from J-aggregates in the mitochondria - green fluorescence from monomeric JC-1 in the cytosol). C and D, mitochondrial fractions were isolated from MDA-MB-231 (C) and MCF-7 (D) cells as described under Materials and Methods. Protein concentrations were measured using the Bradford assay to determine equal amounts per sample. Isolated mitochondria were treated with DMSO (UNT) or 10 nM, 1 μM, 5 μM, 10 μM, and 100 μM RES, 0.5% sodium azide and 25 μM FCCP for 10 min and stained with JC-1. Changes in ΔΨm were measured by monitoring JC-1 red fluorescence intensity; UD, undetectable. Data (A, B, C, and D) represent means ± S.D. of duplicate samples. Results are representative of one of three independent experiments with similar results.

Resveratrol Mediated Release of Apoptogenic Factors from the Mitochondria of MDA-MB-231 cells. Various apoptotic stimuli lead to changes in mitochondrial membrane permeability, resulting in loss of ΔΨm, and the subsequent release of apoptogenic factors, including cyt c and Smac/DIABLO. Western blot analysis was performed on cytosolic and mitochondrial fractions isolated from untreated or RES-treated breast cancer cells. In MDA-MB-231 cells, cyt c and Smac/DIABLO could be detected in the cytosolic compartment as early as 4 h after RES exposure (Fig. 3). Both proteins are progressively released into the cytosolic fraction in increasing amounts over 4 to 48 h of RES treatment, after a loss in ΔΨm seen much earlier, at 15 min after treatment. However, similar to our observations in other cancer models, RES could not provoke cyt c or Smac/DIABLO release from isolated mitochondria of breast cancer cells (data not shown), perhaps indicating a requirement for additional cytosolic factors (Sareen et al., 2006).

Resveratrol Activated Caspase-Dependent and -Independent Cell Death in MDA-MB-231 and MCF-7 Cells, Respectively. Mitochondrion- and death receptor-dependent apoptosis is known to be executed by the linkage activation of initiator caspases, which include caspases-2, -8, -9, -10, and -12, and effector caspases, which include caspases-3, -6, and -7. We and others have established that loss of ΔΨm and release of apoptogenic factors accompanies mitochondrial-dependent apoptosis induced by RES (Aggarwal et al., 2004; Sareen et al., 2006). To further determine the involvement of caspases in breast cancer cells upon RES-induced Ca^{2+} deregulation and mitochondria-mediated apoptosis, we examined cleavage of fluorescent peptide substrates that mimic the target cleavage sites of caspases-2, -8, -9, and -3/7. It has been reported that MCF-7 cells lack caspase-3 activity because of a point mutation in the gene coding for this protein (Jänicke et al., 1998). As expected, RES was unable to induce caspase-3 as well as caspase-9 activation in this cell line (Fig. 4, A and B). However, a
demonstrable time-dependent increase in the activities of caspase-9 and -3 can be identified in RES treated MDA-MB-231 cells (Fig. 4, A and B). Slight increase in caspase-9 and -3 activities were already detectable 24 h after the addition of RES, although maximum activation of ~3- to 5-fold was observed after 72 h.

RES-induced apoptosis also could be regulated by the death-receptor pathway via early caspase-2 and -8 activation (Mohsin et al., 2006). To address this possibility, cells were treated with RES and incubated with peptide substrates specific to caspase-2 and -8. RES was unable to induce either caspase-2 or -8 activation in MCF-7 and MDA-MB-231 cells compared with the untreated control (Fig. 4, C and D). This effect could not be attributed to MDA-MB-231 cells being refractory to activation of caspase-2 and -8 because the apoptotic inducers UV radiation, TG, and staurosporine provoked significant activation of the proteases. Caspase-2 activation could not be detected in MCF-7 cells in response to apoptotic stimuli tested. Moreover, we did not observe cleavage of procaspase-12, an ER stress-specific initiator caspase, upon RES treatment (data not shown).

**Resveratrol Increased Intracellular Calcium Levels in Breast Cancer Cells.** In many cases, an early and pivotal event in apoptosis is a Ca$$^{2+}$$ influx through plasma membrane channels and/or release from the ER into the cytosol. RES has been demonstrated to enhance agonist-stimulated [Ca$$^{2+}$$]i increase in endothelial cells of the heart valve; however, there is no information about whether alteration of Ca$$^{2+}$$ homeostasis plays a pivotal role during early RES-mediated cell death (Buluc and Demirel-Yilmaz, 2006). To determine whether this was an early event during RES-induced apoptosis, we first examined whether intracellular Ca$$^{2+}$$ levels increased in log-phase MCF-7 cells after RES exposure using fura-2-AM in a spectrofluorometric assay.

Eight minutes after treatment, RES and ionomycin caused ~3- and 1.7-fold increases in [Ca$$^{2+}$$]i, respectively, compared with the vehicle control (Fig. 5A).

This result was substantiated by performing live cell Ca$$^{2+}$$-imaging on a BD Pathway Bioimaging microscopy system with fura-2 loaded MCF-7 cells. Before drug addition, cells analyzed in different regions of interest (ROI) started to show comparable basal fura-2 fluorescence, reflecting resting intracellular Ca$$^{2+}$$ levels. After RES addition, an elevation in intracellular Ca$$^{2+}$$ levels was observed within different ROI of MCF-7 cells (Fig. 5B), supporting data from our spectrofluorometric assay. The same results were obtained from similar experiments conducted with MDA-MB-231 cells. Figure 5 further illustrates the kinetics of RES-induced changes in [Ca$$^{2+}$$]i, and provides an indication of the source of Ca$$^{2+}$$ release. The basal [Ca$$^{2+}$$]i, level in MDA-MB-231 cells was 142 ± 39 (mean ± S.E.) nM; n = 36. At 10 to 35 s after exposure to RES, cells exhibited a significant increase of ~2- to 4-fold in [Ca$$^{2+}$$]i, with peak levels at 476 ± 96 nM, after which time the levels returned to approximately 283 ± 44 nM, although they never reached the basal levels (Fig. 5C; images with inset and graph). It is noteworthy that, beginning at ~240 s after RES exposure, there was a second gradual rise in [Ca$$^{2+}$$]i, that saturated at ~900 s with a peak value of 422 ± 68 nM and did not return to resting levels within the experimental time of 45 min. The basal level of [Ca$$^{2+}$$]i, (128 ± 29 nM; n = 28) was not affected significantly in both cell lines upon treatment with the DMSO vehicle control (Fig. 5E, top right). To ensure that the RES-induced changes in [Ca$$^{2+}$$]i, detected by fura-2 are Ca$$^{2+}$$-specific, cells preloaded with the intracellular Ca$$^{2+}$$ chelator BAPTA-AM were evaluated by imaging. BAPTA-AM increased the cytosolic Ca$$^{2+}$$ buffering capacity of the cells; the magnitude of the [Ca$$^{2+}$$]i rise after RES exposure was almost completely attenuated (Fig. 5E, bottom right). Untreated or BAPTA-AM-loaded cells did not show fluctuations in basal Ca$$^{2+}$$ levels during the time course of the experiment.

Because the ER is a major intracellular reservoir of Ca$$^{2+}$$, we tested whether the Ca$$^{2+}$$ signal evoked by RES originated from this organelle by employing TG, a known specific mobilizer of the ER Ca$$^{2+}$$ stores that causes rapid and transient increases in [Ca$$^{2+}$$]i. If RES exposure led to release of Ca$$^{2+}$$ stored in the ER, then TG administration should not cause additional Ca$$^{2+}$$ release. If the sequence of drug administration were reversed, additional Ca$$^{2+}$$ release should not be observed. TG alone evoked a typical Ca$$^{2+}$$ response of ~3- to 4-fold over basal [Ca$$^{2+}$$]i, 35 s after exposure; cells reached a maximal concentration of 454 ± 82 nM (Fig. 5D, images and graph). When TG was added to cells after RES, none of the cells that initially responded to RES exhibited a rise in intracellular Ca$$^{2+}$$ levels after TG administration (Fig. 5E, bottom left). Likewise, when RES was added after TG-induced depletion of ER Ca$$^{2+}$$ stores, no measurable spike was observed (Fig. 5E, top left). However, the second gradual rise in [Ca$$^{2+}$$]i, was unaffected by RES addition. We noted that the increase in [Ca$$^{2+}$$]i, (3-4-fold over basal levels, Fig. 5C) observed after exposure to RES was comparable with that elicited by TG (Fig. 5D), further suggesting that the two agents may mobilize the same ER pool of Ca$$^{2+}$$. The percentage of cells responding to RES and TG in a given culture was similar, averaging ~80%.
Resveratrol Activates a Calpain-Dependent Apoptotic Pathway in MCF-7 Cells. Despite the lesion in the intrinsic mitochondrial apoptotic pathway, MCF-7 cells undergo apoptosis in response to RES at an IC₅₀ similar to that of MDA-MB-231 cells that express caspase-3. The rise in \([\text{Ca}^{2+}]_i\) and the resulting \(\text{Ca}^{2+}\) overload is thought to activate \(\text{Ca}^{2+}\)-dependent proteases, such as calpains, leading to structural damage and eventually cell death in certain neuronal models of apoptosis (Liu et al., 2004; Bano et al., 2005). However, little is known about the involvement of calpains in tumor cell death. To avoid the invasive procedure of cellular lysates, we performed the calpain activity assay in intact MCF-7 cells by using a cell-permeable and fluorescent calpain substrate, S-LLVY-AMC. In addition, MCF-7 cells provided an opportunity to unmask a calpain-dependent apoptotic pathway as a result of the absence of an active caspase-dependent intrinsic mitochondrial apoptotic pathway. Calpain activity in RES-treated cells is early and significantly higher compared with the basal levels observed in DMSO-treated control cells, measured at 15 min after drug addition (Fig. 6A). As expected, in samples pretreated with the intracellular \(\text{Ca}^{2+}\)-chelator BAPTA-AM and calpain inhibitors with various specificities (PD 150606, MDL 28170, and SJA 6017), the RES-induced increase in calpain activity was almost completely blocked. This bolsters evidence that the fluorescent signal measured in this assay was dependent upon an increase in intracellular \(\text{Ca}^{2+}\) and is specific for calpain activity. The RES-induced increase in calpain activity remains substantial at 36 h after treatment (data not shown).

Upon apoptotic insult, the mitochondria play an essential role in buffering nontoxic loads of \(\text{Ca}^{2+}\), and the mPTP provides a fast \(\text{Ca}^{2+}\) extrusion mechanism in response to abnormally high levels that accumulate in mitochondria during apoptosis. Some mPTP antagonists, such as CsA, have been shown to inhibit this process, either through specific inhibition of cyclophilin D or through inhibition of calcineurin phosphatase activity (Montero et al., 2004). To determine whether mitochondrial \(\text{Ca}^{2+}\) release from mPTP was involved in RES-induced calpain activation, we employed the mPTP inhibitor CsA. The increase in AMC fluorescence, indicating calpain activation, can be seen in RES-treated MCF-7 cells (Fig. 6B). It is noteworthy that RES-induced calpain activation was completely abolished by CsA pretreatment. The fact that CsA prevented calpain activation suggests that mPTP somehow mediated the observed calpain activation after RES treatment.

Degradation of Calpain-Specific Protein Substrates Contributed to Resveratrol-Induced MCF-7 Cell Death. To further characterize the mechanism of calpain-dependent cell death initiated by RES, we investigated the in vivo cleavage pattern of calpain protein substrates in MCF-7 cell lysates by Western analysis (Fig. 7). Fodrin (α-spectrin) is a known substrate of caspase-3 as well as calpains. Although caspases and calpains share a number of substrates, their cleavage during treatment with RES in MCF-7 cells would indicate calpain activation, because effector caspases are
not activated in this model. Over a period of 24 to 48 h, in the presence of RES, specific calpain-dependent processing of fodrin was detected, evidenced by disappearance of the 240/280-kDa native band. However, in the presence of RES and the calpain inhibitor SJA 6017, the native fodrin remains intact at all times and the 145/150-kDa cleavage was not observed (Fig. 6B, top). As expected, no caspase-3-mediated 120 kDa breakdown product was observed. Mechanisms that regulate the cellular extrusion of Ca\textsuperscript{2+} could potentially rectify the RES-induced Ca\textsuperscript{2+} increase. To determine whether RES-activated calpain can target such a mechanism, we explored the cleavage pattern of Ca\textsuperscript{2+} pumps in the presence of a known calpain inhibitor. Beginning at 24 h after RES treatment, native PMCA1a/b (130–134-kDa) was cleaved in a calpain-dependent manner in MCF-7 cells (Fig. 6B, middle).

Cotreating cells with the calpain inhibitor SJA 6017 in the presence of RES prevented PMCA1a/b cleavage. However, there was no evidence of calpain-dependent PMCA4 degradation in the presence of RES (data not shown).

**Discussion**

In search for novel strategies for further management of breast cancer, we have attempted to identify the molecular mechanisms involved in RES-induced apoptosis, both caspase-dependent and -independent. To the best of our knowledge, this is one of the first studies to describe the chemotherapeutic effects of RES-induced alterations in Ca\textsuperscript{2+} homeostasis.

In the present study, we illustrate the in vivo anticancer efficacy of RES against breast cancer tumor growth in the MDA-MB-231 xenograft model without any toxicity. Data from preliminary studies suggests that RES exhibits similar efficacy against the MCF-7 xenograft model. In vitro studies demonstrate that RES exerts dose- and time-dependent antiproliferative and proapoptotic effects in MCF-7 and MDA-MB-231 cells, thus decreasing cell viability. The antiproliferative activity of RES against tumor cell lines of different origins has been extensively characterized and attributed to inhibition of various factors, such as cyclooxygenase-1 and -2, ribonucleotide reductase, nuclear transcription factor-κB, and its target genes (Aggarwal et al., 2004; Delmas et al., 2006). In contrast to in vitro data on enzyme inhibition, the RES anticancer effect in vivo may involve deregulation of multiple targets, promoting parallel or overlapping cascades of events inducing cell cycle arrest and eventually apoptosis.

Although RES has been shown to instigate apoptosis in various cancer models, data from our studies show that mitochondria were significantly affected shortly after RES treatment and are likely to play a central role in mediating apoptosis. RES treatment rapidly dissipates ΔΨ\textsubscript{m} in whole cells, and lower concentrations of RES were sufficient to influence a loss of ΔΨ\textsubscript{m} in isolated mitochondria, indicating the possibility of a novel RES target protein in the mitochondria. Opening of the mPTP, composed of the adenine-nucleotide...
translocator and the voltage-dependent anion channel, has been suggested to play important roles in mediating loss of $\Delta \Psi _m$ and cyt c release (Martinou et al., 2000; Petronilli et al., 2001). Whether resveratrol’s ability to directly target mitochondria and cause a loss of $\Delta \Psi _m$ in breast cancer cells is somehow linked through these protein complexes requires further investigation.

Disruption of $\Delta \Psi _m$ leading to mitochondrial permeabilization commonly accompanies or precedes release of cyt c and Smac/DIABLO into the cytoplasm, leading to formation of an active apoptosome complex and activation of caspase-9, which then activates the executioner caspase-3 to orchestrate apoptosis (Green, 2005). We demonstrate that RES triggered release of cyt c and Smac/DIABLO from mitochondria of MDA-MB-231 cells, which precedes the activation of caspase-9 and -3, confirming previous findings from other groups in tumor cell lines of different origins (Aggarwal et al., 2004; Jiang et al., 2005; Pozo-Guisado et al., 2005). Although the precise mechanism that mediates the release of cyt c and Smac/DIABLO from the mitochondria is unclear, apoptosis-associated mitochondrial events induced by RES in many cancer cell types have been shown to be facilitated by the altered expression and mitochondrial localization of apoptotic regulators, such as down-modulation of the antiapoptotic proteins Bcl-2 and Bcl-X$\text{L}$ and up-regulation and mitochondrial translocation of pro-apoptotic Bax and Bak (Mahyar-Roemer et al., 2002; Jiang et al., 2005; Pozo-Guisado et al., 2005). As anticipated, activation of caspase-9 and -3 was not detectable upon RES treatment of MCF-7 cells. Alternatively, extrinsic death receptor mediated apoptosis proceeding through the activation of initiator caspases-2 and -8 has been elicited by RES (Delmas et al., 2003; Mohan et al., 2006). However, the absence of caspase-2 and -8 activation in response to RES treatment of MDA-MB-231 and MCF-7 cells indicates that the death receptor pathway is not a likely early mechanism of RES-induced apoptosis in these cells.

Our results reveal that RES evokes a rapid and biphasic increase in $[\text{Ca}^{2+}]_i$ in both breast cancer cell lines, supporting our hypothesis that homeostatic mechanisms for regulating cellular $\text{Ca}^{2+}$ possibly play a central role during RES-induced apoptosis. The initial rise seems to be dependent upon the ability of RES to stimulate the TG-sensitive $\text{Ca}^{2+}$ stores, likely the ER. The second rise is possibly due to the release of $\text{Ca}^{2+}$ from the mitochondrial stores or extracellular influx of $\text{Ca}^{2+}$ by plasma membrane channels. To confirm the source of this RES-induced $\text{Ca}^{2+}$ release, organelle-specific $\text{Ca}^{2+}$-sensitive indicators need to be employed.

During apoptosis, the amplitude of the initial $[\text{Ca}^{2+}]_i$ elevation is usually within the range of nonlethal stimulations, whereas the subsequent rise leading to a massive $\text{Ca}^{2+}$ accumulation requires additional mechanisms to terminally deregulate cellular $\text{Ca}^{2+}$ handling (Orrenius et al., 2003). Our results demonstrate for the first time that RES treatment induces calpain activation in MCF-7 cells, which can be blocked by active-site calpain inhibitors and BAPTA-AM. Because no difference in the substrate specificity of the calpain isoforms has been found, considering the level of RES-induced elevation in $[\text{Ca}^{2+}]_i$, we conclude that RES activates $\mu$-calpain and possibly also other calpains. In the present study, activated calpain targets cytoskeletal proteins such as fodrin and the high-affinity $\text{Ca}^{2+}$ pump, PMCA1, for degradation in cells exposed to RES. The calpain-dependent degradation of PMCA1 possibly prevents it from functioning and maintaining $\text{Ca}^{2+}$ homeostasis. This, in turn, could facilitate $\text{Ca}^{2+}$ leakage down its concentration gradient into the cytosol, providing a secondary sustained $\text{Ca}^{2+}$ elevation that results in proteolytic degradation and ultimately apoptosis. Coadministration of RES and calpain inhibitor successfully abrogates calpain-induced fodrin and PMCA1 cleavage. Previously, in vitro studies have shown PMCA1, 2, and 4 to be susceptible to calpain degradation with differing sensitivities, and the erythrocyte calcium pump has been shown to be a preferred substrate of calpain in vivo (Guerini et al., 2003).

To the best of our knowledge, this is the first study demonstrating an in vivo calpain-induced cleavage of PMCA1 in response to RES.

The mitochondria play an essential role in buffering physiological loads of $\text{Ca}^{2+}$ upon insult, whereas the mPTP provides a fast $\text{Ca}^{2+}$ extrusion mechanism in response to abnormally high levels of $\text{Ca}^{2+}$ that accumulate in mitochondria during apoptosis. RES has been demonstrated to promote $\text{Ca}^{2+}$-mediated mPTP opening by activating a $\text{Ca}^{2+}$-induced $\text{Ca}^{2+}$ release (CICR) from rat liver mitochondria, and this effect was completely inhibited by CsA (Tian et al., 2006). It is noteworthy that we observed that RES-induced calpain activation was significantly inhibited in the presence of CsA,

![Fig. 8. Mechanisms of resveratrol-induced apoptosis.](https://molpharm.aspetjournals.org/article-pdf/10.1124/mol.117.117284/mol.117284-F8.jpg)

**Fig. 8.** Mechanisms of resveratrol-induced apoptosis. 1, RES targets the mitochondria, resulting in mitochondrial depolarization that is frequently associated with mPTP opening. Subsequent mitochondrial release of cyt c and Smac/DIABLO leads to activation of caspase-9 and -3, resulting in apoptosis. 2, RES targets the ER, causing an elevation of $[\text{Ca}^{2+}]_i$, that is biphasic in nature. The initial rise in cytoplasmic $\text{Ca}^{2+}$ is probably buffered by the mitochondria. The second phase is probably due to the release of buffered mitochondrial $\text{Ca}^{2+}$ to the cytoplasm, commonly known as CICR. There is evidence that CICR can either precede or follow mitochondrial depolarization. Subsequent calpain activation may be the result of the first (dotted arrow) or second phase of rise in $[\text{Ca}^{2+}]_i$. Active calpain is responsible for proteolysis of its substrates, ultimately leading to apoptosis.
sugesting that calpain activation may be a postmitochondrial event. The precise mechanism of this mPTP inhibition is still elusive, although it is possible that CsA enhances the mitochondrial uptake and retention of Ca\(^{2+}\) and thereby prevents calpain activation during recovery, as indicated in a recent study in which CsA prevented calpain activation after microcystin-induced cell death in hepatocytes (Ding et al., 2002).

These results support the hypothesis that RES is a multifaceted molecule capable of directly targeting the mitochondria and activating the intrinsic mitochondrial caspase-dependent form of apoptosis. In addition, RES targets the thapsigargin-sensitive ER Ca\(^{2+}\) stores to cause an elevation of intracellular Ca\(^{2+}\) levels in both breast cancer cell lines. Subsequent Ca\(^{2+}\)-dependent activation of calpain is observed. This mechanism of apoptosis may be especially relevant in tumors lacking caspase-3 activity (Devarajan et al., 2002). Thus, it is likely that resveratrol's pro-apoptotic mechanism involves deregulation of multiple targets associated with the mitochondria and ER, leading to the activation of different enzymatic cascades described in Fig. 8.

Together, these data for the first time link changes in Ca\(^{2+}\) homeostasis to the RES-mediated initiation of apoptosis. Sustained elevations in intracellular Ca\(^{2+}\), therefore, might serve as a universal cell death signal that can be exploited for antitumor therapy. Differences in expression of a RES target and/or Ca\(^{2+}\) regulatory mechanisms in cancer versus normal cells may allow RES to induce apoptosis selectively in breast cancer cells. Identification of a putative RES mitochondrial and/or ER target could lead to the synthesis of more efficacious apoptotic cancer agents. We hope that our findings will aid in the development of therapeutic strategies for the use of RES as a nontoxic alternative to conventional anticancer therapies for breast cancer.

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References


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