

**Inhibition of  $\text{Ca}^{2+}$  influx is required for mitochondrial Reactive Oxygen  
Species-induced Endoplasmic Reticulum  $\text{Ca}^{2+}$  depletion and cell death in  
leukemia cells**

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Abbreviations: ANT: Adenine Nucleotide Tranporter, AA: Antimycin A, Atr: Atractyloside, BHT: Butylated hydroxytoluene, Ec: Econazole, ER: Endoplasmic Reticulum, MMP: Mitochondrial Membrane Potential, Nac: N-Acetyl-L-cysteine, OS: Oxidative Stress, PMA: Phorbol 12-myristate 13-acetate, ROS: Reactive Oxygen Species, Tg: Thapsigargin, Tu: Tunicamycin, UPR: Unfolded Protein Response

## Abstract

Disturbances of endoplasmic reticulum(ER)  $\text{Ca}^{2+}$  homeostasis or protein processing can lead to ER stress-induced cell death. Increasing evidence suggests that oxidative stress (OS) play an important role in a variety of cell death mechanisms. To investigate the role of OS in ER stress, we measured OS in response to three ER stress agents: econazole(Ec), which stimulates ER  $\text{Ca}^{2+}$  release and blocks  $\text{Ca}^{2+}$  influx, thapsigargin(Tg), a SERCA inhibitor that releases ER  $\text{Ca}^{2+}$  and stimulates  $\text{Ca}^{2+}$  influx, and tunicamycin(Tu), a glycosylation inhibitor that causes protein accumulation in the ER. Ec, but not Tg or Tu, caused a rapid increase in OS. Reactive Oxygen Species (ROS) generation was observed within mitochondria immediately after exposure to Ec. Furthermore, Ec hyperpolarized the mitochondrial membrane and inhibited adenine nucleotide transport in cell-free mitochondria suggesting a mitochondrial target. Antimycin A, an inhibitor of complex III in electron transport, reversed mitochondrial hyperpolarization, OS generation, ER  $\text{Ca}^{2+}$  depletion and cell death by Ec, suggesting complex III dependence for these effects. Antioxidants BHT and Nac prevented ER  $\text{Ca}^{2+}$  depletion and cell death by Ec. However, inhibition of  $\text{Ca}^{2+}$  influx by Ec was unaffected by either Antimycin A or the antioxidants, suggesting that this target is distinct from the mitochondrial target of Ec. Atractyloside, an adenine nucleotide transport inhibitor, generated ROS and stimulated ER  $\text{Ca}^{2+}$  release, but did not block  $\text{Ca}^{2+}$  influx, deplete the ER or induce cell death. Taken together, these results demonstrate that combined mitochondrial ROS generation and  $\text{Ca}^{2+}$  influx blockade by Ec is required for cell death.

## Introduction

The endoplasmic reticulum (ER) is a major intracellular calcium store and the organelle responsible for the synthesis and post-translational modification of proteins destined for secretion or surface expression. These post-translational processes include protein folding, glycosylation, disulfide bond formation, and ER-Golgi protein trafficking. Disturbances of ER calcium homeostasis and protein processing cause accumulation of unfolded or misfolded proteins in the ER lumen and initiate the unfolded protein response (UPR) (Ferri and Kroemer, 2001; Kaufman, 1999; Patil and Walter, 2001). Cells exhibit a variety of responses in their attempt to mitigate such ER stress. These include increased expression of ER-resident  $\text{Ca}^{2+}$ -dependent molecular chaperones such as GRP78 (Bip) and GRP94 (Kozutsumi et al., 1988), and suppression of protein synthesis to reduce the unfolded protein load. Pre-conditioning with sublethal levels of ER stress have been shown to protect cells, in part through upregulation of chaperones (Hung et al., 2003; Liu et al., 1998). However, sustained ER stress will eventually result in prolonged protein synthesis inhibition that leads to cell death (Soboloff and Berger, 2002; Zhang and Berger, 2004). Important mediators of ER stress-associated death include the cleavage and activation of the ER-associated caspase-12 (Szegezdi et al., 2003) and increased expression of CHOP/GADD153 (Wang et al., 1996), a transcription factor that sensitizes cells to apoptosis.

Disruption of  $\text{Ca}^{2+}$  homeostasis in the ER, such as after treatment with the SERCA inhibitor Thapsigargin (Tg) (Thastrup et al., 1990), can stimulate sustained  $\text{Ca}^{2+}$  influx from the extracellular milieu. In some cell types, this leads to both cytosolic and mitochondrial  $\text{Ca}^{2+}$  overload (Babich et al., 1994; Soboloff and Berger, 2002), triggering apoptosis (Orrenius et al., 2003). Econazole (Ec), an imidazole antifungal, also

stimulates depletion of the Tg-sensitive ER calcium store. However unlike Tg, Ec additionally blocks  $\text{Ca}^{2+}$  influx resulting in sustained ER  $\text{Ca}^{2+}$  depletion (Franzius et al., 1994; Jan et al., 1999; Soboloff and Berger, 2002). In previous studies, we have shown that the  $\text{Ca}^{2+}$  depletion caused by Ec induces activation enhanced cell death in leukemic cells, breast cancer cells and murine bone marrow-derived mast cells through sustained inhibition of protein synthesis (Gommerman and Berger, 1998; Soboloff and Berger, 2002; Soboloff et al., 2002; Zhang and Berger, 2004; Zhang et al., 2002). However, the mechanism of how this compound affects the intracellular ER store and the subsequent fate of the cell remains unknown.

Increasing evidence suggests that reactive oxygen species (ROS) and the oxidation-reduction (redox) state play important roles in a variety of cell death mechanisms induced by widely used anti-tumour drugs or by environmental toxic substances (Orrenius, 1985; Orrenius and Nicotera, 1987; Slater et al., 1995) (Feinendegen, 2002; Ueda et al., 2002). Since oxidative damage to the ER has been implicated in some forms of cell death (Hayashi et al., 2003; Lai et al., 2003; Watanabe et al., 2003), we investigated the possible role of oxidative stress (OS) in the induction of ER stress by different agents. Here we show that ER  $\text{Ca}^{2+}$  depletion and cell death induced by Ec but not Tg or Tunicamycin is dependent on ROS production at the mitochondria, thus identifying a mediating role for ROS in communicating mitochondrial disruption to the ER.

## Materials and Methods

### *Cell culture, cell death and caspase assays*

Human promyelocytic leukemia HL-60 cells were grown in RPMI 1640 containing 10% heat-inactivated fetal bovine serum (FBS) and 2.5mM L-glutamine. HL-60 cells were treated with Ec (15  $\mu$ M) in the presence or absence of AA (125 nM), BHT (5  $\mu$ M), or Nac (1mM) at 37°C for 2 hours, in medium containing 1% FBS. Drugs were washed out and the cells were recovered in 10% FBS drug-free RPMI 1640 for 6 hours. Samples were co-stained with Annexin V-Cy5 (BioVision) and propidium iodide (P.I.), and cell death was determined by flow cytometry. Early (Annexin V positive, P.I. negative) and late (Annexin V positive, P.I. positive) events were scored as dead cells. Caspase 3/7 activation was measured using the Vybrant FAM caspase assay kit from Molecular Probes-Invitrogen as described by the manufacturer.

### *Detection of oxidative stress and mitochondrial ROS*

To examine the generation of OS, HL-60 cells were incubated with the indicated concentrations of Ec, Tu or Tg in RPMI 1640 containing 2% FBS at 37°C for 2 hrs and then loaded with the OS indicator 5-(and-6)-chloromethyl-2',7'-dichlorodihydrofluorescein diacetate (CM-H<sub>2</sub>DCFDA, 8  $\mu$ M, 37°C, 30 minutes, Molecular Probes). Fluorescence was measured by flow cytometry using excitation at 488nm and emission at 530nm at indicated intervals following treatment. Mitochondrial-specific ROS generation was measured using the MitoSox Red fluorescent dye (Invitrogen) as described by the manufacturer. This dye accumulates in the mitochondria, is oxidized by superoxide and emits at 580nm.

### *Measurement of cytosolic $Ca^{2+}$ concentration*

Cytosolic  $Ca^{2+}$  measurements ( $[Ca^{2+}]_c$ ) were performed by flow cytometry. HL-60 cells were serum-deprived for 2 hours in Tyrode's buffer [HEPES (10 mM), NaCl (100 mM), KCl (5 mM),  $CaCl_2$  (1.4 mM),  $MgCl_2$  (1 mM), glucose (5.6 mM), BSA (0.05%)] containing Ec, atractyloside, antioxidants and/or hydrogen peroxide where indicated. Cells were then incubated in loading buffer (37°C, 30 min; 5  $\mu$ M indo-1AM, 0.03% pluronic F-127 in Tyrode's buffer, both from Molecular Probes), washed and incubated (15 min; room temperature) to allow for the complete conversion of indo-1AM to  $Ca^{2+}$ -sensitive indo-1 through hydrolysis. Measurements were performed using a laser tuned to 338 nm while monitoring emissions at 405 nm and 450 nm. FloJo software (Treestar Software; Oregon) was used to analyze the flow cytometric data. The concentration of intracellular free  $Ca^{2+}$  was calculated according to the following formula (Grynkiewicz et al., 1985):

$$[Ca^{2+}]_i = K_d \times (F_{min}/F_{max}) \times (R - R_{min})/(R_{max} - R),$$

where R is the ratio of the fluorescence intensities measured at 405 nm and 450 nm during the experiments and F is the fluorescence intensity measured at 450 nm.  $R_{min}$ ,  $R_{max}$ ,  $F_{min}$  and  $F_{max}$  were determined from *in situ* calibration of viable cells using 4 $\mu$ M ionomycin in the absence ( $R_{min}$  and  $F_{min}$ ; 10 mM EGTA) and presence of ( $R_{max}$  and  $F_{max}$ ) of  $Ca^{2+}$ .  $K_d$  (250 nM) is the dissociation constant for indo-1 at 37°C.  $R_{min}$ ,  $R_{max}$ ,  $F_{min}$  and  $F_{max}$  varied depending upon settings and were determined at the beginning of each experimental procedure and experimental condition.

### *Potentiometric measurement of mitochondria membrane potential (MMP)*

MMP measurements were performed by flow cytometry. Cells ( $5 \times 10^5$  cells/ml) were growth factor-deprived for ~2 hours in Tyrode's buffer and then incubated with JC-1

(Molecular Probes; Eugene, Oregon, 5 µg/ml; 15 min, room temperature in Tyrode's buffer) and washed (3 times) to remove extracellular JC-1. Measurements were performed using a laser tuned to 488 nm while monitoring the emissions of JC-1 monomers at 530 nm and JC-1 aggregates at 585 nm. MMP measurements were normalized using a modification of a formula from (Rottenberg and Wu, 1998):

$$\text{MMP} = (R - R_{\text{Fccp}}) / (R_0 - R_{\text{Fccp}}) \times 100$$

where R is the ratio of the fluorescence intensities measured at 530 nm and 585 nm during the experiments,  $R_0$  is the fluorescence ratio of untreated cells and  $R_{\text{Fccp}}$  was the fluorescence intensity measured after the addition of carbonyl cyanide p-(trifluomethoxy) Phenylhydrazone (FCCP, Sigma; 2 µM), a procedure which collapses the mitochondrial membrane potential and performed at the beginning of each experiment.

#### *ANT-dependent ADP import assay*

Adenosine nucleotide transfer across the mitochondrial membrane in ER stressed cells was measured as described by Vander Heiden et al. (Vander Heiden et al., 1999). Briefly,  $5 \times 10^7$  HL-60 cells were disrupted by mechanical lysis through homogenization in a mitochondria isolation buffer (200 mM mannitol, 70mM sucrose, 10 mM HEPES pH 7.4, 1 mM EGTA). Following centrifugation (750 X g 10 min. to remove debris followed by 10,000 X g, 10 min of the supernatant), mitochondrial pellets were resuspended in ADP import buffer (250 mM Sucrose, 20 mM HEPES pH7.2, 10 mM KCl, 5 mM succinate, 3 mM  $\text{KH}_2\text{PO}_4$ , 1.5 mM  $\text{MgCl}_2$ , 1 mM EGTA, 5 µM rotenone) with or without the adenine nucleotide transporter inhibitor atractyloside (50 µM, Sigma).  $^{14}\text{C}$ -ADP (NEN; 1 µCi) was added to the mitochondrial suspension and incubated (10 min) on ice. After washing (2x) in ADP import buffer, the samples were resuspended in scintillant (Packard) and quantified using a Beta Counter (Wallac). ANT-dependent ADP transport



activity was determined by calculating the difference in counts between samples that were or were not pre-incubated with atractyloside.

#### *ATP Bioluminescence Assay*

ATP levels were measured by using ATP bioluminescence assay kit CLS II (Roche). Briefly, Cells ( $5 \times 10^5$  cells/ml) treated with Ec (15  $\mu$ M), Antimycin A (125 nM), or both at 37° C for 2 hours or 6 hours in RPMI 1640 with 0.05% BSA. After washing in cold PBS, cells were resuspended in 100  $\mu$ l of dilution buffer, add 900  $\mu$ l of boiling buffer (100mM Tris, 4mM EDTA, pH7.5), boiled for 2 minutes, and centrifuged at 1000 X g for 1 minute. The supernatants were transferred to a fresh tube and kept on ice until measurements. ATP concentration was measured with a luminometer (Luminoskan, Labsystems) by adding 100  $\mu$ l of luciferase reagent to 100  $\mu$ l of sample or ATP standards ( $10^{-9}$  M to  $10^{-4}$  M). ATP values were calculated from a log-log plot of the standard curve.

#### *Statistical Analysis and Reproducibility*

Data was analyzed by ANOVA with Bonferroni's Post tests and are expressed as means  $\pm$  SEM. All measurements were performed in triplicate and repeated at least twice with similar results. \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.005$ .

## Results

### *Oxidative Stress generation by ER stress agents*

To investigate the possibility that ER stress inducers generate ROS, we exposed HL60 cells to the agents Econazole (Ec), Thapsigargin (Tg) and Tunicamycin (Tu) for 2 hours and measured OS levels in the cells by flow cytometry using the generalized OS-sensitive fluorescent dye CM-H<sub>2</sub>DCFDA (Halliwell and Whiteman, 2004). As shown in Fig. 1A-D, increased fluorescence levels indicating increases in OS levels was observed for cells treated with Ec but not Tg or Tu. We have previously demonstrated that all 3 agents induce ER stress within the chosen 2 hr time period, as indicated by induction of EIF2 $\alpha$  phosphorylation and Bip expression, along with suppression of protein synthesis (Soboloff and Berger, 2002; Zhang and Berger, 2004). However, this is achieved differently for each agent. Thus, Tu is an inhibitor of glycosylation (Kuo and Lampen, 1974) and causes ER stress through the accumulation of protein in the ER (Dorner et al., 1990). Tg inhibits the SERCA pump responsible for refilling ER Ca<sup>2+</sup> stores (Thastrup et al., 1990) leading to rapid depletion of ER Ca<sup>2+</sup> stores, followed by influx of Ca<sup>2+</sup> from the extracellular milieu. While Ec is best known as an inhibitor of Ca<sup>2+</sup> influx, it also promotes ER Ca<sup>2+</sup> depletion (Jan et al., 1999), although the mechanism of this Ca<sup>2+</sup> release has not previously been addressed.

To determine the kinetics of OS generation by Ec, we followed CM-H<sub>2</sub>DCFDA fluorescence over time. As shown in Fig 1E, fluorescence changes were observed with a short delay following addition of Ec suggesting a relatively rapid generation of reactivity.

### *Hyperpolarization of mitochondrial membrane potential by Ec*

The most common mechanism of OS generation by toxic agents is the disruption of electron transport in mitochondria (Eckert et al., 2003; Inoue et al., 2003; Kadenbach, 2003; Rego and Oliveira, 2003; Ueda et al., 2002). To investigate the effect of Ec on mitochondrial function, we first measured mitochondrial membrane potential, a useful indicator of mitochondrial activity and status, after exposure to Ec. As shown in Fig. 2A, the addition of Ec to cells caused an immediate hyperpolarization of the mitochondrial membrane. In contrast, Tg and Tu had no effect, while the protonophore FCCP caused an immediate collapse of the potential. These observations suggested that Ec, but not Tg or Tu, had a mitochondrial target.

To further investigate the possibility of a mitochondrial target for Ec-induced ROS generation, we used the MitoSox Red dye, a mitochondrial-specific superoxide indicator (Invitrogen). To confirm that MitoSox measures ROS generated at the mitochondria, we used the phorbol ester PMA, which stimulates oxidase activity at the plasma membrane (Dooley et al., 2004; Teufelhofer et al., 2003) and atractyloside, which generates mitochondrial ROS via inhibition of adenine nucleotide activity (see below) as controls. As shown in Fig. 2B, the CM-H<sub>2</sub>DCFDA dye detects similar levels of fluorescence by Ec, PMA and atractyloside over a 2 hr time period. In contrast, Ec and atractyloside, but not PMA, generate the superoxide anion, as detected with MitoSox (Fig. 2C).

Interestingly, a nearly 3.5-fold increase in superoxide accumulation was observed in the presence of Ec, a far greater change than observed when DCF fluorescence was assessed. Cells were then stained with MitoSox and the effect of Ec addition was followed over time. As shown in Fig. 2D, Ec stimulated a rapid and sustained increase in MitoSox fluorescence in contrast to the somewhat slower change in total DCF fluorescence (Fig. 1E). These observations are consistent with DCF indicating ROS generation and mitochondria as the source of Ec-induced ROS.

### *Ec inhibits adenine nucleotide transport*

Adenine nucleotide transport, performed by the mitochondrial adenine nucleotide transporter (ANT), is one of the final steps in the generation of ATP and its inhibition has been shown to cause mitochondrial membrane hyperpolarization (Vander Heiden et al., 1999). We therefore investigated the effect of Ec, Tg and Tu on adenine nucleotide transport. Cell-free mitochondria were prepared, exposed to the ER stress agents and adenine nucleotide transport was measured. As shown in Fig. 2E, at the concentrations used to treat cells, Ec is a very potent inhibitor of ANT function while Tg or Tu have no effect. This observation suggests that Ec acts directly on mitochondria to inhibit ANT, either directly or indirectly.

### *Antimycin A reverses mitochondrial hyperpolarization by Ec*

Since adenine nucleotide transport is coupled to electron transport, it is possible that a member of the electron transport chain is the direct target of Ec, leading to ROS production and suppression of ANT function. To further investigate this possibility, we determined the effect of various inhibitors of electron transport on the ability of Ec to hyperpolarize the mitochondrial membrane. The inhibitors used are illustrated in Fig. 3A. As shown in Fig. 3B, pre-exposure of cells to TTFA, rotenone or KCN, inhibitors of electron transport complexes I, II, and IV respectively, had no effect on the ability of Ec to hyperpolarize the mitochondrial membrane. In contrast, the complex III inhibitor Antimycin A both partially reduced mitochondrial membrane potential on its own and completely neutralized mitochondrial membrane hyperpolarization by Ec (Fig. 3C). Furthermore, the ability of Antimycin A to neutralize Ec-induced hyperpolarization persisted for two hours. These results therefore suggest that Ec is targeting the electron transport chain in a complex III-dependent manner, resulting in ROS generation and inhibition of ANT function.

### *Antimycin A reverses ROS generation by Ec*

The fact that Antimycin A neutralizes Ec-induced hyperpolarization appears somewhat paradoxical given that Antimycin A on its own has been reported to generate reactive oxygen. To further investigate the interaction between Ec and Antimycin A, we measured ROS production after treatment with Ec, Antimycin A, or both compounds together. Cells were incubated with the two compounds for 2 hours and ROS content was measured as above. As shown in Fig. 4A, Antimycin A alone, at the concentration used in this study, did not have any effects on ROS levels. However, it clearly suppressed ROS generation by Ec. This result therefore correlates Ec-induced hyperpolarization with ROS production and provides further evidence that the ability of Ec to generate ROS is dependent on complex III activity.

### *ATP depletion by Ec*

Given the inhibition of adenine nucleotide transport by Ec and its other effects on electron transport, it was of interest to determine the effect of Ec treatment on ATP levels. We therefore exposed cells to Ec for 2 hours, and measured total ATP content. As shown in Fig. 4B, exposure to Ec for 2 hours resulted in a decline in ATP content of 50%. Although a 2 hr exposure to Antimycin A caused a similar depletion of ATP content, exposure to both agents simultaneously resulted in significantly less ATP depletion than either agent alone. Extending the incubation time to 6 hours (Fig. 4C) resulted in even greater depletion of ATP by Ec or Antimycin A. However as with the 2 hour endpoint, combined exposure to both agents resulted in less ATP depletion than with either agent alone. These observations suggest that Ec and Antimycin A both target complex III, with distinct and opposing effects.

*Antioxidants do not reverse mitochondrial membrane hyperpolarization by Ec*

The results described above show that Ec hyperpolarizes the mitochondrial membrane and generates ROS. Moreover, both of these endpoints could be reversed by the complex III inhibitor Antimycin A. These results however, do not address the causal nature of ROS production. Specifically, are increased ROS levels required for Ec-induced changes in membrane potential? To address this question, we pre-treated cells with the antioxidants BHT or Nac and then followed mitochondrial membrane potential after exposure to Ec. Control experiments demonstrated that both antioxidants suppressed ROS generation by Ec (data not shown). As shown in Fig. 5, Nac slightly lowered the resting mitochondrial membrane potential compared to untreated cells. However neither Nac nor BHT prevented Ec from hyperpolarizing the membrane above the resting level. Furthermore, the hyperpolarizing effect of Ec persisted for over 2 hours. Therefore, it is likely that the generation of ROS occurs either in parallel with, or downstream of changes in mitochondrial membrane potential.

*ER  $\text{Ca}^{2+}$  depletion by Ec is inhibited by Antimycin A and antioxidants*

We have previously documented that Ec, in addition to blocking  $\text{Ca}^{2+}$  influx also causes  $\text{Ca}^{2+}$  depletion from the ER (Soboloff and Berger, 2002; Zhang and Berger, 2004). In order to determine the role of Ec's mitochondrial activity in ER depletion, we treated cells with Ec or Ec plus Antimycin A, and then measured the amount of  $\text{Ca}^{2+}$  present in the ER by releasing it into the cytoplasm with Tg while blocking the influx of  $\text{Ca}^{2+}$  with the non-specific  $\text{Ca}^{2+}$  channel blocker  $\text{Ni}^{2+}$ . As shown in Fig. 6A, no  $\text{Ca}^{2+}$  was released into the cytoplasm by Tg after pre-treatment of cells with Ec, demonstrating that Ec depletes the ER. Antimycin A alone had little effect on Tg-releasable  $\text{Ca}^{2+}$ . However, Ec-induced depletion of the Tg-sensitive store was reversed by Antimycin A, revealing a key role for the mitochondrial target of Ec in ER  $\text{Ca}^{2+}$  depletion. In order to assess the role of mitochondria on  $\text{Ca}^{2+}$  influx, experiments were then performed in the absence of  $\text{Ni}^{2+}$ .

The difference between the magnitude of Tg-induced  $\text{Ca}^{2+}$  influx in the presence of  $\text{Ni}^{2+}$  vs. the absence of  $\text{Ni}^{2+}$  reflects  $\text{Ca}^{2+}$  influx. Since Ec blocks  $\text{Ca}^{2+}$  influx in addition to depleting the ER of  $\text{Ca}^{2+}$ , no Tg-induced changes in  $\text{Ca}^{2+}$  concentration occur after Ec pretreatment even when  $\text{Ni}^{2+}$  is not present. (Fig. 6B). Antimycin A alone had no effect on Tg-induced  $\text{Ca}^{2+}$  release or influx. However, the Tg-induced  $\text{Ca}^{2+}$  concentration observed with both Antimycin A and Ec present was comparable to that observed in experiments when  $\text{Ni}^{2+}$  was present in Fig 6A. Hence, Antimycin A neutralized Ec-induced ER  $\text{Ca}^{2+}$  depletion, but had little or no effect on Ec-induced inhibition of  $\text{Ca}^{2+}$  influx.

We also assessed the ability of the antioxidants BHT and Nac to prevent Ec-mediated ER  $\text{Ca}^{2+}$  depletion and/or  $\text{Ca}^{2+}$  influx. As shown in Fig. 6C, in the presence of  $\text{Ni}^{2+}$ , BHT alone had no effect on Tg-releasable  $\text{Ca}^{2+}$ . Similar to Antimycin A however, BHT prevented Ec from fully depleting the Tg-sensitive store. Moreover, BHT did not alter Ec-induced inhibition of  $\text{Ca}^{2+}$  influx, as illustrated in Fig. 6D where, in the presence of BHT and Ec, Tg releasable  $\text{Ca}^{2+}$  was similar in magnitude to that released by Tg in the presence of  $\text{Ni}^{2+}$  (Fig. 6C). Similar results were observed with the antioxidant Nac (Figs. 6E&F). These results indicate that Ec-induced ER  $\text{Ca}^{2+}$  depletion is likely due to its ROS production, presumably via its action on complex III within the mitochondria. They further demonstrate that Ec-induced ER  $\text{Ca}^{2+}$  depletion is a distinct phenomenon from Ec-induced block of  $\text{Ca}^{2+}$  influx, which can be separated via the actions of Antimycin A, BHT and Nac.

#### *Antimycin A and antioxidants protect cells from Ec-induced cell death*

Since Antimycin A and the antioxidants BHT and Nac prevent ER  $\text{Ca}^{2+}$  depletion by Ec, we tested its effect on Ec-induced toxicity. Cells were exposed to Ec plus Antimycin A or the antioxidants for 2 hours. The agents were then removed and the cells were

incubated in medium for an additional 6 hours. Antimycin A, BHT and Nac were non-toxic at the concentrations used under these conditions (not shown). The cells were then evaluated by flow cytometry using annexin V staining. As shown in Fig. 7A, Antimycin A, BHT and Nac provided significant protection from Ec-induced cell death, revealing a key role for mitochondrially generated ROS and the release of ER  $\text{Ca}^{2+}$  in Ec toxicity.

*Antimycin A and antioxidants prevent caspase activation in response to Ec*

Previously, we had demonstrated in other cell types that Ec-induced cell death was associated with a variety of apoptotic indicators including PARP cleavage and protection from cell death by caspase inhibitors (Gommerman and Berger, 1998). However we have also observed that some cells such as human MCF-7 breast cancer cells undergo a non-apoptotic form of cell death (Zhang et al., 2002) associated with a lack of DNA fragmentation and a necrotic phenotype. We previously observed that Ec-treated HL60 cells display classic apoptotic endpoints including membrane blebbing and nuclear condensation (Zhang and Berger, 2004). However caspase activation in these cells was not investigated. We therefore examined the degree of caspase activation in these cells in response to Ec, focusing on caspase 3/7, the major effectors of apoptotic cell death. Initial experiments indicated that caspase 3/7 were not activated after exposure to the drug for 2 hours followed by a 6 hour incubation in medium (not shown). However as shown in Fig. 7B, extensive caspase 3/7 activation was observed if the incubation in medium was extended to 18 hours. Furthermore, the number of cells displaying caspase activation could be reduced significantly by antimycin A or the antioxidants. These observations therefore indicate that caspase activation is a relatively late event that is at least partially dependent on the mitochondrial activity of Ec.

*Hydrogen peroxide and Atractyloside mobilize  $\text{Ca}^{2+}$  from the ER without depleting the store*



Other studies have shown that ROS stimulate  $\text{Ca}^{2+}$  release from the ER (Downey, 1990). Consistent with these observations, we observed that  $\text{H}_2\text{O}_2$  caused a slow, but significant  $\text{Ca}^{2+}$  transient in HL60 cells (Fig. 8A). When cells were exposed to Ec, followed by  $\text{H}_2\text{O}_2$ , we observed that  $\text{H}_2\text{O}_2$  failed to stimulate additional release of  $\text{Ca}^{2+}$  (Fig 8B). This observation suggests that  $\text{Ca}^{2+}$  released by Ec and  $\text{H}_2\text{O}_2$  are likely from the same intracellular store. Interestingly, when cells were treated for 2 h with  $\text{H}_2\text{O}_2$ , we observed that significant levels of  $\text{Ca}^{2+}$  could still be mobilized from the ER with Tg (Fig 8C). This observation suggests that, unlike Ec (Fig. 6), ROS alone stimulate  $\text{Ca}^{2+}$  release without fully depleting the ER of  $\text{Ca}^{2+}$ , presumably because they do not block the refilling process.

Atractyloside (Atra) is an inhibitor of the adenine nucleotide transporter (Robinson et al., 1975). Our results with Ec predict that Atra should also generate ROS which would stimulate ER  $\text{Ca}^{2+}$  mobilization. To test this possibility, we exposed cells to Atra and measured ROS content. As shown in Fig. 9A, increased ROS levels were observed following Atra treatment. Furthermore, we observed that Atra could stimulate  $\text{Ca}^{2+}$  mobilization in HL60 cells (Fig. 9B). However unlike Ec, extended incubation with Atra failed to fully deplete the Tg-sensitive store (Fig 9C). Furthermore, despite generating ROS and stimulating  $\text{Ca}^{2+}$  release from the ER, Atra did not induce cell death in HL60 cells (data not shown), consistent with the concept that the cell death associated with ER  $\text{Ca}^{2+}$  release requires ER  $\text{Ca}^{2+}$  depletion.

## Discussion

High levels of ROS have multiple effects on proteins, lipids and nucleic acids in key organelles such as the mitochondria, ER and nucleus. Emerging evidence also supports the concept that subtoxic levels of ROS act as endogenous signaling messengers, especially in calcium signaling and protein phosphorylation (Nathan, 2003). In the course of investigating the role of OS in ER stress, we observed that Ec, an imidazole that blocks  $\text{Ca}^{2+}$  influx and stimulates ER  $\text{Ca}^{2+}$  depletion, increased OS levels in cells. In contrast, Tg or Tu, two other agents that also induce ER stress-related cell death did not generate increased OS. Ec was also observed to cause rapid hyperpolarization of the mitochondrial membrane. This hyperpolarization was associated with inhibition of adenine nucleotide transport, observed in cell free mitochondria. The complex III inhibitor Antimycin A neutralized Ec-induced hyperpolarization of the mitochondrial membrane, suppressed ROS increases by Ec, partially reversed ATP depletion by Ec, prevented ER  $\text{Ca}^{2+}$  depletion and protected cells from Ec-induced cell death. The antioxidants BHT and Nac also blocked  $\text{Ca}^{2+}$  mobilization from the ER by Ec and protected from Ec-induced cell death, consistent with a role for ROS in ER depletion. Taken together, these results suggest that Ec decouples complex III from downstream steps in electron transport, resulting in relatively rapid ROS generation, inhibition of adenine nucleotide transport and ATP depletion. The reactive oxygen produced is responsible for stimulating  $\text{Ca}^{2+}$  release from the ER. The combination of ROS generation stimulating ER  $\text{Ca}^{2+}$  mobilization with  $\text{Ca}^{2+}$  influx blockade results in the sustained ER  $\text{Ca}^{2+}$  depletion associated with cell death. This model is illustrated in Fig. 10.

Since Antimycin A reverses Ec-induced hyperpolarization, ROS generation, ER  $\text{Ca}^{2+}$  depletion and cell death, complex III activity is likely required for ROS generation by Ec.

Furthermore, the inhibition of ANT activity by Ec suggests that electron transport does not continue down the chain to the transporter. Taken together, these observations suggest that Ec decouples complex III from complex IV, presumably by providing an alternative outlet for complex III electrons (directly or indirectly). While further work will be required to identify how Ec targets complex III causing ROS generation, our observations show that the mitochondrial target is critical for Ec-induced cell death. Previously, we demonstrated that cancer and leukemia cells are highly sensitive to Ec-induced cell death (Gommerman and Berger, 1998; Soboloff et al., 2002; Zhang et al., 2002). Our identification of a mitochondrial target for Ec may prove to be useful in further identifying the cellular factors associated with sensitivity to this compound.

In addition to its inhibitory effects on complex III function, Antimycin A has also been reported to bind to and inhibit bcl-2 and related family members (Tzung et al., 2001). However we suspect that this activity is unrelated to the ability of Antimycin A to inhibit Ec function since the concentration of the drug required for bcl-2 inhibition is much higher than that used in the current study. As well, we previously reported that cell death induced by Ec was unaffected by high levels of bcl-2 in cells (Gommerman and Berger, 1998) suggesting that bcl-2 does not affect Ec's mechanism of action. Nevertheless, given the importance of bcl-2 family members and their effects on mitochondrial function, it would be of interest to further investigate a potential role for these proteins in ROS generation and  $\text{Ca}^{2+}$  depletion.

We previously demonstrated that exposure to Ec for 2 hours was sufficient to initiate an irreversible cell death process. It is of interest to note that after 2 hours of exposure, the mitochondrial membrane remains hyperpolarized and ATP content is reduced, but only by approximately 50%. Antimycin A exposure also results in a similarly reduced ATP level, while the combination of the two agents results in a slightly increased ATP

content. This increase may be due to reduced ATP consumption associated with decreased ROS levels rather than a restoration of ATP production.

Cells exposed to lethal agents generally undergo variations of necrotic or apoptotic cell death (Orrenius et al., 2003). Following exposure to Ec, HL60 cells exhibit clear endpoints associated with apoptosis such as membrane blebbing, annexin positivity and nuclear condensation (Zhang and Berger, 2004), however these endpoints occur late in the cell death process. In the present study, caspase activation was observed at 18 hours following Ec exposure (Fig. 7B), but not at 6 hours. The inability to detect caspase activation early may be partly due to inactivation of caspases by ROS as has been documented in other cell systems (Hampton et al., 1998; Samali et al., 1999).

Alternatively, apoptosis may be a secondary or indirect consequence of the ER stress process and is likely not absolutely required for cell death. Previously, we observed in a variety of cell systems that 2 hour exposure to Ec optimizes the difference in sensitivity between cancer or leukemia cells and normal cells (Soboloff et al., 2002; Zhang et al., 2002). We have also found that ER  $\text{Ca}^{2+}$  release is stimulated at lower Ec concentrations than those required for blocking influx (Soboloff and Berger, 2002). Taken together, these observations suggest that longer term exposure to lower doses of Ec may result in a qualitatively different form of cell death that is more dependent on mitochondrial dysfunction than ER  $\text{Ca}^{2+}$  depletion.

The ER  $\text{Ca}^{2+}$  store is a dynamic entity requiring constant energy and SERCA activity to maintain the large concentration gradient across the ER membrane. It is likely that as cells undergo various forms of cell death, depleted energy levels of the cell will be insufficient to maintain the  $\text{Ca}^{2+}$  gradient resulting in indirect ER  $\text{Ca}^{2+}$  depletion (Nicotera and Orrenius, 1998). In contrast, agents such as the ANT inhibitor atractyloside and others (Le Bras et al., 2005) generate ROS and cause  $\text{Ca}^{2+}$  release from

the ER rapidly, well before energy levels are depleted. If the cell can maintain sufficient energy levels, then these agents will not be toxic. However if the oxidative burden is too high, eventually, as energy levels deplete, the cell will undergo cell death(Richter et al., 1996).

Our observations are consistent with a general role for ROS generated at the mitochondria in stimulating ER  $\text{Ca}^{2+}$  release. The full spectrum of ROS targets in the ER remain unknown. However one likely target is the SERCA, since ROS have been reported to inhibit SERCA function (Barnes et al., 2000). Our observations that Ec and  $\text{H}_2\text{O}_2$  both targeted the Tg-sensitive store is consistent with the concept that SERCA is the ROS target responsible for ER  $\text{Ca}^{2+}$  release.

Both Antimycin A and the antioxidants neutralized the ability of Ec to deplete the ER with no discernable effect on Ec-induced inhibition of  $\text{Ca}^{2+}$  influx. Furthermore, Antimycin A and the antioxidants provided significant protection from cell death and caspase activation induced by Ec. Similarly, although atractyloside caused  $\text{Ca}^{2+}$  release from the ER, this did not lead to ER  $\text{Ca}^{2+}$  depletion or significant cell death. These observations are in agreement with our model that sustained  $\text{Ca}^{2+}$  depletion of the ER is required for lethality (Soboloff and Berger, 2002; Zhang and Berger, 2004). This would seem to suggest that, while Ec releases ER  $\text{Ca}^{2+}$  content via ROS just like atractyloside, blocking store-operated  $\text{Ca}^{2+}$  is required for its toxicity and conversely, blocking  $\text{Ca}^{2+}$  entry is only fully toxic when ER  $\text{Ca}^{2+}$  content is depleted. This is consistent with our previous observation in mast cells and breast cancer cells, where Ec-induced cell death was strongly enhanced by the addition of agents which stimulate  $\text{Ca}^{2+}$  release (Gommerman and Berger, 1998; Soboloff and Berger, 2002; Zhang et al., 2002).

Large increases in cytoplasmic  $\text{Ca}^{2+}$  caused by ER depletion coupled with influx can result in rapid increases in mitochondrial  $\text{Ca}^{2+}$ . Excessive mitochondrial  $\text{Ca}^{2+}$  has been linked to activation of the mitochondrial permeability transition and induction of apoptosis (Orrenius et al., 2003). Our results suggest that ROS can perform the opposite function, namely communicating mitochondrial dysfunction to the ER through the stimulation of  $\text{Ca}^{2+}$  release.

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## Footnotes

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## Figure Legends

**Figure 1. Generation of OS in ER stress agent treated cells.** HL-60 cells were incubated with different ER stress agents: **A:** Ec (15  $\mu$ M), **B:** Tg (1  $\mu$ M) or **C:** Tu (1  $\mu$ g/ml) for 2 hours, then loaded with H<sub>2</sub>DCFDA (8  $\mu$ M) for 30 minutes at 37 °C and rinsed with PBS. Fluorescence was monitored by flow cytometry at FL-1. The grey tracing is the untreated control. The data depicted is a representative experiment. **D:** Comparison of DCF fluorescence in arbitrary units for Ec, Tg or Tu treated cells compared to control. Reported values are averages of 3 independent determinations and are reported +/- S.E.M. \*\*  $p < 0.01$  compared to control. **E:** Time course of DCF fluorescence in response to Ec (15 $\mu$ M).

**Figure 2. Ec hyperpolarizes mitochondrial membrane potential (MMP), generates mitochondrial ROS and inhibits ADP transport.** **A:** JC-1 loaded HL-60 cells were exposed to Ec (15  $\mu$ M), Tg (1  $\mu$ M), Tu (1  $\mu$ g/ml) or FCCP (2  $\mu$ M), respectively, and the membrane potential was monitored by flow cytometry as described in the Methods section. **B:** HL60 cells were exposed to Ec (15  $\mu$ M), PMA (2  $\mu$ M) or Atractyloside (50  $\mu$ M) for 2 hours then loaded with H<sub>2</sub>DCFDA (8  $\mu$ M) for 30 minutes at 37 °C and rinsed with PBS. The mean fluorescence intensity was measured by flow cytometry. **C:** HL60 cells were treated with ROS-generating agents as in B, but loaded with MitoSox (5  $\mu$ M) for 30 minutes at 37 °C and rinsed with PBS. The mean fluorescence intensity was measured by flow cytometry. **D:** Time course of MitoSox-sensitive ROS in response to Ec (15 $\mu$ M). **E:** Cell-free mitochondria were prepared as described in Materials and Methods. Samples were incubated with ER stress agents for 10 minutes in the presence or absence of atractyloside followed by the addition of <sup>14</sup>C-ADP. ANT-dependent ADP transport activity was determined by calculating the atractyloside inhabitable counts.

ANT-dependent ADP transport was inhibited by Ec (15  $\mu$ M), but not by Tg (1  $\mu$ M) or Tu (1  $\mu$ g/ml). Values are reported as mean  $\pm$  S.E.M.

**Figure 3. Antimycin A reverses mitochondrial membrane hyperpolarization by Ec.**

**A:** Illustration of the sites of action of inhibitors of mitochondrial electron transport. **B:** JC-1-loaded cells were pre-treated for 20 minutes with 10  $\mu$ M rotenone, 10  $\mu$ M TTFA or 400  $\mu$ M KCN. The arrow indicates where 15  $\mu$ M Ec or 2  $\mu$ M FCCP was added to the cells. **C:** The effect of Antimycin A on membrane hyperpolarization, Cells stimulated with Antimycin A (125 nM), Ec or FCCP. Mitochondrial membrane potential was recorded for 2 hours.

**Figure 4. Antimycin A inhibits and reverses OS generation induced by Ec and partially restores ATP production. A:** Cells were incubated with Ec (15  $\mu$ M), Antimycin A (125 nM), or both at 37 °C for 2 hours, and DCF fluorescence was

measured as described in the Methods section. Data are shown as mean  $\pm$  S.E.M.

\* $p < 0.05$ , \*\* $p < 0.01$ . **B&C:** Intracellular ATP was measured in cells ( $0.5 - 1.0 \times 10^6$  cells/ml) treated with Ec (15  $\mu$ M), Antimycin A (125 nM), or both, at 37 °C, for 2 hours (panel **B**) or 6 hours (panel **C**). Values shown are reported as mean  $\pm$  S.E.M. \* $p < 0.05$ , \*\* $p < 0.01$ .

**Figure 5. Antioxidants do not reverse MMP hyperpolarization by Ec.** Cells were pre-treated with or without BHT (5  $\mu$ M) or Nac (1  $\mu$ M) at 37 °C for 20 minutes followed by JC-1 loading and flow cytometry procedures described in the Methods section. Mitochondrial potential was followed for 2 hours after Ec (15  $\mu$ M) or FCCP (2  $\mu$ M) was added.

**Figure 6. Ec-generated OS targets ER  $\text{Ca}^{2+}$  stores.** Cells were loaded with Indo-1AM in Tyrode's buffer as described in Materials and Methods.  $\text{Ca}^{2+}$  concentration was monitored by flow cytometry. **A:** Cells were pre-incubated in the absence (Ctl) or presence of Ec (15  $\mu\text{M}$ ) or Ec + AA (125 nM) for 2 hours.  $\text{Ni}^{2+}$  (5 mM) was added to the cells to non-specifically prevent influx.  $\text{Ca}^{2+}$  released by Tg (3  $\mu\text{M}$ ) into the cytoplasm was used as an indicator of ER  $\text{Ca}^{2+}$  content. **B:** As in A, however  $\text{Ni}^{2+}$  was not added to cells before Tg. **C:** As in A except 5  $\mu\text{M}$  BHT was used. **D:** As in C however  $\text{Ni}^{2+}$  was not added before Tg. **E:** As in A except 1 mM Nac was used. **F:** As in E however  $\text{Ni}^{2+}$  was not added before Tg.

**Figure 7. Ec-induced cell death and caspase activation is suppressed by Antimycin A, BHT and Nac.** Cells were treated with Ec (15  $\mu\text{M}$ ) in the presence or absence of AA (125 nM), BHT (5  $\mu\text{M}$ ), or Nac (1mM) at 37 °C for 2 hours, in medium containing 1% FBS. Drugs were washed out and the cells were recovered in RPMI plus 10% FBS for **A:** 6 hours. Samples were co-stained with Annexin V-Cy5 and propidium iodide, and cell death was determined by flow cytometry. Values include both early and late stage apoptotic cells. \*\*  $p < 0.01$ , \*\*\*  $p < 0.001$  compared to Ec. **B:** Cells were treated as above except the recovery time was extended to 18 hours. Cells were then incubated with the FLICA reagent (Invitrogen) to detect active caspases 3 or 7 and analyzed by flow cytometry. Reported values are % of cells that are positive for activated caspase 3/7 and are averages of two repeat measurements with standard errors.

**Figure 8. Ec and  $\text{H}_2\text{O}_2$  both target the Tg-releasable  $\text{Ca}^{2+}$  store.** **A:**  $\text{H}_2\text{O}_2$  (200  $\mu\text{M}$ ) - induced changes in cytoplasmic  $\text{Ca}^{2+}$  concentration. Indo-1AM-loaded cells were exposed to  $\text{H}_2\text{O}_2$  and cytoplasmic  $\text{Ca}^{2+}$  was followed over time. **B:** As in A except cells were pre-incubated in Ec (15  $\mu\text{M}$ ). **C:** Tg-induced release of ER  $\text{Ca}^{2+}$  content can still be



detected in cells pre-treated with  $\text{H}_2\text{O}_2$  (200  $\mu\text{M}$ ; 2 hours).  $\text{Ni}^{2+}$  (5 mM) was used to demonstrate that this was release of  $\text{Ca}^{2+}$  from intracellular stores and not  $\text{Ca}^{2+}$  entry.

**Figure 9. Atractyloside-generated ROS targets ER  $\text{Ca}^{2+}$  stores.** **A:** HL-60 cells were incubated with atractyloside (50  $\mu\text{M}$ ) for 2 hours, then loaded with  $\text{H}_2\text{DCFDA}$  (8  $\mu\text{M}$ ) for 30 minutes at 37 °C.  $\text{H}_2\text{DCFDA}$  fluorescence was measured by flow cytometry. **B:** Indo-1 loaded HL60 cells were treated with Atractyloside (50  $\mu\text{M}$ ) and cytoplasmic  $\text{Ca}^{2+}$  was followed by flow cytometry. **C:** Cells were pre-treated with atractyloside (50  $\mu\text{M}$ ) for 2 hours. ER  $\text{Ca}^{2+}$  content was measured by releasing ER  $\text{Ca}^{2+}$  into the cytoplasm with Tg (3  $\mu\text{M}$ ) in the presence of  $\text{Ni}^{2+}$  to prevent  $\text{Ca}^{2+}$  influx.

**Figure 10. Model for how Ec-stimulated mitochondrial ROS contributes to ER stress.** **1)** Ec targets complex III in the electron transport chain resulting in hyperpolarization of the mitochondrial membrane; **2)** decoupling of electron transport from adenine nucleotide transport and ATP production; **3)** inhibition of ANT and ROS generation; **4)** ROS stimulates ER  $\text{Ca}^{2+}$  release; **5)** Ec also blocks  $\text{Ca}^{2+}$  influx resulting in an ER stress response.

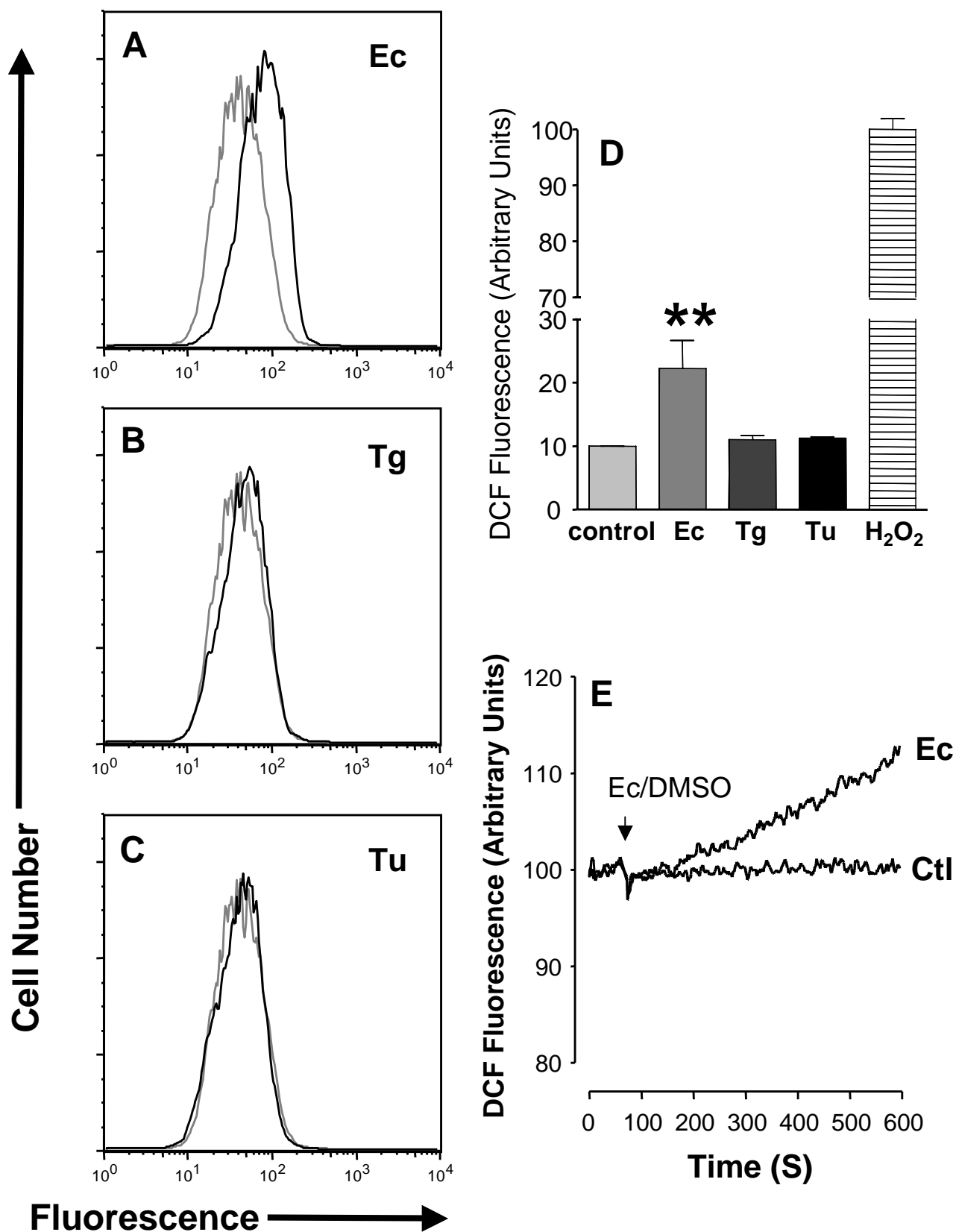


Figure 1

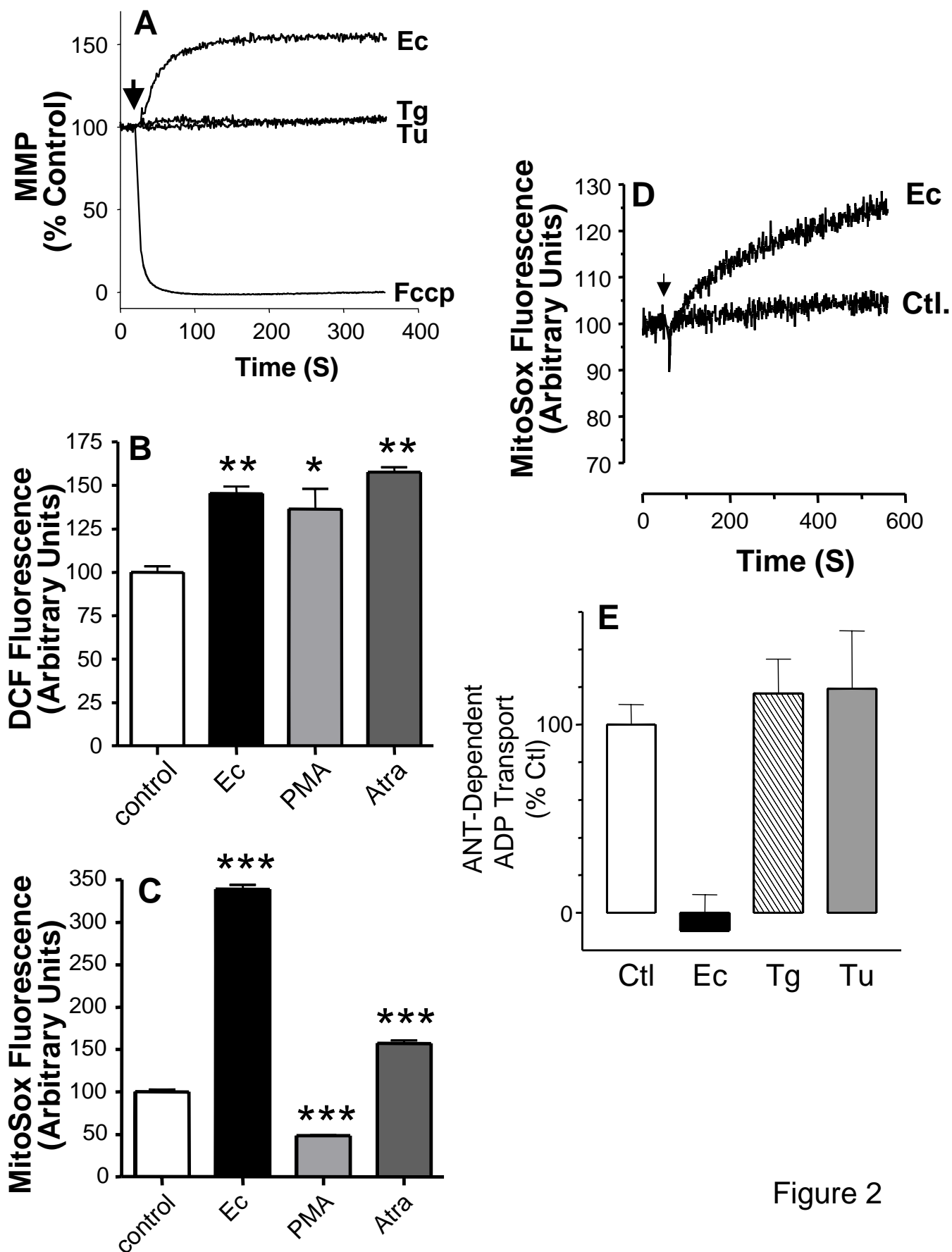


Figure 2

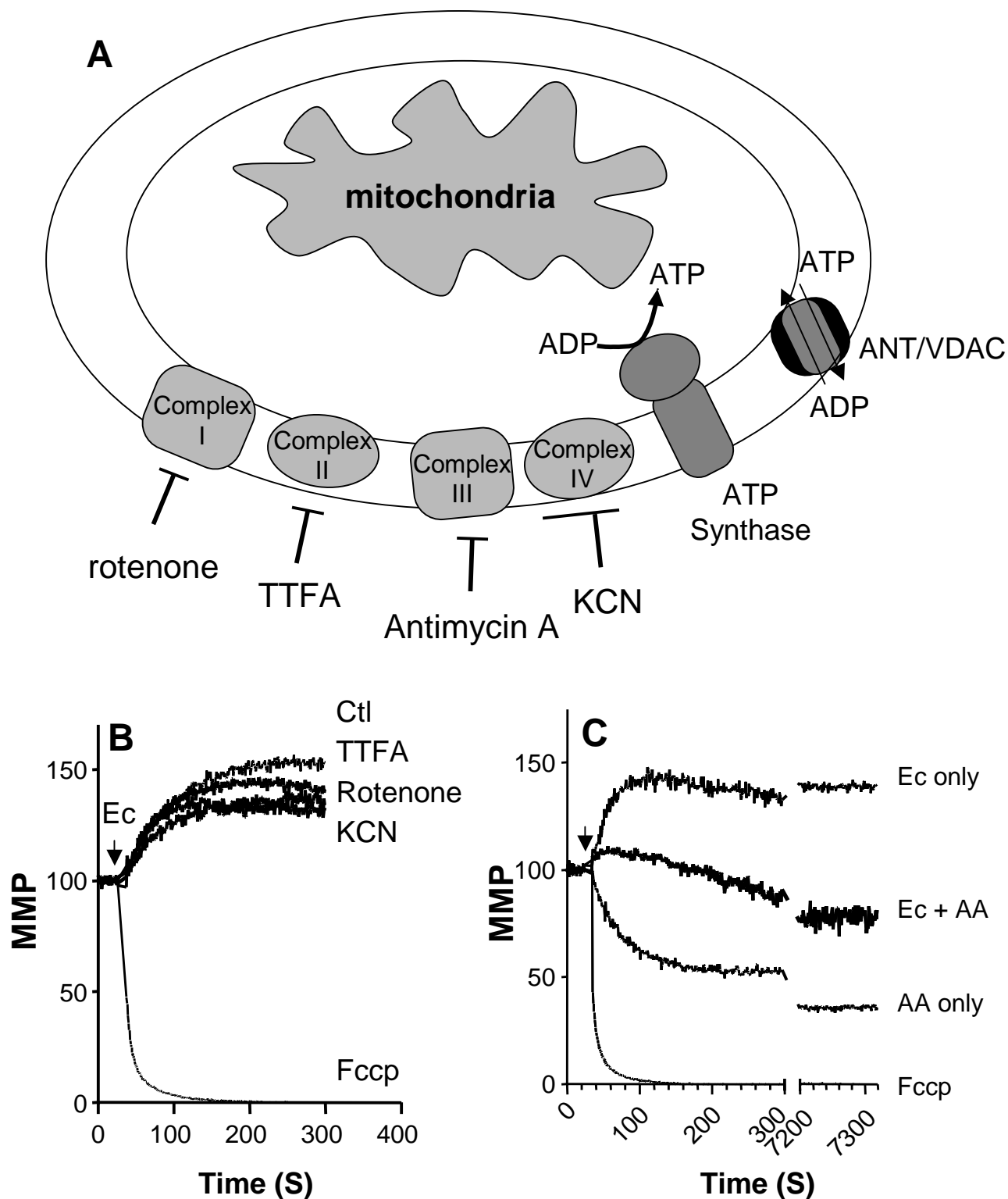


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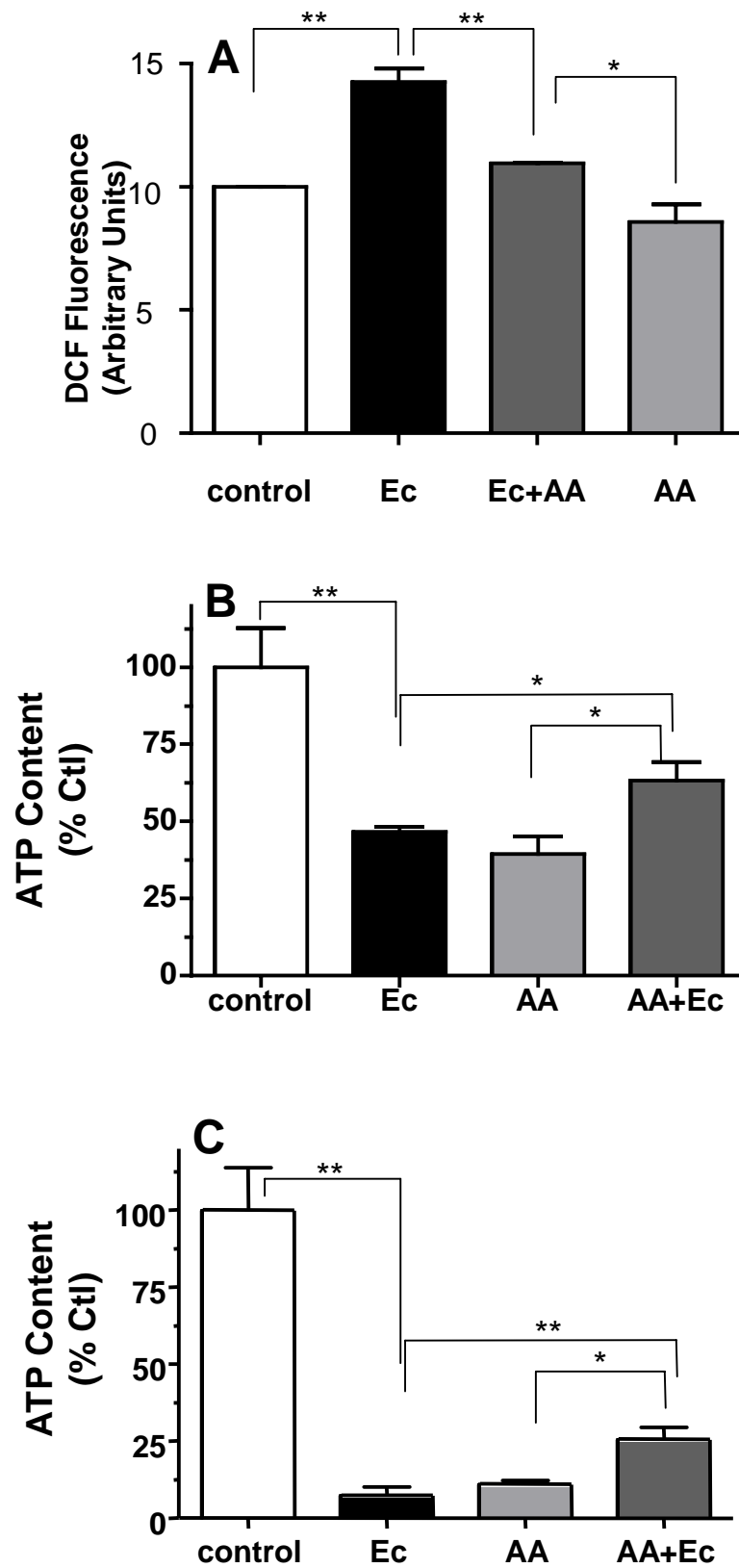


Figure 4

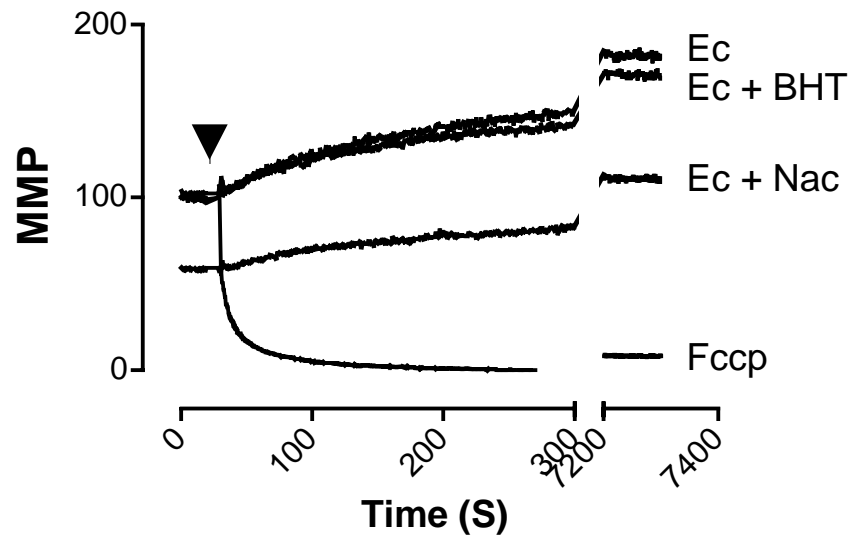


Figure 5

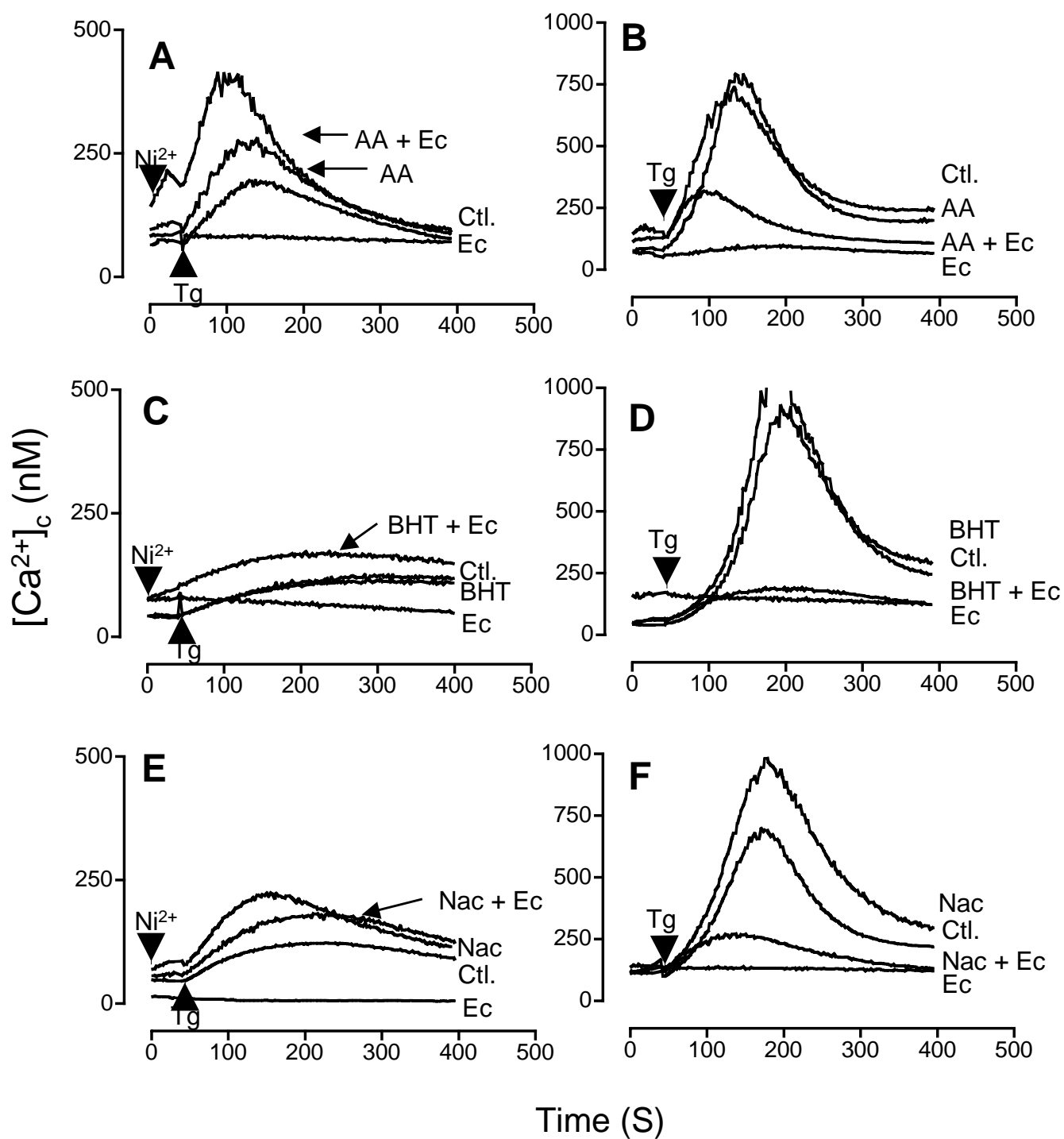


Figure 6

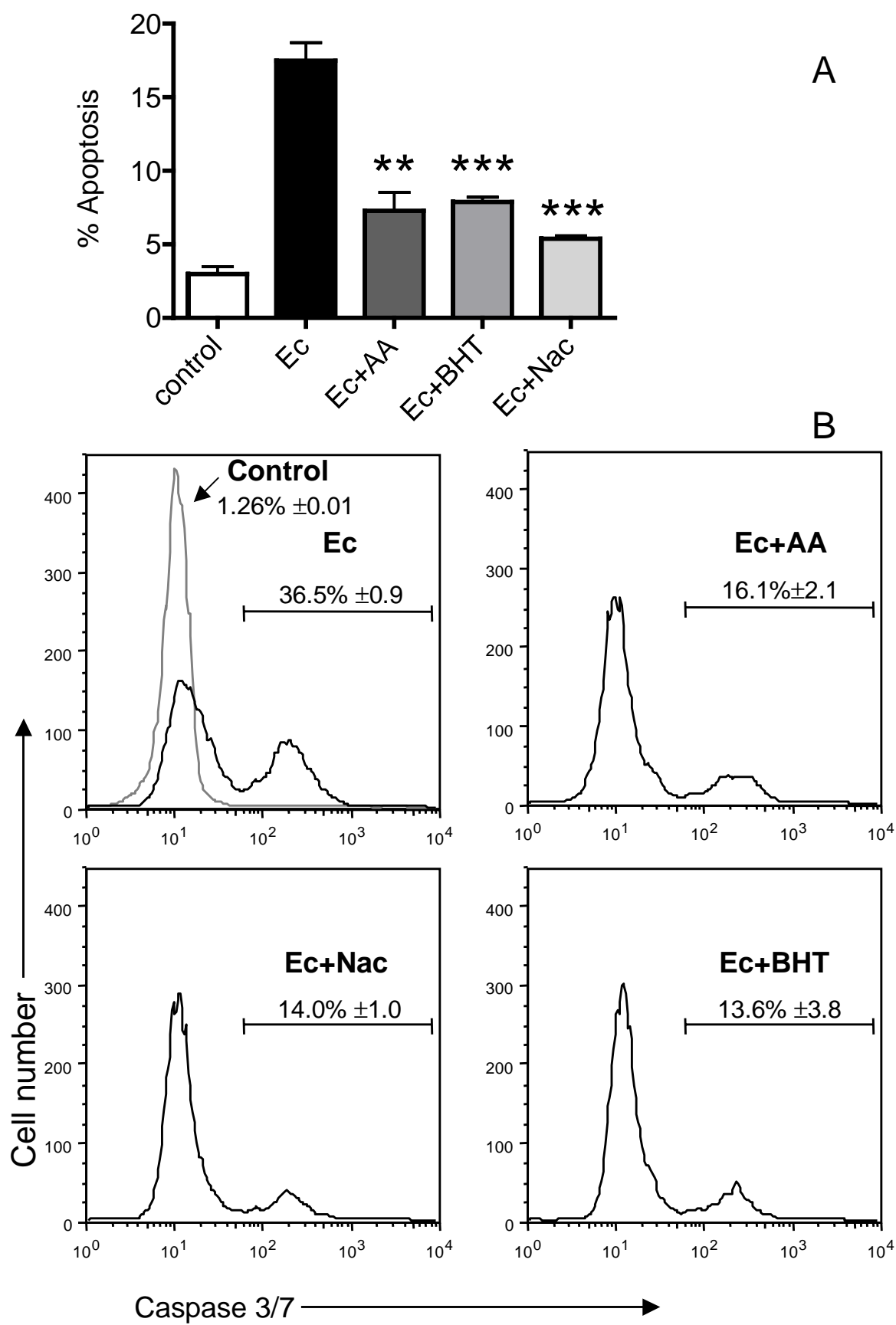


Figure 8



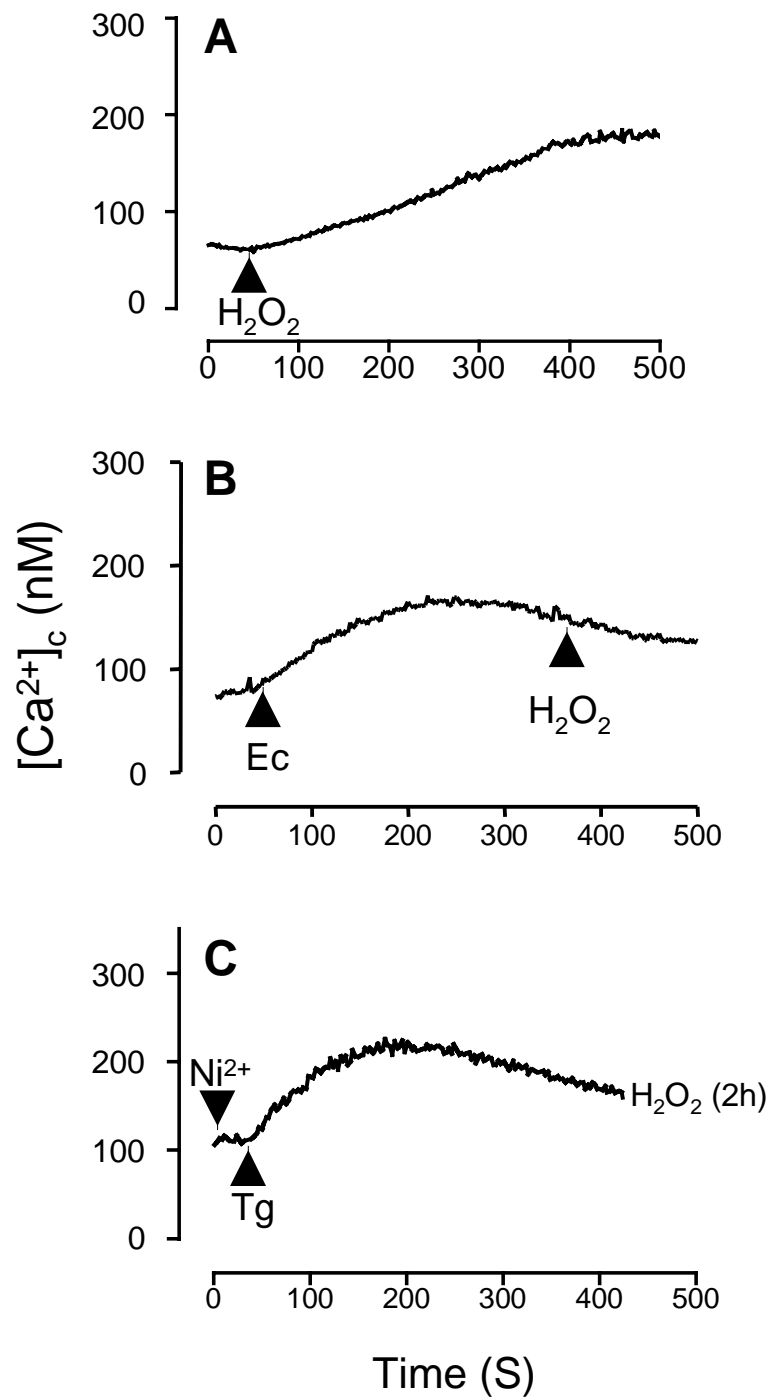


Figure 8

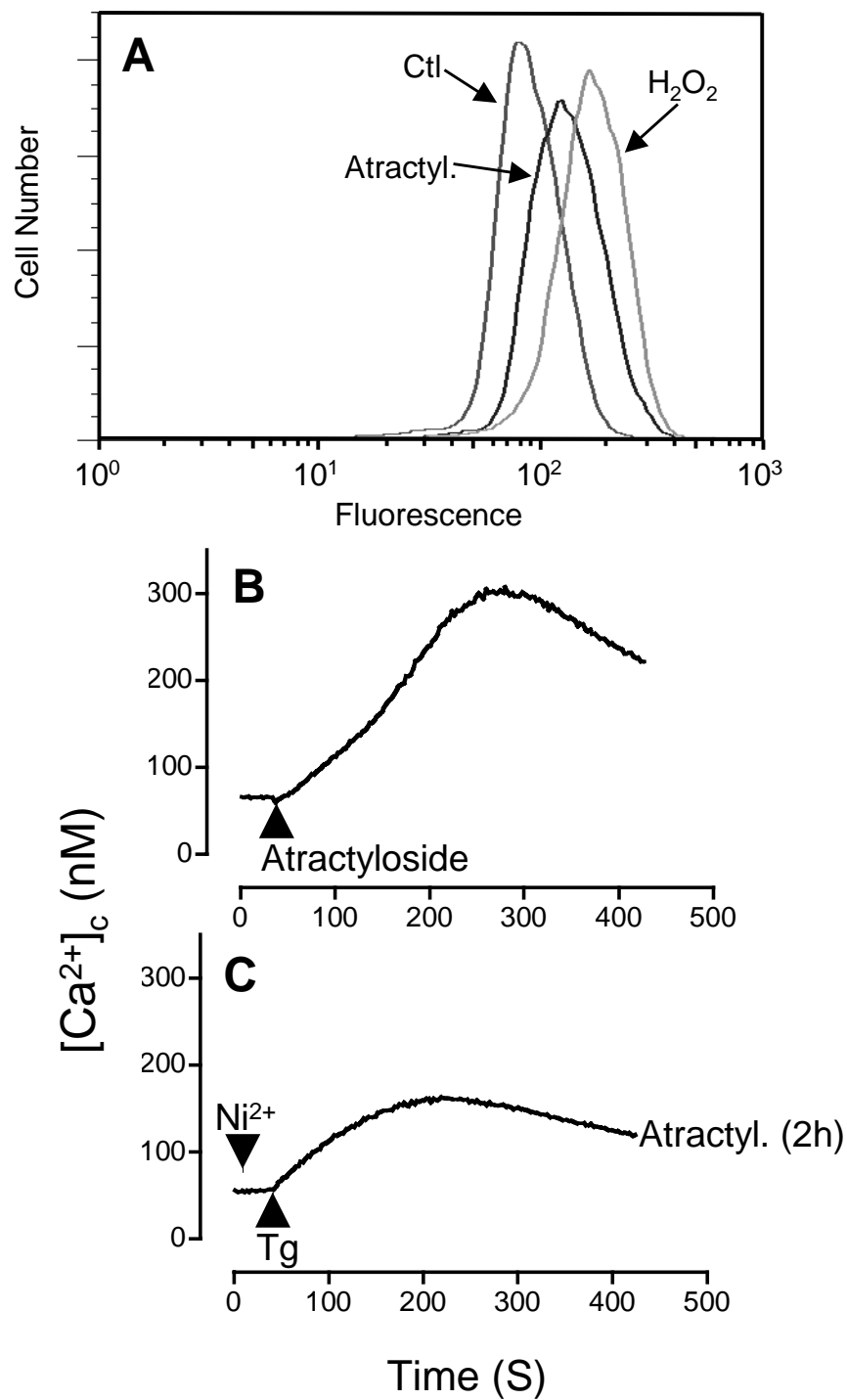


Figure 9

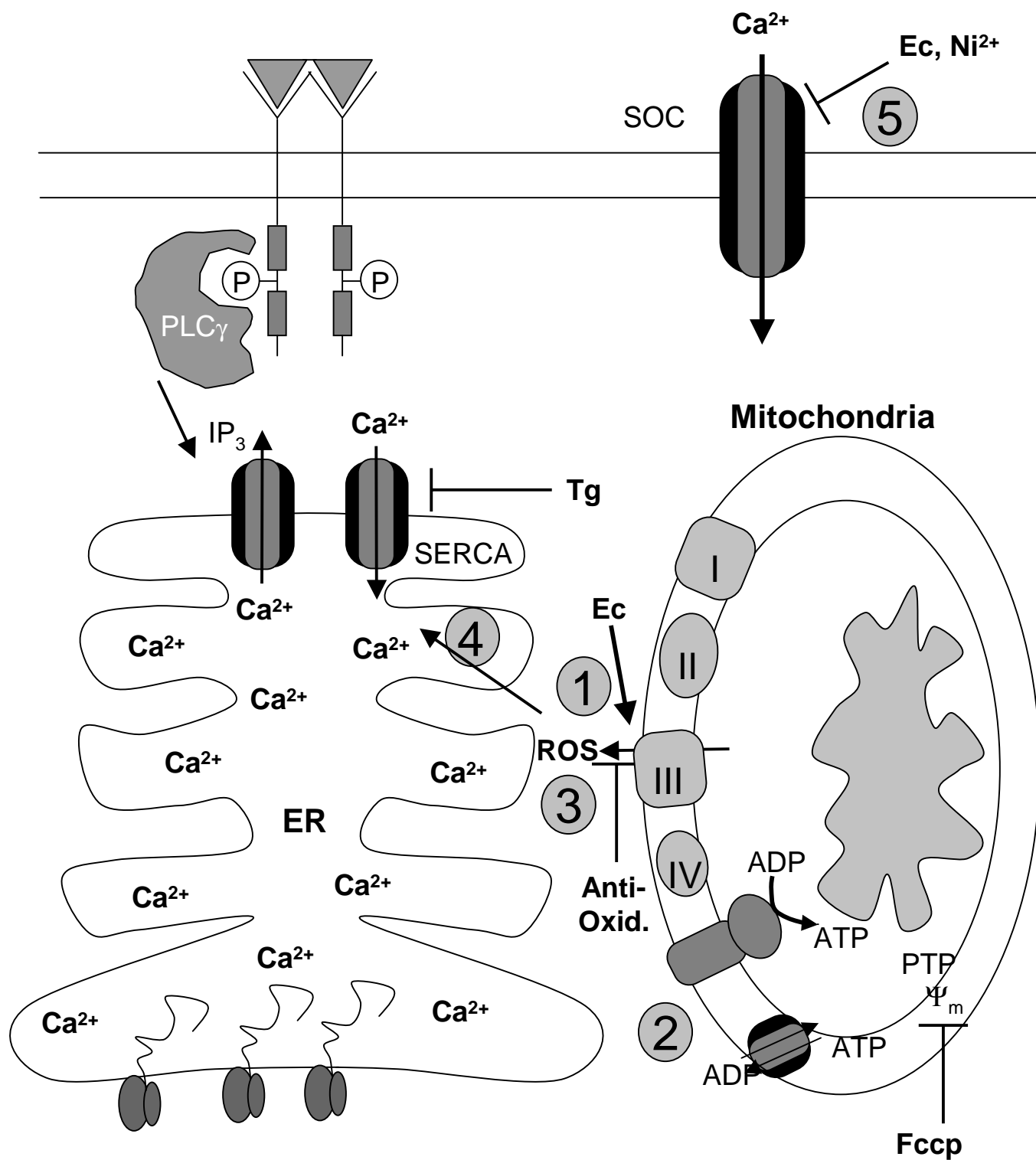


Figure 10