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Pho4 mediates phosphate acquisition in *Candida albicans* and is vital for stress resistance and metal homeostasis

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ABSTRACT During interactions with its mammalian host, the pathogenic yeast *Candida albicans* is exposed to a range of stresses such as superoxide radicals and cationic fluxes. Unexpectedly, a nonbiased screen of transcription factor deletion mutants revealed that the phosphate-responsive transcription factor Pho4 is vital for the resistance of *C. albicans* to these diverse stresses. RNA-Seq analysis indicated that Pho4 does not induce stress-protective genes directly. Instead, we show that loss of Pho4 affects metal cation toxicity, accumulation, and bioavailability. We demonstrate that *Δpho4* cells are sensitive to metal and nonmetal cations and that Pho4-mediated polyphosphate synthesis mediates manganese resistance. Significantly, we show that Pho4 is important for mediating copper bioavailability to support the activity of the copper/zinc superoxide dismutase Sod1 and that loss of Sod1 activity contributes to the superoxide sensitivity of *Δpho4* cells. Consistent with the key role of fungal stress responses in countering host phagocytic defenses, we also report that *C. albicans* *Δpho4* cells are acutely sensitive to macrophage-mediated killing and display attenuated virulence in animal infection models. The novel connections between phosphate metabolism, metal homeostasis, and superoxide stress resistance presented in this study highlight the importance of metabolic adaptation in promoting *C. albicans* survival in the host.

INTRODUCTION

The fungus *Candida albicans* is a constituent of the normal human microbiome. It resides on the skin, in the oral cavity, and in the gastrointestinal and urogenital tracts of most healthy individuals (Odds, 1988). However, as an opportunistic pathogen, this fungus is poised to cause superficial infections in otherwise healthy individuals or life-threatening systemic infections in immunocompromised hosts. *Candida* species are the fourth-most-common cause of nosocomial bloodstream infections (Wisplinghoff et al., 2004), and estimates indicate that *C. albicans* is responsible for ∼400,000 systemic infections per year (Brown et al., 2012). Such infections, which are associated with alarming crude mortality rates of >40%, occur after entry of the fungus into the bloodstream, followed by dissemination to internal organs such as the kidney, liver, and brain (Morgan, 2005). Therefore *C. albicans* can colonize diverse anatomical sites of the human host, demonstrating its significant capacity to adapt to contrasting environments.

A major factor underlying this adaptability is the ability of *C. albicans* to rapidly mount transcriptional responses after exposure to host-imposed stresses (for a review, see Wilson et al., 2009). For example, consistent with neutrophils and macrophages producing high levels of reactive oxygen species (ROS), genome-wide profiling has revealed that *C. albicans* induces many oxidative stress–responsive genes after phagocytosis (Fradin et al., 2003, 2005; Rubin-Bejerano et al., 2003; Lorenz et al., 2004; Enjalbert et al., 2007). During invasion of the liver, a number of pH-responsive genes and heat shock...
proteins, together with genes encoding transporters for vital micronutrients, including iron and phosphate, are induced (Thewes et al., 2007). In a mucosal infection model of oral candidiasis, the fungus up-regulates nitrosative stress-responsive genes, as well as genes indicating that C. albicans also faces a nitrogen-, glucose-, and phosphate-poor environment in the oral tissue (Zakhikhany et al., 2007). Such genome-wide profiling studies, which have captured the transcriptional response of C. albicans in different infection models, provide significant insight into the particular stresses encountered by this pathogen when colonizing specific host environments.

The ability of C. albicans to mount such stress responses within different host niches is essential for virulence (for a review, see Brown et al., 2014b). For example, the inactivation of genes that are induced in the host and encode enzymes that detoxify ROS (catalase, Cat1; superoxide dismutases, Sod1, Sod5; thioredoxin, Trx1; glutaredoxin, Grx2) or reactive nitrogen species (the hemoprotein Yhb1) attenuates the virulence of C. albicans in mouse models of systemic candidiasis (Wysong et al., 1998; Hwang et al., 2002; Martchenko et al., 2004; Hromatka et al., 2005; Chaves et al., 2007; da Silva Dantas et al., 2010). In addition, mutants lacking the Hog1 stress-activated protein kinase, which plays key roles in stress signaling and stress-responsive gene expression, display impaired virulence in multiple infection models (Alonso-Monge et al., 1999; Prieto et al., 2014). The ability to acquire essential nutrients is also vital for C. albicans to colonize nutrient-poor environments within the host (Brown et al., 2014a). For example, C. albicans cells lacking Pga7 or Pra1, which play major roles in the scavenging of iron and zinc, respectively, exhibit reduced virulence (Kuznets et al., 2014).

Although adaptation to host niches and virulence are intimately linked, there is still much to be learned about the mechanisms underlying the adaptability of C. albicans to the diverse environments encountered within the host. After phagocytosis, microbes are exposed to high levels of superoxide anions generated by the respiratory burst (Reeves et al., 2002). The resulting accumulation of anionic charge is compensated by a rush of potassium (K⁺) ions into the endocytic vacuole, which also imposes a cationic stress on the microbe (Reeves et al., 2002). However, we know little regarding the transcriptional regulators required for C. albicans resistance to these phagocyte-imposed stresses. Here we performed a nonbiased screen of transcription factor deletion mutants to identify the Pho4 transcription factor as being essential for resistance to both superoxide and cationic stresses in C. albicans. We find that Pho4 is an important virulence determinant in C. albicans, consistent with stress adaptation being vital for fungal pathogenesis. However, rather than Pho4 directly regulating the expression of stress-protective genes, we provide evidence that many of the stress phenotypes exhibited by pho4Δ cells relate to effects on metal homeostasis.

RESULTS

Cells lacking PHO4 display pleiotropic stress phenotypes

To identify transcription factors that promote resistance to cationic stress or superoxide stress, we screened a C. albicans transcription factor deletion library (Homann et al., 2009) for mutants that display impaired fitness compared with wild-type cells upon exposure to NaCl (1 M) or the superoxide-generating drug menadione (300 μM). Strain fitness was measured by quantitative fitness analysis (QFA), in which liquid cultures of exponentially growing cells were spotted onto solid agar and growth monitored by time-course photography. Images were processed and quantitative growth parameters determined using Colonyzer software (Lawless et al., 2010), allowing for the generation of fitness plots (Figure 1, A and B). Deviations from wild-type fitness generated a stress interaction score (SIS), with the lowest SIS indicative of most-impaired fitness. The SIS of all mutants after exposure to NaCl or menadione stress is listed in Supplemental Table S1. More mutants showed impaired fitness to menadione-induced superoxide stress than to cationic stress. The 10 strains with the greatest impairment of resistance to these stress conditions are highlighted in red in Figure 1, A and B, and listed in Table 1.

Three transcription factors listed in Table 1 are required for optimal fitness in response to both cationic and superoxide stress: Pho4, Efg1, and Rim101. Efg1 has well-characterized roles in regulating hyphal growth (Stoldt et al., 1997), whereas Rim101 is important for the alkaline pH response (Davis et al., 2000). Previous phenotypic profiling showed that Rim101 was important for resistance to the cationic stress—inducing agent LiCl, and cells lacking Efg1 or Rim101 were shown to display marginal sensitivity to menadione (Homann et al., 2009). In contrast, the cationic and menadione stress-protective roles of Pho4 have not previously been reported in C. albicans. Here it is noteworthy that in the original phenotypic screen of the transcription factor deletion collection (Homann et al., 2009), a lower concentration of menadione (90 μM) was used than in this study (300 μM). This likely underlies why, in the original screen, pho4Δ cells were not designated as menadione sensitive (Homann et al., 2009). The analogous Pho4 transcription factor in Saccharomyces cerevisiae plays vital roles in phosphate acquisition and storage (Ogawa et al., 2000), and although it is required for growth under alkaline pH conditions (Sambade et al., 2005), cationic and oxidative stress-sensitive phenotypes have not been reported. On the basis of these observations, we decided to investigate further the stress-protective roles of the Pho4 transcription factor in C. albicans.

The stress sensitivities of the pho4Δ mutant were confirmed in spot-test experiments. The pho4Δ cells were more sensitive than wild-type cells to cationic and superoxide stresses imposed by NaCl and menadione, respectively, and these stress phenotypes were rescued upon reintegration of the PHO4 gene (Figure 1C). We also noted that pho4Δ cells grew more slowly than wild-type cells on rich medium (Figure 1C). Cells lacking PHO4 were not sensitive to sorbitol, indicating a cation-specific rather than an osmotic stress—protective role (Figure 1C). In addition, pho4Δ cells were not notably sensitive to hydrogen peroxide, suggesting that Pho4 plays a specific role in superoxide protection (Figure 1C). Pho4 was also vital for the growth of C. albicans cells under alkaline but not acidic pH environments (Figure 1C), similar to that reported in S. cerevisiae (Sambade et al., 2005). Related to the neutral/alkaline pH of serum, the growth of cells lacking PHO4 was also impaired on medium containing serum (Figure 1D), and serum-induced filamentation was significantly delayed (Figure 1D).

C. albicans Pho4 is required for phosphate acquisition and storage

In S. cerevisiae, the Pho4 transcription factor plays a central role in phosphate acquisition when extracellular inorganic phosphate (P) concentrations are low. In P-rich environments Pho4 is phosphorylated by the Pho85-Pho80 cyclin-dependent protein kinase (CDK) complex, which prevents its nuclear accumulation (Schneider et al., 1994; O’Neill et al., 1996). However, when P levels are limiting, the Pho85-Pho80 CDK is inhibited via the action of the Pho81 CDK inhibitor, and the resulting unphosphorylated Pho4 accumulates in the nucleus. Subsequently Pho4 induces genes encoding proteins involved in phosphate acquisition and in the synthesis of the phosphate storage molecule polyphosphate (polYP; Ogawa et al., 2000). However, sequence homology between the S. cerevisiae and C. albicans Pho4 transcription factors is largely restricted to the C-terminal...
FIGURE 1: Cells lacking PHO4 display pleiotropic stress phenotypes. Quantitative fitness analysis plot of the transcription factor deletion library grown on media containing (A) 1 M NaCl and (B) 300 μM menadione. The line of equal growth (dashed line) and a multiplicative model of expected fitness (solid line) are indicated. The top 10 sensitive strains are indicated by red dots. (C) Exponentially growing strains were spotted in serial dilutions onto YPD plates containing 1 M NaCl, 300 μM menadione, 1.2 M sorbitol, or 5 mM H2O2. The pH of YPD was adjusted using 1 M Tris-HCl (pH 8.25) for pH 8 medium and 1 M succinic acid for pH 4 medium. Plates were incubated for 24 h at 30°C. (D) pho4Δ cells are sensitive to serum and display delayed serum-induced hyphal growth. Exponentially growing strains were spotted onto YPD plates containing 20% fetal bovine serum (left), or stationary-phase cells were diluted 1:10 in YPD medium containing 10% fetal bovine serum and incubated at 37°C for 4 h (right).

<table>
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<th>Standard name</th>
<th>SIS NaCl</th>
<th>Systematic name</th>
<th>Standard name</th>
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Mutants sensitive to both stresses are indicated in bold.

TABLE 1: Stress interaction scores (SIS) of 10 most sensitive transcription factor deletion mutants to cationic (NaCl) and superoxide (menadione [Men]) stress.
blue staining of RNA/polyP extracts after electrophoresis on urea-polyacrylamide gels. polyphosphate. Visualization of polyphosphate by (C) Neisser staining of cells and (D) toluidine visualization by a dark red coloration. (C, D) Pho4 is required for the storage of Pi as subjected to an agar-overlay coloration assay in which secreted acid phosphatase activity is visualized by a dark red coloration. (C, D) Pho4 is required for the storage of Pi as polyP extracts after electrophoresis on urea-polyacrylamide gels.

DNA-binding domain (Urrialde et al., 2015), and key phosphorylation sites implicated in Pho4 regulation in S. cerevisiae do not appear to be conserved in C. albicans Pho4. Therefore we ascertained whether the function of Pho4 in phosphate accumulation and storage is conserved in C. albicans.

We created a C. albicans strain expressing Pho4-GFP and examined the cellular localization of Pho4. Pho4 gradually accumulates in the nucleus after growth in Pi-limiting medium, and this is rapidly reversed after addition of phosphate (Figure 2A). C. albicans also responds to phosphate limitation by increasing the level of secreted acid phosphatase activity in a Pho4-dependent manner (Figure 2B). We examined the role of Pho4 in polyP accumulation using two different techniques to visualize polyP. Neisser staining is routinely used to detect polyP in whole cells and uses a basic methylene blue dye that stains the polyP granules metachromatically a purple/black color (Gurr, 1965). A second method involves electrophoresis of polyP extracted from cells on urea-polyacrylamide gels, followed by staining with a different basic dye, toluidine blue (Smith and Morrissey, 2007). Toluidine blue staining of polyP results in a metachromatic shift in the absorption spectrum of this dye to give a purple/pink color. C. albicans Pho4 was found to be critical for polyP accumulation, as revealed both by Neisser staining of whole cells (Figure 2C) and toluidine blue staining of polyP resolved on polyacrylamide gels (Figure 2D). Thus, despite sequence differences with its S. cerevisiae orthologue, the C. albicans Pho4 transcription factor is responsive to Pi-limiting environments and plays key roles in phosphate accumulation and storage.

polyP is not required for Pho4-mediated stress resistance

Pho4 in C. albicans is required for resistance to a range of distinct stress conditions (Figure 1) in addition to phosphate uptake and storage (Figure 2). Therefore we asked whether Pho4 played a direct role in stress-protective gene expression or whether the stress phenotypes displayed by pho4Δ cells were due to the role of Pho4 in phosphate acquisition. Initially, we examined whether Pho4 accumulated in the nucleus after cationic, superoxide, and alkaline pH stresses, similar to what occurs in Pi-limiting environments. Pho4 rapidly accumulated in the nucleus after alkaline pH stress, but we could not detect changes in the cellular localization of Pho4 after cationic or superoxide stress (Figure 3A). The lack of nuclear accumulation after cationic or superoxide stress suggested that Pho4 might play an indirect, nontranscriptional role in mediating resistance to these stresses. Related to this, the phosphate storage molecule polyP has been implicated in stress adaptation and osmoregulation in bacteria and lower eukaryotic species, such as yeast, fungi, and trypanosomes (reviewed in Moreno and Docampo, 2013). Hence we investigated whether polyP synthesis was a key determinant in mediating Pho4-dependent stress resistance. Initially, we examined whether polyP was mobilized after exposure to different stresses. Neisser staining and gel electrophoresis revealed that there was a drastic decrease in polyP levels 10 h after transferring cells from P₀-replete to P₀-limiting medium (Figure 3, B and C). No obvious differences were observed after superoxide stress (Figure 3B and Supplemental Figure S1). A rapid decrease in polyP levels was observed, however, after alkaline pH stress and, to some extent, cationic stress (Figure 3, B–D). This suggested that perhaps the role of Pho4 in mediating resistance to alkaline and cationic stresses was due to its role in polyP production.

To examine this directly, we tested whether the physical presence of polyP was important for stress resistance in C. albicans. In S. cerevisiae, polyP synthesis is dependent on the yeast vacuolar transporter chaperone (VTC) complex, which is a membrane protein assembly comprising the Vtc1-4 proteins (Figure 4A). Vtc4 has been identified as the polyP polymerase within the VTC complex (Hothorn et al., 2009), and S. cerevisiae vtc4Δ and vtc1Δ null mutants lack detectable polyP (Ogawa et al., 2000; Hothorn et al., 2009). Hence we generated C. albicans strains lacking homologues of the VTC1

FIGURE 2: Cells lacking PHO4 cannot acquire or store phosphate. (A) Pho4 accumulates in the nucleus under phosphate-limiting conditions. Cells expressing Pho4-GFP were transferred to YPD medium lacking phosphate, and localization was determined by fluorescence microscopy over a 14-h time course. +Pi indicates phosphate addition (10 min) to the 14-h sample. DAPI staining illustrates nuclear positioning. (B) Under phosphate-limiting conditions, Pho4 is required for acid phosphatase activity. Strains grown on PNMC agar plates with or without P₀ were subjected to an agar-overlay coloration assay in which secreted acid phosphatase activity is visualized by a dark red coloration. (C, D) Pho4 is required for the storage of P₀ as polyP. Visualization of polyphosphate by (C) Neisser staining of cells and (D) toluidine blue staining of RNA/polyP extracts after electrophoresis on urea-polyacrylamide gels.

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and VTC4 polyP synthesis genes and explored polyP levels and stress resistance phenotypes of these mutants. PolyP levels were markedly reduced in cells lacking VTC1 or VTC4 (Figure 4, B and C). Phenotypic analyses of these mutants, however, revealed no overlap with the cationic, superoxide, and alkaline pH stress–sensitive phenotypes exhibited by pho4Δ cells (Figure 4D) and supplemental Figure S2A) or defects in serum-induced filamentation (Supplemental Figure S2B). The vtc4Δ + VTC4 mutant was unexpectedly but reproducibly slightly more sensitive to menadione than wild-type cells (Figure 4D), indicating the presence of additional genome changes during strain construction. Nonetheless, these results indicate that the drastic reduction of polyP levels in pho4Δ cells does not underlie the phenotypes associated with loss of Pho4.

**RNA-sequencing analysis defines the Pho4-regulon**

Although the lack of nuclear accumulation of Pho4 after cationic and superoxide stress (Figure 3A) suggested that this transcription factor might not directly regulate stress-protective genes, we reasoned that the identification of the Pho4-regulon in C. albicans might provide insight into the mechanism underlying the stress-protective roles of this transcription factor. To this end, we used RNA-sequencing (RNA-Seq) analysis to compare the transcription profiles of wild-type and pho4Δ null cells under both phosphate-replete (+Pi) and phosphate-limiting (–Pi) conditions. We grew cells in phosphate-limiting medium for 16 h and then harvested them (–Pi samples). For the +Pi samples, we subsequently added 10 mM phosphate to the phosphate-starved cultures and harvested samples 2 h later. We analyzed three independent replicates for each condition and validated the RNA-Seq output by targeted analysis of specific transcripts (described later). The complete data set is presented in Supplemental Table S2.

Figure 5A shows heat maps depicting C. albicans gene regulation in response to phosphate limitation and PHO4 deletion. Genes that displayed a twofold or smaller decrease in transcript levels in pho4Δ cells in comparison to wild-type cells were classified as Pho4-dependent targets. From this analysis, 822 genes were found to be significantly up-regulated in wild-type cells in phosphate-limiting medium compared with phosphate-replete conditions. Of these, 150 displayed Pho4 dependence for their induction (see Supplemental Table S2 for the full data set). We constructed a Cytoscape network that illustrates the functional categories (Gene Ontology [GO] terms) that are significantly enriched in the subset of C. albicans genes induced in wild-type cells under phosphate-limiting conditions and the contribution of Pho4 to these processes (Figure 5B). The following functional categories were significantly enriched: Phosphate Accumulation, Response to Single Organism Metabolic Processes, Cellular Response to Stress, Oxidation/Reduction Processes, and Cellular Response to DNA Damage Stimulus (Figure 5B). Consistent with the phenotypes we observed for pho4Δ cells, Pho4 contributes to several of these functional categories, including Phosphate Accumulation, Oxidation/Reduction Processes, and Cellular Response to Stress (Figure 5B).
An examination of genes with predicted roles in phosphate accumulation and storage revealed that Pho4 was required for the expression of the high-affinity phosphate transporter PHO84, several acid phosphatase genes (PHO100, PHO112 and PHO113), and the VTC1 and VTC3 genes implicated in polyphosphate synthesis. The Pho4 dependence of PHO84 and PHO100, which was confirmed by Northern blotting (Figure 5C), is in line with the roles of Pho4 in phosphate sensing and accumulation (Figure 2). In addition, the role of Pho4 in mediating the induction of VTC1 and VTC3 is consistent with the lack of polyphosphate in pho4Δ cells (Figure 2, C and D). In agreement with previous reports (Bishop et al., 2011, 2013), Pho4 was also required for induction of the GIT1-3 genes, which encode transporters for glycerophosphodiesterases, and the GDE1 gene, which encodes a glycerophosphocholine phosphodiesterase. Glycerophosphodiesterases are products of phospholipase-mediated deacylation of phospholipids and an important source of phosphate in C. albicans (Bishop et al., 2011).

### Pho4-dependent genes and stress phenotypes

We next explored whether genes deregulated in pho4Δ cells under phosphate-limiting conditions could account for the superoxide and cationic stress phenotypes associated with loss of Pho4 (Figure 1C). No genes implicated in superoxide tolerance were identified, but a comparison of the Pho4-dependent gene set to the cationic stress–induced regulon in C. albicans (Enjalbert et al., 2006) revealed an overlap of five genes: C3_01540W_A, C3_02140C_A, C6_03320W_A, GDP2 and RHR2. Three of these genes are of unknown function, but GDP2 and RHR2 work in tandem to produce glycerol, an osmoprotectant and a source of phosphate. Northern blotting confirmed that the induction of GDP2 and RHR2 seen in wild-type cells after P limitation is impaired in pho4Δ cells (Figure 5C). NaCl-induced induction of GDP2 and RHR2 depends on the stress–induced regulon (Enjalbert et al., 2006), with no cellular processes significantly enriched. Thus we found no obvious connection between Pho4-dependent and cationic stress–induced genes in C. albicans. Intriguingly, however, three of the four copper-requiring superoxide dismutase genes—SOD1, SOD5, and SOD6—were up-regulated in pho4Δ cells under phosphate-replete conditions, whereas the manganese-dependent SOD3 gene was down-regulated (Supplemental Table S2). The effect of Pho4 loss on SOD1 and SOD3 levels was validated by Northern blotting (Figure 5C). Therefore, a key question was, Why was the induction of Cu-SOD genes unable to confer superoxide stress resistance to pho4Δ cells?

### Pho4 is required for Sod1 superoxide dismutase activity

To investigate why SOD gene induction failed to trigger superoxide stress resistance in pho4Δ cells, we performed in-gel activity assays to assess any effect of Pho4 loss on superoxide dismutase activity. Strikingly, Sod1 activity was lower in pho4Δ cells than with the wild-type and pho4Δ + PHO4 reconstituted strains (Figure 7A). This was even more apparent after exposure of cells to menadione (Figure 7A). A previous phenotypic screen of the transcription factor deletion collection reported that cells lacking PHO4 are resistant to copper (Homann et al., 2009). In addition, our RNA-Seq experiment revealed that when wild-type (WT) cells were exposed to copper, we identified genes up-regulated in copper-stressed cells that encode copper metallothioneins (Enjalbert et al., 2009). Such genes are known to be induced under Cu-limiting environments (such as the CTR1 and FRE7 genes necessary for Cu acquisition and the Mn-dependent cytosolic SOD3 enzyme; Li et al., 2015). However, pho4Δ cells did not (Supplemental Table S2, pho4 + P vs. WT + P). Perhaps most significant, however, is the up-regulation of the CRD2 copper metallothionein gene in pho4Δ cells. The sequestration of copper by this metallothionein could possibly account for the apparent copper resistance of C. albicans pho4Δ cells. Taken together, these results indicated that copper homeostasis was impaired in some way in pho4Δ cells. We confirmed that pho4Δ cells are resistant to copper (Figure 7B) and used
FIGURE 5: Genome response to phosphate limitation in C. albicans. (A) Heat map illustrating the fold induction of genes induced (greater than twofold) in wild-type cells after phosphate limitation (top) and fold expression of these genes in pho4Δ cells (middle), as measured by RNA-Seq analysis. Of the 822 genes significantly induced in wild-type cells, 150 display a decrease of twofold or lower in pho4Δ cells upon comparing the expression ratio pho4Δ-Pi/Wt-Pi (bottom). These are designated as Pho4-dependent genes. (B) Cytoscape network illustrating all 822 up-regulated genes in wild-type cells after phosphate limitation. Those that display Pho4-dependence are shown in red. GO_Term family members are represented in the same color, and the size of each node representing each GO_Term corresponds to its gene enrichment level. Genes that were mapped according to Candida Genome Database Biological Process Unknown are clustered in the category Unknown. (C) Validation of gene expression profiles observed in RNA-Seq analysis. Northern blot analysis of RNA isolated from wild-type (Wt) and pho4Δ cells following the same −Pi and +Pi conditions used for RNA-Seq experiments. Blots were analyzed with probes specific for the indicated genes, with ACT1 as a loading control. Fold induction compared with Wt cells +Pi.
inductively coupled plasma mass spectrometry (ICP-MS) to determine the effect of Pho4 loss on cellular copper levels in *C. albicans*. However, ICP-MS analysis revealed no change in total cellular copper levels in *pho4Δ* cells compared with wild-type cells (Figure 7C). Thus, although cells lacking Pho4 have wild-type levels of copper, they are resistant to this metal and do not appear to respond as effectively as wild-type cells to a copper-limiting environment. This indicated that Pho4 might play a role in regulating the bioavailability of copper. Indeed, up-regulation of the CRD2 copper metallothionein could account for the apparent reduction in biological availability of copper in *C. albicans pho4Δ* cells. Defects in the delivery of copper to SODs, such as mutations that inactivate the Ccs1 copper metallochaperone, can be suppressed by addition of excess copper to the growth medium (Rae et al., 1999). Hence we tested whether...
investigate this, we used ICP-MS analysis to determine whether loss of PHO4 affected the cellular levels of a range of metal cations. As illustrated in Figure 8A, C. albicans pho4Δ cells containing lower cellular phosphorous levels (∼40% of wild type) also contained notably lower levels of manganese (∼16%) and magnesium (∼30%) compared with wild-type cells (p < 0.01). Possibly related to this, cells lacking PHO4 displayed impaired growth on medium containing manganese (Figure 8C). Because cells lacking PHO4 are deficient in the phosphate storage molecule polyP, which is predicted to be able to chelate metal cations due to its high negative charge, we examined whether polyP synthesis was also important for manganese resistance in C. albicans. Indeed, polyP-deficient vtc1Δ and vtc4Δ cells displayed similar enhanced sensitivity to manganese as the pho4Δ mutant (Figure 8D and Supplemental Figure S2A). Thus the potential role of polyP in sequestering excess manganese in C. albicans likely underlies the impaired resistance of pho4Δ cells to this metal.

In contrast to manganese and magnesium, an analysis of the cellular levels of other metal cations in pho4Δ cells revealed more modest differences. Levels of zinc and iron were higher in pho4Δ cells (123 and 125%, respectively) than in wild-type cells, whereas levels of sodium and potassium were lower (89 and 80%, respectively; Figure 8A). All such differences, with the exception of sodium, were
Pho4 is required for virulence in multiple infection models

Given that cells lacking Pho4 are particularly sensitive to stresses encountered after phagocytosis, such as superoxide anions and cationic fluxes (Figure 1), we explored the effect of PHO4 loss upon C. albicans-macrophage interactions. pho4Δ cells were acutely sensitive to macrophage-mediated killing compared with the wild type and reconstituted controls (p < 0.01; Figure 9A). To explore this further, we infected macrophages with wild-type, pho4Δ, and pho4Δ + PHO4 cells and followed the phagocytic process by live-cell videomicroscopy. Quantitatively, there were no significant differences between the migration speed of J774.1 macrophages toward wild-type or pho4Δ mutant cells or in rate of engulfment of fungal cells (unpublished data). However, cells lacking the Pho4 transcription factor were significantly defective in killing macrophages (Figure 9B) and displayed impaired filamentation after phagocytosis (Figure 9C). After this, we examined the effect of Pho4 loss on C. albicans virulence in animal models of infection. First, we used the invertebrate model host Caenorhabditis elegans (Pukkila-Worley et al., 2009). The survival of C. elegans was significantly extended after infection with pho4Δ cells compared with wild-type and pho4Δ + PHO4 cells (p < 0.001), clearly illustrating the importance of Pho4 in mediating C. albicans virulence in this infection model (Figure 9E). Next we used the 3-d murine intravenous challenge model of C. albicans infection (MacCallum et al., 2009b, 2010). This

significant (p < 0.01). We asked whether the NaCl toxicity exhibited by pho4Δ cells (Figure 1C) was due to the excess accumulation of sodium after NaCl stress. However, similar increases in sodium levels were observed in pho4Δ and wild-type cells after exposure to NaCl (Figure 8B). Nonetheless, despite modest differences in the intracellular levels of a number of metal cations, cells lacking PHO4 were significantly more sensitive than wild-type cells to a range of different metals, including sodium (Figure 1C), potassium, calcium, and iron (Figure 8C). In contrast to manganese, polyP function was not required for resistance to any of these other metals (Supplemental Figure S2A). Because the impaired growth exhibited by pho4Δ cells in the presence of metal cations does not always correlate with drastic effects on intracellular levels of the metals, we reasoned that maintaining the levels of the abundant phosphate anion within the cell might underlie the role of Pho4 in cation resistance. Consistent with this hypothesis, loss of PHO4 also affects the cellular resistance to the organic cation spermidine, in addition to the broad range of biologically important metal cations (Figure 8C).

FIGURE 9: Pho4 is required for C. albicans virulence in macrophage and animal infection models. (A) Macrophage model of infection. Percentage of C. albicans killed after coincubation with J774.1 macrophages (**p < 0.01). (B) Macrophage survival. Percentage of macrophages killed after coculture with the indicated C. albicans strains (**p ≤ 0.01). (C) Percentage of C. albicans cells that undergo filamentation after phagocytosis. (**p ≤ 0.01). (D) Cells lacking PHO4 display defective intracellular hyphal formation after phagocytosis. Images were taken from videos; numbers indicate time of the phagocytic events. Black arrows indicate positioning of C. albicans hyphal cells within the macrophage; white arrows indicate nonfilamentous cells. (E) C. elegans model of infection. C. albicans cells lacking PHO4 displayed significantly impaired killing of the nematodes compared with Wt and pho4Δ + PHO4 reconstituted strains (p < 0.001). Nematodes (n = 65, 68, 69) were infected with Wt, pho4Δ, and pho4Δ + PHO4 strains, respectively, and survival monitored daily. These data are from a single experiment representative of three independent biological replicates. (F) Mouse model of infection. Outcome score measurements of mice (n = 6) infected with the indicated strains. Comparison of Wt- and pho4Δ-infected groups by Kruskal–Wallis statistical analysis demonstrated a significant difference with pho4Δ-infected mice giving a significantly lower outcome score (**p ≤ 0.01).
model eliminates the need for standard 28-d survival experiments and combines weight loss and kidney fungal burden measurements after 3 d of infection to give an outcome score calculated as log(renal colony-forming units [CFU]/gram) = (0.5 × percentage weight change), with a higher score indicating greater virulence. Previous studies showed a strong correlation between mouse body weight loss over 3 d and kidney fungal burdens at 3 d after intravenous challenge with C. albicans and survival times up to 28 d (MacCallum et al., 2009a, 2010). Thus this model, which has been validated and widely used (Cheetham et al., 2011; Ene et al., 2012), is used over the standard 28 model to maximize concordance with the 3Rs (replacement, reduction, and refinement). Mice infected with pho4Δ cells had a significantly lower outcome score than those with wild-type cells (p < 0.01; Figure 9F). This virulence defect was only partially restored in mice infected with the pho4Δ + PHO4 reconstituted strain, possibly due to haploinsufficiency. Indeed, reintroduction of a single copy of PHO4 only partially rescues the acid phosphatase defect of pho4Δ cells (Figure 2B). It is also of interest that although C. albicans cells lacking PHO4 had a significant effect on weight loss, kidney fungal burdens were comparable to those with wild-type cells (Supplemental Figure S3). Similar findings were reported in Cryptococcus neoformans, in which cells defective in phosphate acquisition displayed attenuated virulence in a murine model of cryptococcosis, and yet the fungal burdens in the lungs and brain of infected animals were comparable to those of wild-type cells (Kretschmer et al., 2014). Nonetheless, the results from two distinct animal models indicate that in C. albicans, the Pho4 transcription factor is important for virulence. Moreover, the attenuated pathogenicity of pho4Δ cells observed in the murine infection model is consistent with the importance of Pho4 in preventing macrophage-mediated killing of C. albicans.

DISCUSSION

In this study we show that the Pho4 transcription factor plays vital roles in stress resistance and virulence in C. albicans. Because Pho4 does not appear to directly regulate stress-protective genes, we propose that the stress sensitivities exhibited by the pho4Δ mutant may be linked to the reduced intracellular phosphate levels in this mutant. This adds to an emerging concept that metabolism and stress resistance are intricately linked in this major pathogen of humans (Brown et al., 2014a). A model summarizing the multifaceted roles of Pho4 in mediating C. albicans stress responses and virulence is shown in Figure 10.

Although there is considerable sequence divergence between the Pho4 transcription factors in C. albicans and S. cerevisiae, we show that C. albicans Pho4 accumulates in the nucleus in Pi-limiting environments and regulates both phosphate acquisition and polyP synthesis. A comparison of the Pho4-regulated genes in C. albicans with those identified in S. cerevisiae (Zhou and O’Shea, 2011) identified a core set of 10 genes. These include the PHO81 CDK inhibitor, phosphate transporters (PHO84), acid phosphatases (PHO112, PHO113), polyphosphate synthase components (VTC1, VTC3), enzymes required for phosphate acquisition from glycerophosphodiester (GIT1, GDE3) or glycerol-3-phosphate (RHR2), and a transporter of ferriehemochromophores (SIT1/ARN4). Consistent with reports in S. cerevisiae that a phosphate starvation response is triggered upon growth in alkaline environments (Serrano et al., 2002), exposure of C. albicans to alkaline pH stress also results in rapid mobilization of polyP and nuclear accumulation of Pho4. Taken together, these results strongly suggest that the critical role of the C. albicans Pho4 transcription factor after exposure to phosphate-limiting or alkaline environments is to induce a gene expression program that promotes phosphate acquisition and storage as polyP. It is also likely that the slightly slow-growth phenotype of pho4Δ cells is due to reduced intracellular phosphate levels, which may delay cell cycle progression. In S. cerevisiae, genes within the PHO regulon are specifically induced during M phase to meet the high metabolic demands of P, associated with mitosis (Neef and Kladde, 2003).

PolyP function has been extensively studied in bacteria, in which it is linked to multiple processes, including growth, stress responses, biofilm formation, and virulence (reviewed in Rao et al., 2009). These diverse phenotypes may be linked to recent findings that polyP functions as a protein chaperone in bacteria (Gray et al., 2014). Less is known, however, about polyP function in eukaryotic cells, although in lower eukaryotes, polyP has been linked to stress adaptation and osmoregulation (reviewed in Docampo et al., 2010). For example, exposure of Trypanosoma cruzi to hypo-osmotic stress results in rapid mobilization of polyP, whereas hyper-osmotic stress triggers an increase in polyP level (Ruiz et al., 2001). In this study, we report the first phenotypic characterization of C. albicans mutants that lack polyP. Whereas polyP is mobilized in C. albicans after hypo-osmotic stress (Supplemental Figure S2C), hyper-osmotic stress, and growth in alkaline pH conditions (Figure 3, C and D), polyP is dispensable in mediating resistance to such stresses (Supplemental Figure S2A). However, polyP is required for manganese resistance, and our data suggest that polyP plays an important role in the sequestration of this metal in C. albicans (Figure 8D and Supplemental Figure S2A).

Although cells lacking Pho4 are acutely sensitive to both cationic and superoxide stress, this appears to be independent of this transcription factor regulating the induction of stress-protective genes. Instead, we propose that many of the stress phenotypes exhibited by pho4Δ cells relate to the effect of intracellular phosphate on metal homeostasis. Because negatively charged inorganic compounds such as phosphate can bind metal cations, it is beginning to emerge that metal–phosphate interactions play important mechanistic roles in regulating cellular metal homeostasis (Rosenfeld et al., 2010). S. cerevisiae cells lacking the negative regulator of Pho4, the Pho80
cyclin, display constitutively high levels of cytosolic phosphate, and this has widespread effects on metal cation accumulation and toxicity (Rosenfeld et al., 2010). Dramatic increases in cellular levels of calcium and sodium occur in pho80Δ cells, together with an increased toxicity toward these and other metal cations (Rosenfeld et al., 2010). In addition, a phosphate transporter mutant (pho84Δ/pho84Δ/pho 89Δ) in the pathogenic fungus C. neoformans was shown to exhibit low phosphate but high intracellular levels of sodium, iron, and zinc (Kretschmer et al., 2014). In this study, we present several lines of evidence to connect phosphate accumulation with metal cation homeostasis and resistance in C. albicans. We show that pho4Δ cells, which have reduced cellular levels of phosphate, display impaired resistance to a broad number of metal cations (Figure 8C). Such cells also exhibit substantial to moderate differences in the cellular levels of a range of metal cations (Figure 8A) and impaired metal acquisition responses under conditions in which such responses are stimulated in wild-type cells (Figure 6). Although we have not formally proven that defects in intracellular phosphate levels underlie the metal cation homeostasis and resistance phenotypes of pho4Δ cells, many of our observations indicate an important role of the phosphate anion in maintaining a charge balance in the cell. This is supported by our observations that Pho4 is vital for resistance to both metal and non-metal cations in C. albicans (Figure 8).

A notable exception to the metal cation–sensitive phenotypes exhibited by pho4Δ cells is the significant resistance displayed to copper (Figure 7). Yeast cells tightly regulate copper uptake and storage due to the ability of copper to participate in redox reactions and compete with zinc or iron–sulfur clusters for cysteine-rich metal-binding sites. In C. albicans, as in S. cerevisiae, copper-limiting conditions trigger activation of the Mac1 transcription factor, which drives the expression of copper acquisition genes such as CTR1 and FRE7 (Marvin et al., 2004). Resistance to excess copper is provided by the Crp1 P1-type ATPase copper transporter and the copper metallothionine Cup1 and Crd2 (Riggle and Kumamoto, 2000; Weissman et al., 2000). The expression of CRP1 and CUP1 is induced in high-copper environments, whereas CRD2 expression seems to be insensitive to copper levels (Riggle and Kumamoto, 2000; Weissman et al., 2000). Because intracellular copper levels are maintained at extremely low levels, copper chaperones are necessary to deliver copper to target enzymes, and, in C. albicans, the Ccs1 copper chaperone transfers copper to the copper-containing Sod1 enzyme (Gleason et al., 2014). We examined the RNA-Seq data generated in this study to determine whether any of the genes involved in copper homeostasis are deregulated in pho4Δ cells. The CTR1 and FRE7 genes, necessary for high-affinity copper transport, are not induced in the pho4Δ mutant when up-regulation is observed in wild-type cells (Supplemental Table S2; pho4Δ + P, vs. WT + P). Perhaps most significant, however, is the up-regulation of the CRD2 copper metallothionein gene (4.7-fold) in pho4Δ cells. The sequestration of copper by this metallothionein could possibly account for the apparent reduction in biological availability of copper in C. albicans pho4Δ cells. It is noteworthy that a connection between intracellular copper and phosphate levels has been implicated in S. cerevisiae, in that a number of genes in the PHO regulon were up-regulated in cells expressing a constitutively active Mac1 mutant (Gross et al., 2000). Because up-regulation of such genes depended on Pho4, and not Mac1, this suggests that the constitutive activation of Mac1 leads to depletion of the intracellular phosphate pool in S. cerevisiae. It is not clear why expression of a constitutively active Mac1 mutant triggers a reduction in intracellular phosphate levels (Gross et al., 2000). Assuming that this is a physiological response to increased intracellular copper levels, cells that are constitutively deficient in intracellular phosphate (such as pho4Δ cells) may evoke compensatory mechanisms to deal with copper toxicity such as up-regulation of copper metallothionines, which in turn affects the bioavailability of and toxicity to this metal.

The importance of investigating the relationship between intracellular phosphate levels and copper bioavailability is highlighted by our findings, which indicate that the superoxide-sensitive phenotype of pho4Δ cells is due to defects in copper homeostasis and bioavailability. C. albicans has developed sophisticated mechanisms to counteract high levels of superoxide stress, including the unusual expansion of the SOD superoxide dismutase gene family (Broxton and Culotta, 2016) to include, among other enzymes, two cytoplasmic Sodcs—Cu/Zn-Sod1 and Mn-Sod3 (Lamarre et al., 2001; Hwang et al., 2002). The rationale for two distinct cytoplasmic enzymes was recently revealed, in that copper availability within the host dictates whether C. albicans expresses Cu-dependent SOD1 or Cu-independent SOD3 (Li et al., 2015). Thus, even in copper-limiting environments, C. albicans is well equipped via the action of Mn-Sod3 to counteract superoxide stress. However, Sod1 activity is impaired in pho4Δ cells due to apparent defects in copper availability, as both superoxide stress resistance and Sod1 activity can be restored to wild-type levels upon supplementation of the growth medium with excess copper (Figure 7). Moreover, our RNA-Seq data showed that pho4Δ cells failed to switch to Mn-SOD3 expression under conditions that triggered this switch in wild-type cells (Figure 5C), indicating impaired or delayed activity of the Pho4 mutant to sense copper-limiting environments. Future experiments are aimed at examining the cellular distribution of copper in pho4Δ cells compared with wild-type cells, as this will help to define the mechanism(s) linking intracellular phosphate levels with copper sensing and bioavailability. In this regard, it is noteworthy that defects in phosphate homeostasis have been found to affect metal bioavailability in S. cerevisiae (Rosenfeld et al., 2010). Specifically, a robust iron starvation response was elicited in S. cerevisiae cells with an increased cytoplasmic phosphate content despite wild-type levels of intracellular iron (Rosenfeld et al., 2010).

Our observations that Pho4 is important for C. albicans virulence in animal infection models is consistent with studies demonstrating that the Pho4-regulated phosphate transportase gene PHO84 is up-regulated in multiple host environments (Thewes et al., 2007; Walker et al., 2009) and that the Pho4 target genes GIT3 and PHO100 are required for full virulence in murine models of candidiasis (MacCallum et al., 2009b; Bishop et al., 2013). We also find that cells lacking Pho4 are exquisitely sensitive to killing by macrophages. Because the PHO regulon is not significantly induced after phagocytosis (Fradin et al., 2005), we propose that Pho4 promotes C. albicans survival by providing resistance to the cationic and superoxide stresses encountered after macrophage uptake. This is supported by observations that Sod1, which requires Pho4 function for activity, is important for C. albicans survival after phagocytosis (Hwang et al., 2002), as are key regulators of C. albicans cationic stress resistance (Arana et al., 2007). Whether defects in phosphate acquisition impair cationic stress resistance and Sod activity in other fungi is worth investigating, as these are important virulence determinants in a range of pathogenic species (Narasipura et al., 2003; Jiang et al., 2011; Jung et al., 2012; Xie et al., 2012). Indeed, a recent study indicates this may be the case, as a C. neoformans phosphate transporter mutant displayed metal homeostasis defects and impaired survival in macrophages (Kretschmer et al., 2014).

In conclusion, we show that the Pho4 transcription factor plays multifaceted roles in promoting stress resistance and virulence in...
### Table 2: Strains used in this study.

<table>
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<tr>
<th>Strain</th>
<th>Name</th>
<th>Genotype</th>
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<tr>
<td>SN148</td>
<td>arg4Δ/arg4Δ leu2Δ/leu2Δ his1Δ/his1Δ ura3Δ::imm434/ura3Δ::imm434</td>
<td>Noble and Johnson (2005)</td>
<td></td>
</tr>
<tr>
<td>SN152</td>
<td>arg4Δ/arg4Δ leu2Δ/leu2Δ his1Δ/his1Δ URA3/ura3Δ::imm434 IRO1/iro1Δ::imm434</td>
<td>Noble and Johnson (2005)</td>
<td></td>
</tr>
<tr>
<td>ΔΔorf19.2961</td>
<td>SN152 arg4Δ/arg4Δ leu2Δ/leu2Δ his1Δ/his1Δ URA3/ura3Δ::imm434 IRO1/iro1Δ::imm434 pho4Δ::His1/pho4Δ::LEU2</td>
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<td>JC1936</td>
<td>Wt</td>
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<td>This study</td>
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<td>pho4Δ</td>
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<td>This study</td>
</tr>
<tr>
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<td>pho4Δ + PHO4</td>
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<td>Wt</td>
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<td>This study</td>
</tr>
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### Strain construction

The strains used in this study are listed in Table 2, and the oligonucleotides used in their construction are available upon request. The pho4Δ strain was derived from a published transcription factor deletion collection (Homann et al., 2009). To reintegrate PHO4, the open reading frame (ORF) plus promoter and terminator regions were amplified by PCR using the primer pair PHO4BamH1C1/PHO4 BamHI C2 and ligated into the BamHI site of C1p10 to generate C1p10-PHO4. C1p10 and C1p10-PHO4 were linearized with SstI and integrated at the RPS1 locus, which negates the influence of URA3 expression levels on subsequent virulence assays (Brand et al., 2004).

### Deletion of VTC1 and VTC4

To delete VTC1, disruption cassettes containing the HIS1 or ARG4 gene flanked byloxP sites and 91 base pairs 5' and 3' to the VTC1 ORF were generated by PCR using Vtc1delF and Vtc1delR oligonucleotide primers and the plasmid template pPLH or pLAL (Dennison et al., 2005). Disruption cassettes were sequentially transformed into SN148 wild-type C. albicans cells (Noble and Johnson, 2005) to disrupt both alleles of VTC1. The same strategy was used to cleanly delete VTC4, using the oligonucleotide pair Vtc4delF/Vtc4delR. Disruption of each allele was confirmed by PCR, and C1p10 was integrated at the RPS1 locus to restore uridine prototrophy (Murad et al., 2000), generating vtc1Δ (JC1983) and...
vtc4Δ (JC1984) strains. To reintegrate VTC4 into the respective vtc4Δ null strain, the ORF plus promoter and terminator regions was amplified by PCR using primer pair VTC4BamH1C1/VTC4BamH1C2 and ligated into the BarnH1 site of Clp10 to generate Clp10-VTC4. Clp10-VTC4 was linearized with Stul and integrated at the RPS1 locus in vtc4Δ cells, generating the vtc4Δ + VTC4 reconstituted strain (JC2087).

**Tagging of Pho4.** To tag Pho4 at the C-terminus with green fluorescent protein (GFP), the PHO4 ORF was amplified by PCR using the primers Pho4ACT1GFPF and GFPACT1 and ligated into the Sail site of pAICT1-GFP (Barelle et al., 2004). The resulting pAICT1-PHO4GFP plasmid was linearized with Stul and integrated at the RSP1 locus in wild-type cells to generate JC1977. Correct integration at the RPS1 locus was confirmed by PCR and DNA sequencing.

**Quantitative fitness analysis**

The *C. albicans* transcription factor deletion collection (Hommann et al., 2009) was screened by QFA (Banks et al., 2012) to identify genes required for cationic and superoxide stress resistance. Liquid-to-solid agar 384-format robotic spot tests were performed as follows. Individual mutants from the deletion library were picked into 96-well plates containing 200 μl of YPD medium in each well with the BioMatrix BM3-SC robot system (S&P Robotics, Toronto, Canada) using a 96-pin (1-mm-diameter) pin tool and grown overnight without shaking at 30°C. Cultures were then diluted 1/100 in 200 μl of YPD medium, grown without shaking for 8 h at 30°C, and spotted onto YPD agar plates and YPD plates containing 1 M NaCl or 300 μM menadione (Sigma-Aldrich, Dorset, UK). The growth of each strain was monitored by photography over time. Solid agar plates were photographed on a splmager (S&P Robotics) with an integrated camera. Manual settings of the camera were as follows: 0.25 s; aperture, F10; white balance, 3700 K; ISO100; image size, large; image quality, fine; image type, .jpg. Culture density was generated from captured photographs using the Integrated Optical Density measure of cell density provided by the image analysis tool Colonyzer (Lawless et al., 2010). A quantitative measure of fitness was then generated using the product of the maximum doubling rate (MDR; doublings/d), which is the inverse of the doubling time and the maximum potential (MDP; doublings). The SIS was obtained for wild-type (JC1936) and *C. albicans* strains were grown at 30°C to exponential phase, and then 10-fold serial dilutions were manually spotted onto YPD plates containing the indicated compounds. Plates were incubated at 30°C for 24 h.

**Stress sensitivity tests**

*C. albicans* strains were grown at 30°C to exponential phase, and then 10-fold serial dilutions were manually spotted onto YPD plates containing the indicated compounds. Plates were incubated at 30°C for 24 h.

**Yeast-to-hypha transition assay**

To induce morphogenesis, stationary-phase cells were diluted 1:10 in fresh YPD liquid medium containing 10% fetal calf serum (FCS) and incubated at 37°C for 6 h. Differential interference contrast (DIC) images were captured using a Zeiss Axioscope with a 63× oil immersion objective and AxioVision imaging system.

**Localization of Pho4-GFP**

*C. albicans* cells expressing GFP-tagged Pho4 (JC1977) were grown to exponential phase and treated with the stresses indicated or, to induce phosphate limitation, washed three times and resuspended in YPD-Pi. Cells were treated with the various stresses for the indicated times and samples taken and processed as described previously (Enjalbert et al., 2006). 4′,6-Diamidino-2-phenylindole (DAPI) and GFP fluorescence were captured using a Zeiss Axioscope with 63× oil immersion objective and 365-nm and 450- to 490-nm wavelengths for DAPI and GFP.

**Secreted acid phosphatase assay**

Exponential *C. albicans* cells grown in PNMC (Romanowski et al., 2012) + 2 mM Pi were washed and resuspended in PNMC –P. Cells were spotted onto PNMC agar plates with or without P and allowed to grow for 24 h at 30°C. Secreted acid phosphatase activity was detected on plates by an agar-overlay coloration assay as described previously (To et al., 1973). Agar plates containing *C. albicans* colonies were covered with melted agar solution (1%) containing sodium acetate (50 mM, pH 4), naphthyl phosphate (19 μM; Sigma-Aldrich), and Fast blue salt dye (100 μM; Sigma-Aldrich) and incubated at 30°C for 30-60 min. Dark red coloration of the colony indicated secreted acid phosphatase activity.

**Polyphosphate analysis**

The presence of intracellular polyP granules was determined by light microscopy by Neisser staining of *C. albicans* cells (Gurr, 1965). Paraformaldehyde-fixed cells (Enjalbert et al., 2006) were mounted onto a slide and stained with freshly prepared solution A (methylene blue, 0.1% [Sigma-Aldrich]; glacial acetic acid, 5%; ethanol, 5%) and solution B (crystal violet, 10% in ethanol) for 10–15 s. Slides were rinsed with water, and solution C (chrysoidin Y, 1% [Sigma-Aldrich]) was added for 45 s and rinsed off, and slides were allowed to dry. DIC images were captured using a Zeiss Axioscope with a 63× oil immersion objective and AxioVision imaging system.

For urea-PAGE and toluidine blue staining, RNA was extracted as described previously (Smith et al., 2004), as this procedure also releases polyP. Total RNA (20 μg) containing polyP was resolved by electrophoresis on 15% polyacrylamide TBE-urea gels (Bio-Rad, Hercules, CA) by monitoring the RNA integrity number. RNA samples were isolated in biological triplicates and preparatons was analyzed on an Agilent Bioanalyzer (Agilent Technologies, Santa Clara, CA) by monitoring the RNA integrity number. RNA samples were isolated in biological triplicates and stored at 80°C until sequencing processing.

**RNA analysis**

**RNA-Seq sample preparation.** Overnight cultures of *C. albicans* wild-type (JC1936) and pho4A (JC1928) cells grown in YPD at 30°C were diluted to an OD660 of 0.2 in fresh YPD and grown to mid exponential phase (OD660 = 0.6). Cells were washed twice in YPD –P, resuspended in YPD –P to an OD660 of 0.05, and grown for 16 h at 30°C. Cells were harvested, washed in ice-cold H2O, and snap frozen in liquid nitrogen. Phosphate was added to the phosphate-starved culture at a final concentration of 20 mM KH2PO4 (pH 6) and cells grown for 2 h before harvesting as described. Total RNA was isolated from frozen cell pellets using Qiazol reagent as per manufacturer’s instructions (Qiagen, Manchester, United Kingdom) after mechanical shearing with 425- to 600-μm acid-washed glass beads (Sigma-Aldrich, Dorset, United Kingdom) in an IKA-Vibra- VxR at 2200 rpm (B Braun Biotech International, Melsungen, Germany) for 2 min at 2000 rpm. The integrity of total RNA preparations was analyzed on an Agilent Bioanalyzer (Agilent Technologies, Santa Clara, CA) by monitoring the RNA integrity number. RNA samples were isolated in biological triplicates and stored at 80°C until sequencing processing.

**RNA-Seq alignment and analysis.** Samples were processed through the Ion Torrent Proton sequencer at the Centre for Genome-Enabled Biology and Medicine, University of Aberdeen, Genomics Facility.
Raw fastq files were successively processed in the following order through Fastqc (version 10.1), Trimgalore (version 3.1), Samtools (version 1.19), STAR aligner (version 2.4), and Htseq (version 5.4). Genome alignment was conducted against the C. albicans_SC5314_ version_A21-s02-m09-108 chromosomes file provided by the Candida Genome Database (www.candidagenome.org/). Gene expression analysis was performed using Partek Genomics Suite software, version 6.6. GO term analysis was performed in parallel through the Candida Genome Database GO Term Finder and the Cytoscape, version 3. Clue GO plug-in (Bindea et al., 2009). Network construction was performed with Cytoscape, version 3, freeware, Venn diagrams through Venny (version 2.0.2) online freeware, and heat maps with TM4 MultiExperiment Viewer (version 4.9). Statistical comparison among GO term enrichment percentages was performed with GraphPad Prism (version 6).

Northern blot analysis. RNA extraction was performed as described previously (Smith et al., 2004). Gene-specific probes were amplified by PCR from genomic DNA using oligonucleotide primers specific for the indicated genes. Phosphoimage analysis was conducted using a GE Typhoon FLA9500 (GE Healthcare Life Sciences, Buckinghamshire, UK) and quantification performed using ImageQuant software.

Inductively coupled plasma mass spectrometry Exponentially growing cells grown in YPD at 30°C were harvested by centrifugation, washed twice with 25 ml of Tris buffer (50 mM Tris, pH 7.5), incubated in the same buffer containing 10 mM EDTA for 5 min at room temperature to remove surface-bound metal, and then washed twice with 25 ml of the same buffer without EDTA. Washed pellets were digested in 1 ml of 65% (wt/vol) HNO3 (Merck) and incubated for >48 h at room temperature. The triplicate digested samples were centrifuged (13,000 × g, 20 min), and the supernatants were diluted 1:10 with 2% (wt/vol) HNO3 solution that contained 20 μg/l Ag and Pt as internal standards and analyzed by ICP-MS essentially as previously described (Tottey et al., 2008). Each sample was analyzed for sodium (23Na), magnesium (24Mg), phosphorus (31P), potassium (39K), calcium (44Ca), manganese (54Mn), iron (56Fe), copper (63Cu), and zinc (65Zn), as well as for silver (109Ag) and platinum (195Pt), using a Thermo X-series ICP-MS operating in collision cell mode (3.0 ml/min 8% H2 in He as collision gas). Each isotope was analyzed in three channels with 0.02–atomic mass unit separation, each in triplicate. Multichannel concentrations were calculated by comparison to matrix-matched elemental standards (containing 0–1000 μg/l each element) analyzed within the same analytical run and normalized according to the OD600 recorded for each culture. Differences were tested for statistical significance by one-way analysis of variance (ANOVA; **p < 0.01).

SOD in-gel activity assay Mid exponential-phase C. albicans cells were harvested by centrifugation and snap frozen in liquid nitrogen before protein extraction. Cells were resuspended in lysis buffer containing 10 mM sodium phosphate (pH 7.8), 5 mM EDTA, 5 mM ethylene glycol tetraacetic acid, 50 mM NaCl, 0.45% (vol/vol) NP-40, and 10% (vol/vol) glycerol (Aguirre et al., 2013). Protein lysates were prepared by bead beating with glass beads and clarification by centrifugation at 13,000 rpm for 10 min at 4°C. Protein extract (50 μg) was subjected to native-PAGE on 12% gels and SOD activity detected by nitro blue tetrazolium staining (Flohe and Otting, 1984). Cells lacking SOD1 and SOD2 were used as controls (Frohner et al., 2009). Duplicate samples were subjected to SDS–PAGE, followed by Ponceau-S staining of membranes to determine protein loading.

Infection assays C. elegans pathogenesis assay. The method described for pathogen infection of C. elegans (Powell and Ausubel, 2008) was adopted with the following modifications. A 10-μl amount of exponential C. albicans cells was spotted onto the center of a 4-cm Petri dish containing 7 ml of British Heart Infusion agar, ampicillin (100 μg/ml), and kanamycin (45 μg/ml) and allowed to dry overnight at room temperature. The next day, synchronized L4-stage adult gfp-4 C. elegans maintained at 25°C were washed from plates containing their normal food source (Escherichia coli OP50), and 60–70 worms were transferred to plates seeded with C. albicans cells. The C. elegans gfp-4 nematodes are sterile when propagated at the restrictive temperature of 25°C, which prevents progeny formation. Plates were incubated at 25°C, and worm survival was scored daily. Worms were considered to be dead if they did not move in response to probing with a pick and no pharynx contraction was observed. Differences in C. elegans survival were determined by the log-rank test. In all experiments, p < 0.05 was considered significant.

Murine intravenous challenge assay. Murine BALB/c female mice (6–8 wk old; Harlan, United Kingdom) were housed in randomly assigned groups of six with food and water provided ad libitum. Mice (n = 6) were infected intravenously via a lateral tail vein with 4.2e4 CFU/g C. albicans wild-type (Wt; JC1936), phoΔ4 (JC1928), and phoΔ4 + PHO4 (JC1917) strains. Body weights were recorded daily. At 72 h after challenge, the animals were weighed and humanely killed, and kidneys were removed aseptically. Fungal burdens were measured by viable counts for two half-kidneys per animal. Virulence outcome scores were determined by assessing renal fungal burden and percentage weight change at 72 h using outcome score = log(renal CFU/g) − (0.5 × percentage weight change) (MacCallum et al., 2009b, 2010). Differences were tested statistically by Kruskal–Wallis statistical analysis.

C. albicans survival after phagocytosis J774.1 macrophages were seeded at a density of 2 × 10⁵ cells in six-well plates for 24 h. Overnight culture of C. albicans cells was added to the macrophages at a multiplicity of infection (MOI) of 3:1 macrophage/candida or to medium without macrophages. Cells were coincubated for 6 h at 37°C, after which, unphagocytosed C. albicans cells were washed off and macrophages lysed with Triton X-100 (1%) to release C. albicans cells. Cells were plated onto YPD plates and incubated overnight at 30°C, and percentage survival was calculated as (CFUs +macrophages/CFUs –macrophages) × 100. Mean values and SDs were calculated for all phagocytosis assays. Differences were tested for statistical significance by one-way ANOVA (**p < 0.01).

Phagocytosis assays and live-cell video microscopy These experiments were performed as described previously (Bain et al., 2014). The J774.1 mouse macrophage cell line was maintained at 37°C and 5% CO2 in DMEM (Lonza, Slough, United Kingdom) supplemented with 10% heat-activated FCS (Biosera, Ringmer, United Kingdom). Cells were seeded at a density of 1.2 × 10⁵ cells/well in an eight-well slide and incubated overnight at 37°C and 5% CO2. Before coincubation, growth medium in wells was replaced with prewarmed, CO2-independent medium containing 10% FCS (Invitrogen). Overnight cultures of C. albicans strains grown in YPD
were washed in sterile phosphate-buffered saline (pH 7.4) and cocultured with J774.1 cells at a MOI of 3:1. DIC images of cocultured cells were taken at 1-min intervals over a 6-h time course using an Ultra VIEW VoX spinning-disk microscope (Nikon, Surrey, United Kingdom) and an electron-multiplying charge-coupled device camera. Two independent experiments were carried out, and six movies were analyzed from each experiment per C. albicans strain. One hundred macrophages were randomly selected from each movie and phagocytic activity determined. Velocity 5.0 imaging software (ImproVision, PerkinElmer, Coventry, United Kingdom) was used for data acquisition and analysis as described previously (Lewis et al., 2012). The software enabled analysis of macrophage migration and provided details on distance traveled and velocity of individual macrophages, from which the mean track velocity was calculated. The software also enabled the determination of the engulfment time, migration rate, rate of C. albicans filamentation, and macrophage survival. Macrophage survival/killing was determined by detecting data acquisition and analysis as described previously (Lewis et al., 2012). The software enabled analysis of macrophage migration and provided details on distance traveled and velocity of individual macrophages, from which the mean track velocity was calculated. The software also enabled the determination of the engulfment time, migration rate, rate of C. albicans filamentation, and macrophage survival. Macrophage survival/killing was determined by detecting number of ruptured macrophages within sample populations of 100. Differences were tested for statistical significance by one-way ANOVA with Bonferroni’s post hoc comparisons.

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