

Hydrogen Peroxide Induces Hyphal Differentiation in *Candida albicans*[▽]

Olviyani Nasution,¹ Kavitha Srinivasa,¹ Minsun Kim,¹ Yeo-Jung Kim,¹ Wankee Kim,³
 Woojin Jeong,¹ and Wonja Choi^{1,2*}

Division of Life and Pharmaceutical Sciences,¹ and Microbial Resources Research Center,² Ewha Womans University, Seoul 120-750, South Korea, and Institute for Medical Sciences, School of Medicine, Ajou University, Suwon 442-749, South Korea³

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In this study, we demonstrate that hyphal differentiation is induced by the subtoxic concentration of exogenous H₂O₂ in *Candida albicans*. This finding is confirmed by the changing intracellular concentration of H₂O₂. In order to induce the same level of differentiation, low concentrations of exogenous H₂O₂ are required for the null mutants of the thiol-specific antioxidant and catalase, while higher concentrations are needed for cells treated with ascorbic acid, an antioxidant chemical.

Hydrogen peroxide (H₂O₂) directly affects various redox systems to regulate cell differentiation, proliferation, death, signal transduction, and ion transport (3, 12, 13, 19, 20) at subtoxic concentrations (23, 27–29). Therefore, the homeostatic maintenance of H₂O₂ at low levels should be tightly regulated (1, 9, 28).

The yeast *Candida albicans* is a pleomorphic human pathogen. An important virulence factor is the morphological transition involving hyphae formation (6, 16, 24), which is regulated by signaling pathways, including the cyclic AMP/protein kinase A and mitogen-activated protein kinase pathways (4, 7,

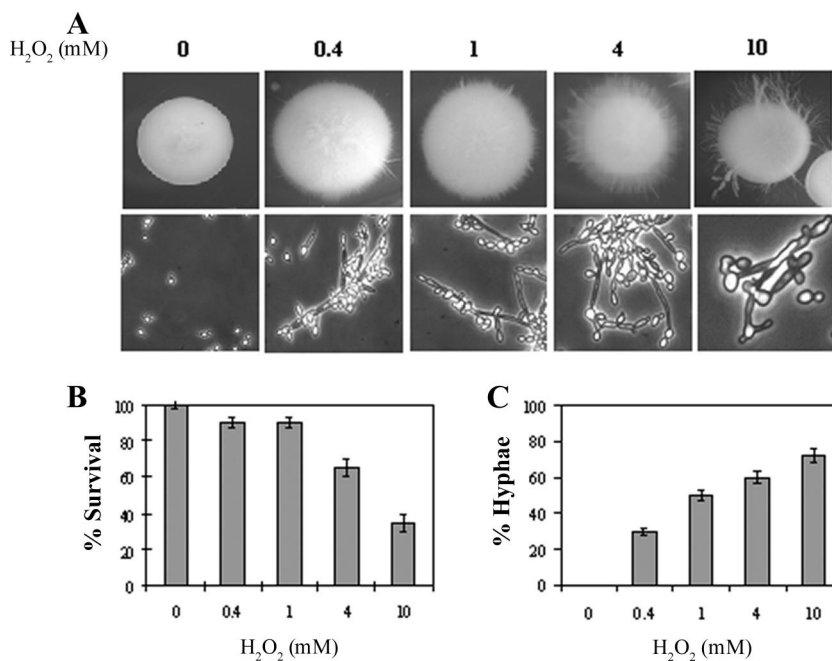


FIG. 1. Hyphal induction by exogenous H₂O₂. (A) Microscopic images of H₂O₂-induced hyphae. Wt cells were grown on YPD solid plates supplemented with the indicated concentrations of H₂O₂ at 30°C for 6 days. Representative colonies were photographed with a stereomicroscope (top). Cells in the mid-log phase were cultured in YPD liquid medium containing H₂O₂ for 6 h at 30°C and observed with a light microscope (bottom). (B) Cytotoxicity of H₂O₂. Standardized cell suspensions were challenged with the indicated concentrations of H₂O₂ for 30 min, plated onto YPD solid medium, and incubated at 30°C for 2 days. The survival rate was expressed as a percentage of the number of colonies in the presence of H₂O₂ divided by the number of colonies in the absence of H₂O₂. (C) Efficiency of hyphal differentiation. Cells were grown on YPD solid medium containing the indicated concentrations of H₂O₂ and incubated at 30°C for 6 days. The percentage of hyphal differentiation was expressed as the number of hyphal colonies divided by the total number of colonies.

* Corresponding author. Mailing address: Science Building A, Room 211, Ewha Womans University, Seoul 120-750, South Korea. Phone: 82-2-3277-2892. Fax: 82-2-3277-2385. E-mail: wjchoi@ewha.ac.kr.

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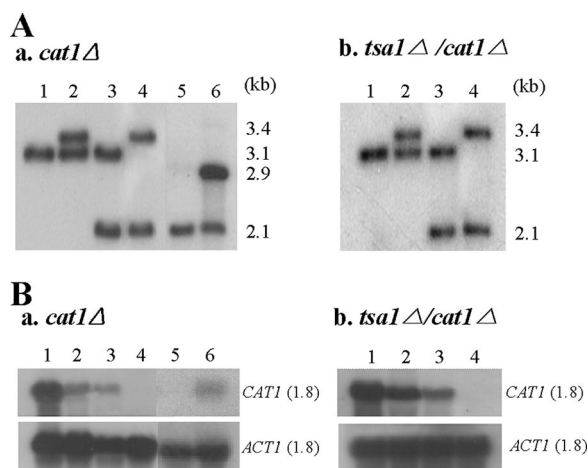


FIG. 2. Construction of *CAT1* null mutants and a revertant. The *CAT1* genes of the wt and the *tsa1*Δ mutant (30, 31) were disrupted using *URA3-dpl200* (32), yielding the *cat1*Δ and *tsa1*Δ *cat1*Δ mutants, respectively. The sense and antisense primers were nucleotide positions 754 to 823 and 2312 to 2381, respectively, of the *CAT1* open reading frame (ORF). To construct a revertant, the DNA fragment containing its own promoter, ORF, and terminator was cloned into pLUX, linearized with *NheI*, and transformed into the *cat1*Δ mutant. Southern (A) and Northern (B) analyses were performed to confirm the authenticity of the constructed strains, using the ³²P-labeled probe prepared from the *MfeI* fragment of the *CAT1* ORF. For the Southern analyses, genomic DNA was digested with *NsiI* and *NcoI*. Lanes 1, parental strains (CA14 and the *tsa1*Δ mutant in panels A and B, respectively); lanes 2, strains with one allele disrupted; lanes 3, strains with *URA3* popped out from the lane 2 strains; lanes 4, null mutants (the *cat1*Δ and *tsa1*Δ *cat1*Δ mutants in panels A and B, respectively); lanes 5, strains with *URA3* popped out from the *cat1*Δ mutant; lanes 6, *CAT1*-reintroduced strains of the *cat1*Δ mutant.

18, 21, 22). Pathway triggers are varied (8) and include specific carbohydrates or amino acids (5, 26), serum (11), temperature (17), pH (10), *N*-acetylglucosamine (2), and starvation (7).

Following infection, *C. albicans* encounters macrophages but survives ingestion by rapidly adopting a hyphal morphology (25). Since the intracellular concentration of H₂O₂ in a macrophage is intrinsically high, it was presently germane to examine whether H₂O₂ can induce hyphal differentiation.

Hyphal differentiation by H₂O₂. When wild-type (wt) SC5314 cells were grown on YPD solid or liquid medium containing 0, 0.4, 1, 4, or 10 mM H₂O₂, the extent of differentiation was augmented in a dose-dependent manner (Fig. 1A). At the 10 mM concentration, however, the cells were severely swollen due to the cytotoxic effects of H₂O₂, which was inferred by the survival rate (35%) in contrast to the survival rate at 0.4 mM and 1 mM (90%) (Fig. 1B). Interestingly, undifferentiated colonies also appeared at all concentrations, enabling the evaluation of induction efficiency expressed as a percentage of the number of differentiated colonies in the total number of colonies. The induction efficiency was dose dependent as expected, but 100% differentiation did not occur even at 10 mM (Fig. 1C).

Next, we increased or decreased the endogenous intracellular H₂O₂. The increase was achieved by nullifying two H₂O₂-scavenging genes, the thiol-specific antioxidant *C. albicans* *TSA1* (30, 31) and the catalase *C. albicans* *CAT1*, individually (*tsa1*Δ or *cat1*Δ) or simultaneously (*tsa1*Δ *cat1*Δ) (Fig. 2). The

growth of null mutants was impeded, and mutants were more H₂O₂ sensitive than the wt over the concentration range (data not shown). The decrease was achieved by the addition of ascorbic acid, an antioxidant chemical (14, 15) (see Fig. 4 and 5).

The enhanced sensitivity of the mutants to exogenous H₂O₂ was presumably caused by an increase in the concentration of intracellular H₂O₂. The relative amount of intracellular H₂O₂ was measured by visualizing fluorescent dichlorodihydrofluorescein (DCF) produced by esterase and H₂O₂ from 5-chloromethyl-2',7'-DCF diacetate (CM-H₂DCFDA) (Invitrogen, Carlsbad, CA). At exogenous H₂O₂ concentrations of 0.2 mM and 1 mM, fluorescent intensity was enhanced to some degree in the *tsa1*Δ and *cat1*Δ mutants and in the *tsa1*Δ *cat1*Δ mutant (Fig. 3A). When the intensities were converted to arbitrary units for quantitative comparison, the intracellular H₂O₂ concentration increased about 1.5-fold in the *tsa1*Δ and *cat1*Δ mutants and about twofold in the *tsa1*Δ *cat1*Δ mutant compared with that of the wt (Fig. 3B).

The hyphal differentiation efficiencies of the wt and null mutants were compared using 0.2 mM exogenous H₂O₂. As shown in Fig. 3C, efficiency was considerably enhanced from 5% in the wt to about 25% in the *tsa1*Δ and *cat1*Δ mutants and to about 35% in the *tsa1*Δ *cat1*Δ mutant. This efficiency was obtained when the wt cells were treated with 1 mM H₂O₂ (Fig. 1C). The effective promotion of hyphal differentiation at a low concentration of exogenous H₂O₂ in mutants in which intracellular H₂O₂ increased indicated that H₂O₂ is a genuine inducer of *C. albicans* hyphal differentiation. When the functional *CAT1* gene was reintroduced, the percentage of hyphae reduced to the level between the wt and the *cat1*Δ mutant.

The effects of a decreased intracellular H₂O₂ concentration on hyphal differentiation were examined in the presence of ascorbic acid, which reduces the number of intracellular reactive oxygen species in some organisms. When wt cells were cultured under the full differentiation conditions (YPD plus 10% fetal bovine serum [FBS], 37°C), the level of intracellular H₂O₂ increased about sevenfold, from 8 to 65 arbitrary units (Fig. 4B and C). However, the addition of 50 mM or 100 mM ascorbic acid to the medium reduced the amount of intracellular H₂O₂ to the same or a lower level of serum depletion (Fig. 4B and C). Microscopic examination revealed that hyphal differentiation was markedly inhibited by ascorbic acid (Fig. 4A). Although the mechanisms of H₂O₂-induced hyphal transition are unclear, it is highly possible that increased intracellular H₂O₂ might be partly or completely involved. We further confirmed the above effects in the *tsa1*Δ, *cat1*Δ, and *tsa1*Δ *cat1*Δ mutants. When 50 mM ascorbic acid, an antioxidant chemical, was added to the medium 30 min after the treatment of mutant cells with different concentrations of exogenous H₂O₂, hyphal differentiation was induced even at otherwise toxic concentrations: 10 mM for the wt, 4 mM for the *tsa1*Δ and *cat1*Δ mutants, and 1 mM for the *tsa1*Δ *cat1*Δ mutant (Fig. 5). Thus, ascorbic acid lowered the intracellular concentration of H₂O₂ and inhibited hyphal differentiation. Also, efficient hyphal differentiation in the presence of ascorbic acid required exogenous H₂O₂.

The above results suggest that the mere increase of intracellular H₂O₂ is insufficient for complete hyphal differentiation. The intracellular H₂O₂ concentration of cells cultured in

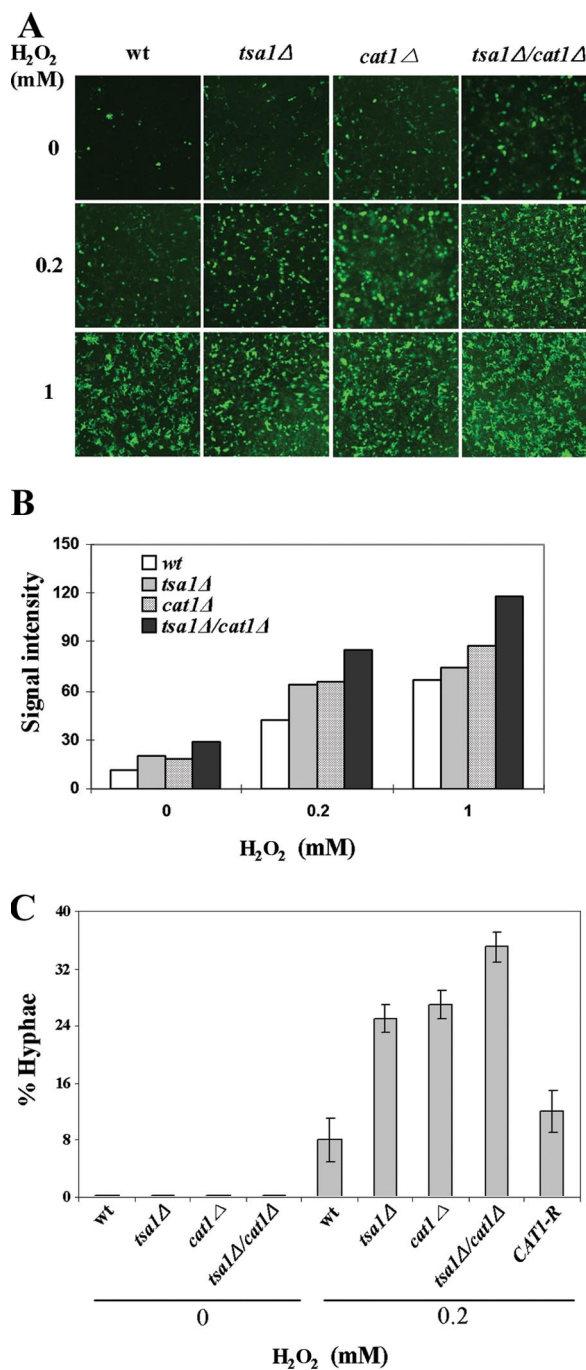


FIG. 3. Effects of increased intrinsic H₂O₂ on hyphal differentiation. Cells were grown in YPD medium containing 0.2 and 1 mM H₂O₂ for 6 h, washed, and resuspended in Hank's balanced salt solution. After the addition of CM-H₂DCFDA (10 μM final), the cells were further incubated at RT for 10 min. (A) Images of DCF fluorescence were taken by using a confocal microscope with excitation and emission wavelengths at 488 nm and 520 nm, respectively. (B) Relative concentrations of intracellular H₂O₂ were derived from the confocal microscope-aided integration of fluorescence signal intensity within a scope. (C) Efficiency of hyphal differentiation at 0.2 mM H₂O₂ was determined as described in the legend to Fig. 1C. CAT1-R represents the strain into which the functional CAT1 gene was introduced.

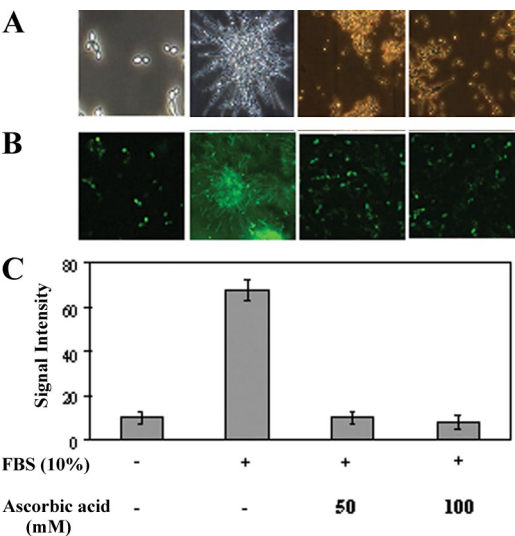


FIG. 4. Effects of ascorbic acid on hyphal differentiation in FBS-treated cells. Wt cells were grown in YPD in the absence (–) or presence (+) of 10% FBS for 30 min, followed by supplementation with 50 mM or 100 mM ascorbic acid. A portion of the cells was removed to take light microscopic images (A). For the rest of cells, fluorescence images (B) were taken, and the relative concentrations of intracellular H₂O₂ (C) were determined as described in the legend to Fig. 3.

FBS-supplemented YPD was identical to cells grown in YPD in the presence of exogenous 4 mM H₂O₂ (Fig. 4C and 5B), although differentiation was 100% and 60%, respectively (Fig. 1C). This indicates that some factors present in the serum are required for full hyphal differentiation in addition to increased intracellular H₂O₂. Based on these observations, we propose that hyphal differentiation in *C. albicans* occurs through two separate, but not mutually exclusive, steps: (i) initiation by

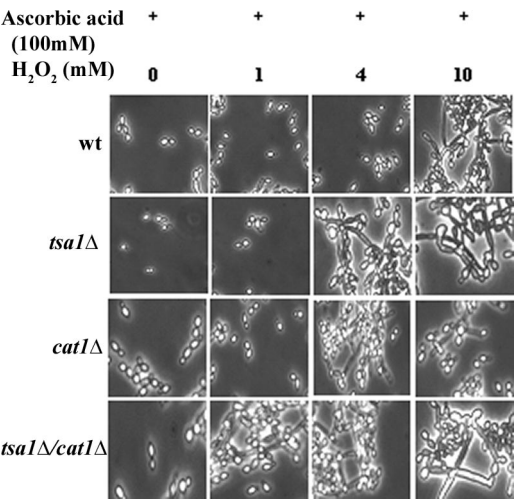


FIG. 5. Effects of ascorbic acid on hyphal differentiation. After the wt and *tsa1Δ*, *cat1Δ*, and *tsa1Δ cat1Δ* mutant cells were grown in YPD medium supplemented with 4 concentrations of exogenous H₂O₂ for 30 min at 30°C, 100 mM ascorbic acid was added, and the cells were further grown for 6 h at 30°C, the cultures were observed with a light microscope (magnification, ×400).

intracellular H₂O₂ above a certain concentration and (ii) promotion by currently unknown additional factors in serum.

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