A Mitogen-Activated Protein Kinase That Senses Nitrogen Regulates Conidial Germination and Growth in *Aspergillus fumigatus*

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We show that the mitogen-activated protein (MAP) kinase pathway that responds to osmotic stress in *Aspergillus fumigatus* is also involved in nutritional sensing. This MAP kinase regulates conidial germination in response to the nitrogen source and is activated upon starvation for either carbon or nitrogen during vegetative growth.

Mitogen-activated protein (MAP) kinases play a central role in regulating cellular homeostasis in microbial eukaryotes in response to environmental changes (3, 4, 7, 9–12, 15–18, 20). We have been studying the role of the MAP kinase *sakA* in *Aspergillus fumigatus*, an opportunistic human pathogen. We were interested in *sakA* because in other fungi homologues of this protein kinase have been shown to play a role in stress responses and pathogenesis (1, 2, 6, 8, 10, 13–15, 19, 21, 22). It is therefore possible that *SakA* plays a role in pathogenesis and response to immune cell action.

A *sakA* deletion strain was made by using *sakA* 5′ and 3′ flanking sequences that were amplified by PCR from genomic DNA (strain AF293) with oligonucleotides (Table 1) that incorporated specific restriction sites that facilitated cloning around the hygromycin phosphotransferase gene (Fig. 1A). The selective marker was first cloned into the EcoRI site of the plasmid Bluescript (5). Deletion of *sakA* was confirmed by Southern blot analysis (Fig. 1B), and initial experiments were conducted with three independent deletion strains to confirm that phenotypes were associated with deletion of the gene and not an unlinked mutation resulting from transformation. Specific oligonucleotide pairs were used to make PCR probes for the genes *msnA*, *ptpA*, *pbsA*, and *actin* with genomic DNA as the template (Table 1). Strain AF293 and those derived from it were used throughout these studies and cultured on minimal medium (MM; 70 mM NaNO₃, 7 mM KCl, 2 mM MgSO₄, 12 mM KPO₄ [pH 6.8], trace elements, 1% [wt/vol] glucose) or medium (MM; 70 mM NaNO₃, 7 mM KCl, 2 mM MgSO₄, 12 mM KPO₄ [pH 6.8], trace elements, 1% [wt/vol] glucose) or

We assessed the conservation of the *SakA* MAP kinase signaling pathway in *A. fumigatus* using Northern blotting to measure changes in the abundances of transcripts for the genes *msnA*, *ptpA*, *pbsA*, and, as a control, *actin*. We looked at these genes because the mRNAs for *msnA*, *ptpA*, and *pbsA* are known to increase in response to osmotic stress in other fungi (3, 9, 12). We found that the abundances of transcripts for *msnA*, *ptpA*, and *pbsA* all increased in response to increasing osmotic stress in the wild-type control strain but not in the *sakA* deletion (Δ*sakA*) strain (Fig. 1C). This demonstrates that the transcriptional response to osmotic stress is conserved in *A. fumigatus*. Similarly, we found levels of *sakA* transcripts increased in response to hydrogen peroxide, a response also seen in some fungi (data not shown) (3, 9, 12).

We next examined the growth response of actively growing germings and conidia to increased osmolarity. We found that germings of the Δ*sakA* strain undergo growth arrest in response to increased osmolarity, whereas conidia germinated in

**TABLE 1. Oligonucleotides used during this study**

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<th>Oligonucleotide</th>
<th>Sequence</th>
<th>Product size (kb)</th>
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<td>sakA-1</td>
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<td>2.2</td>
</tr>
<tr>
<td>sakA-2</td>
<td>GTAGAATTGAGTGACTCCTG</td>
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<tr>
<td>sakA5-2</td>
<td>TCTACGGGAGGTAAGAAGC</td>
<td>2.7</td>
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<tr>
<td>sakA5-1</td>
<td>GATCCTCAATCTGAGTGTCAACG</td>
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<td>sakA3-2</td>
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<tr>
<td>sakA3-1</td>
<td>CTTCTCGGATCCACTGTATCC</td>
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<tr>
<td>ptp-5</td>
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<td>actin-3</td>
<td>GCACCTGGGGTGAGACGAAG</td>
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FIG. 1. Deletion of the sakA gene. (A) Strategy used to delete sakA. The hph-selective marker was flanked by DNA sequences from around sakA. Integration of the linear molecule by homologous recombination replaces sakA with hph in the chromosome. (B) Southern blot showing the wild-type and ΔsakA patterns of hybridization. One representative is shown for each. (C) Northern blots of RNA from the ΔsakA strain and AF293, the wild-type strain, exposed to increasing concentrations of NaCl. The first lane in each set had CM; lanes 2 to 6 had in addition 0.25, 0.5, 0.75, 1, and 1.5 M NaCl, respectively. The probes used for hybridization of each set of lanes are indicated on the left.

FIG. 2. Photomicrographs of the wild-type parental strain AF293 and a ΔsakA strain grown continuously (continuous) in CM with 1 M NaCl or shifted to CM with 1 M NaCl after 5 h of germination in CM (germinated). Fields of germlings were also photographed after 11 and 13 h of growth. Scale bar, 20 μm.
depends on the nitrogen source in the medium. As contrast, on MM the AF293 conidia were significantly slower to germinate than those of the ∆sakA strain. (B) The germination of conidia depends on the nitrogen source.

During the course of these initial studies, we found that conidia of the ∆sakA strain and the parent germinated differently on MM and CM (Fig. 3A). On CM the parental and ∆sakA strains germinated equally well. In contrast, on MM the wild-type strain germinated more slowly than the ∆sakA strain. A major difference between MM and CM is the inclusion of yeast extract, peptone, and tryptone, all sources of reduced nitrogen. We therefore tested germination of the wild-type and ∆sakA strains starved for nitrogen (lanes -N) or glucose (lanes -C) for 30 min. The probes used for hybridization of each set of lanes are indicated on the left.

Conidial germination is altered in the sakA deletion strain and is dependent on the nitrogen source. (A) Conidial germination in CM is the same for AF293 and ∆sakA strains after 6 h of growth. In contrast, on MM the AF293 conidia were significantly slower to germinate than those of the ∆sakA strain. (B) The germination of conidia depends on the nitrogen source in the medium.

high-osmolarity medium were able to grow hyphae but did so more slowly than the parental control, suggesting that signaling through this MAP kinase pathway in conidia is different from that in growing germlings (Fig. 2). We also observed that ∆sakA strains failed to produce a pigment secreted into the medium of plates by control strains (data not shown).

During the course of these initial studies, we found that conidia of the ∆sakA strain and the parent germinated differently on MM and CM (Fig. 3A). On CM the parental and ∆sakA strains germinated equally well. In contrast, on MM the wild-type strain germinated more slowly than the ∆sakA strain. A major difference between MM and CM is the inclusion of yeast extract, peptone, and tryptone, all sources of reduced nitrogen. We therefore tested germination of the wild-type and ∆sakA strains on MM containing different nitrogen sources (Fig. 3B). Conidia of the wild-type strain germinated more slowly than those of the ∆sakA strain on MM containing the poor nitrogen source sodium nitrate or sodium nitrite, but both strains germinated equally well on MM with the reduced-nitrogen source ammonium chloride or proline. When phenylalanine was used as a nitrogen source, both strains germinated less well, suggesting that this amino acid is less suitable as a nitrogen source. Interestingly, we found no difference in germination on a variety of carbon sources, including glycerol, acetate, sorbitol, and lactose (data not shown). These results indicate that SakA functions to negatively regulate conidial germination in response to less-preferred nitrogen sources but not in response to the carbon sources.

Finally, because of the newly discovered role for SakA in sensing nitrogen in the medium, we investigated the effect of starvation for carbon and nitrogen on transcriptional activation of the genes in this pathway (Fig. 4). When hyphae are transferred from rich medium to MM lacking either a nitrogen or carbon source, we find a robust activation of transcription for sakA but not for msnA, ptpA, or pbsA and no changes in the ∆sakA strain are observed.

In summary, the osmotic stress response pathway in A. fumigatus is conserved. We have shown that this MAP kinase pathway negatively regulates conidial germination and is activated in response to starvation for nitrogen or carbon sources.

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REFERENCES

FIG. 3. Conidial germination is altered in the sakA deletion strain and is dependent on the nitrogen source. (A) Conidial germination in CM is the same for AF293 and ∆sakA strains after 6 h of growth. In contrast, on MM the AF293 conidia were significantly slower to germinate than those of the ∆sakA strain. (B) The germination of conidia depends on the nitrogen source in the medium.

FIG. 4. sakA RNA levels change following starvation for nitrogen or glucose. Northern blots of RNA prepared from hyphae from ∆sakA and AF293 strains starved for nitrogen (lanes -N) or glucose (lanes -C) for 30 min. The probes used for hybridization of each set of lanes are indicated on the left.