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Camaron R Hole  
*Washington University School of Medicine in St. Louis*

Woei C Lam  
*Washington University School of Medicine in St. Louis*

Rajendra Upadhya  
*Washington University School of Medicine in St. Louis*

Jennifer K Lodge  
*Washington University School of Medicine in St. Louis*

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**Recommended Citation**  
Hole, Camaron R; Lam, Woei C; Upadhya, Rajendra; and Lodge, Jennifer K, "Cryptococcus neoformans chitin synthase 3 plays a critical role in dampening host inflammatory responses." mBio. 11,1. . (2020).  
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Cryptococcus neoformans Chitin Synthase 3 Plays a Critical Role in Dampening Host Inflammatory Responses

Cameron R. Hole,a Woei C. Lam,a Rajendra Upadhya,a Jennifer K. Lodgea

aDepartment of Molecular Microbiology, Washington University School of Medicine, St. Louis, Missouri, USA

ABSTRACT Cryptococcus neoformans infections are significant causes of morbidity and mortality among AIDS patients and the third most common invasive fungal infection in organ transplant recipients. One of the main interfaces between the fungus and the host is the fungal cell wall. The cryptococcal cell wall is unusual among human-pathogenic fungi in that the chitin is predominantly deacetylated to chitosan. Chitosan-deficient strains of C. neoformans were found to be avirulent and rapidly cleared from the murine lung. Moreover, infection with a chitosan-deficient C. neoformans strain lacking three chitin deacetylases (cda1Δcda2Δcda3Δ) was found to confer protective immunity to a subsequent challenge with a virulent wild-type counterpart. In addition to the chitin deacetylases, it was previously shown that chitin synthase 3 (Chs3) is also essential for chitin deacetylase-mediated formation of chitosan. Mice inoculated with the chs3Δ strain at a dose previously shown to induce protection with the cda1Δcda2Δcda3Δ strain die within 36 h after installation of the organism. Mortality was not dependent on viable fungi, as mice inoculated with a heat-killed preparation of the chs3Δ strain died at the same rate as mice inoculated with a live chs3Δ strain, suggesting that the rapid onset of death was host mediated, likely caused by an overexuberant immune response. Histology, cytokine profiling, and flow cytometry indicate a massive neutrophil influx in the mice inoculated with the chs3Δ strain. Mice depleted of neutrophils survived chs3Δ inoculation, indicating that death was neutrophil mediated. Altogether, these studies lead us to conclude that Chs3, along with chitosan, plays critical roles in dampening cryptococcus-induced host inflammatory responses.

IMPORTANCE Cryptococcus neoformans is the most common disseminated fungal pathogen in AIDS patients, resulting in ~200,000 deaths each year. There is a pressing need for new treatments for this infection, as current antifungal therapy is hampered by toxicity and/or the inability of the host’s immune system to aid in resolution of the disease. An ideal target for new therapies is the fungal cell wall. The cryptococcal cell wall is different from the cell walls of many other pathogenic fungi in that it contains chitosan. Strains that have decreased chitosan are less pathogenic and strains that are deficient in chitosan are avirulent and can induce protective responses. In this study, we investigated the host responses to a chs3Δ strain, a chitosan-deficient strain, and found that mice inoculated with the chs3Δ strain all died within 36 h and that death was associated with an aberrant hyperinflammatory immune response driven by neutrophils, indicating that chitosan is critical in modulating the immune response to Cryptococcus.

KEYWORDS chitin, chitin synthase, chitosan, inflammation, neutrophils

Cryptococcus neoformans is a ubiquitous encapsulated fungal pathogen that causes pneumonia and meningitis in immunocompromised individuals. C. neoformans is the most common disseminated fungal pathogen in AIDS patients, with an estimated quarter million cases of cryptococcal meningitis each year resulting in ~200,000 deaths.
and it remains the third most common invasive fungal infection in organ transplant recipients (3). Current antifungal therapy is often hampered by toxicity and/or the inability of the host’s immune system to aid in resolution of the disease; treatment is further limited by drug cost and availability in the resource-limited settings (4). The acute mortality rate of patients with cryptococcal meningitis is between 10 and 30% in medically advanced countries (5, 6), and even with appropriate therapy, at least one third of patients with cryptococcal meningitis will undergo mycologic and/or clinical failure (4). Patients that do recover can be left with profound neurological sequelae, highlighting the need for more-effective therapies and/or vaccines to combat cryptococcosis.

One of the main interfaces between the fungus and the host is the fungal cell wall. Most fungal cell walls contain chitin; however, the cryptococcal cell wall is unusual in that the chitin is predominantly deacetylated to chitosan. Chitin is a homopolymer of β-1,4-linked N-acetylglucosamine (GlcNAc) and is one of the most abundant polymers in nature. Immunologically, chitin can induce allergy and strong Th2-type immune responses (7). Chitin is polymerized from cytoplasmic pools of UDP-GlcNAc by a multiple transmembrane protein chitin synthase (Chs), and there are eight Chs enzymes encoded in the C. neoformans genome (8). Chitosan, the deacetylated form of chitin, is generally less abundant in nature than chitin, but it is found in the cell walls of several fungal species depending on growth phase (8). Chitosan is not synthesized de novo but is generated from chitin through enzymatic conversion of GlcNAc to glucosamine (GlcN) by chitin deacetylases (CDAs), and C. neoformans makes three CDAs (9). Why Cryptococcus converts chitin to chitosan and what advantages this conversion provides to the organism are not well understood.

Deletion of a specific chitin synthase (CHS3) or deletion of all three chitin deacetylases causes a significant reduction in chitosan in the vegetative cell wall (9). These chitosan-deficient strains of C. neoformans are avirulent and rapidly cleared from the murine lung (9). Moreover, infection with a chitosan-deficient C. neoformans strain lacking three chitin deacetylases, cda1Δcda2Δcda3Δ (called cda1Δ2Δ3Δ throughout this work), was found to confer protective immunity to a subsequent challenge with a virulent wild-type counterpart (10). These findings suggest that there is an altered host response to chitosan-deficient strains. Therefore, we wanted to determine the nature of host immune response to an infection with chitosan deficiency caused by the deletion of the C. neoformans CHS3 gene.

Surprisingly, we observed that all mice inoculated with the chs3Δ strain died within 36 h. Death was not dependent on live organisms or the mouse background. We hypothesized that the rapid onset of mortality was likely due to an aberrant immune response. Histology, cytokine profiling, and flow cytometry indicate a massive influx of neutrophils in the mice inoculated with chs3Δ. Mice depleted of neutrophils all survived inoculation of the chs3Δ strain, indicating that the observed mortality is neutrophil mediated. Together, these results suggest that chitin synthase 3 (Chs3) is important in modulating the immune response to Cryptococcus.

RESULTS

Complete deletion and complementation of C. neoformans chitin synthase 3 (Chs3). With better annotation of the cryptococcal genome, we found that our previously reported chs3Δ strain (8) did not contain a complete deletion of the chs3 gene. While the protein is not functional, as the catalytic domain was deleted, the original strain still harbored 689 bp of gene sequence potentially sufficient to encode an ~25-kDa protein. As this gene is highly expressed under vegetative growth, the truncated protein might influence growth of the mutant strain, its virulence, or the host immune response to the mutant strain. To eliminate this concern, we generated a complete deletion of the CHS3 gene, including the 5’ untranslated region (UTR) to delete the promoter as well, in strain KN99 by biolistic transformation. All the isolates were characterized by diagnostic PCR screening and Southern blot hybridization.
The original, partial chs3Δ strain exhibited a large number of phenotypes including changes in morphology with two- to threefold enlarged cells and a budding defect, temperature sensitivity, leaky melanin, and chitosan deficiency, among others (8). Cells of the new chs3Δ strain with a complete gene deletion exhibited the same morphologic changes observed in the original strain (Fig. 1A). Additionally, like the original chs3Δ strain, the new chs3Δ strain is also temperature sensitive (Fig. 1B) and deficient in chitosan (Fig. 1C). Phenotypically, the new and original chs3Δ strains appear to be very similar, with the one exception being that the new strain grows faster than the original strain, perhaps due to the lack of the truncated protein.

Previously we attempted to complement the original chs3Δ strain a multitude of ways, and all attempts failed, leading us to conclude that the cell wall of the chs3Δ strain was compromised to a point that the cryptococci could not survive any of the transformation procedures. (9). With this in mind, we attempted to complement the new chs3Δ strain using electroporation into the endogenous locus, replacing the nourseothricin (NAT) resistance marker, and were successful. The complemented strain (chs3Δ::CHS3) reversed all the observed phenotypes including the changes in morphology, temperature sensitivity, and chitosan deficiency (Fig. 1A to C). Because the new chs3Δ is a complete deletion and we have been able to generate a fully complemented strain, we focused most of the work described here on the new chs3Δ strain.

Inoculation with the chs3Δ strain induces rapid mouse mortality. We have previously shown that chitosan is essential for growth in the mammalian host. Strains with three different chitosan deficiency genotypes (chs3Δ, csr2Δ, and cda1ΔΔ3Δ3Δ) all show rapid pulmonary clearance in a mouse model of cryptococcosis and complete loss
of virulence (9) when given in an inoculation of $10^5$ CFU. An inoculation of $10^5$ wild-type (WT) strain KN99 is sufficient to routinely induce disease and cause death at 18 to 20 days postinfection. Mice that received a high inoculation ($10^7$ CFU) of the strain lacking chitin deacetylases, cda1Δ, were also able to clear the infection and were protected against a subsequent challenge with WT C. neoformans KN99 (10). Notably, this chitosan-deficient strain is protective even when heat killed (10). Protective immunization is dependent on the inoculum size, as only mice that received $10^7$ CFU of cda1Δ were protectively immunized, mice that received a lower inoculation were not protected (10).

On the basis of these data, we set out to test whether inoculation with other chitosan-deficient strains would also confer protection. We started this process using the new chs3Δ strain, which is chitosan deficient (Fig. 1C). We inoculated C57BL/6 mice intranasally with $10^7$ CFU of live cda1ΔΔΔ, chs3Δ, chs3Δ::CHS3, or WT C. neoformans KN99 and were monitored for survival. As expected, mice that received cda1ΔΔΔ all survived the infection and mice that received the WT KN99 or chs3Δ::CHS3 all died or were euthanized due to morbidity around day 6 (KN99) or day 8 (chs3Δ::CHS3) postinoculation with this high inoculum (Fig. 2). What was surprising, however, was that the mice inoculated with chs3Δ all died within 36 h after instillation of the organism (Fig. 2).

The rapid rate of mortality suggested that death was not due to fungal proliferation or burden. Furthermore, we previously showed that the original chs3Δ strain is rapidly cleared from the host at a lower inoculum (9). On the basis of these findings, we examined whether mortality was dependent on viable fungi. We heat killed (HK) WT KN99, chs3Δ, and chs3Δ::CHS3 strains at 70°C for 15 min. Complete killing was confirmed by plating for CFU. C57BL/6 mice then received an intranasal inoculation with $10^7$ CFU of HK WT KN99, HK chs3Δ, or HK chs3Δ::CHS3 and were monitored for survival. Mice that received HK WT KN99 or HK chs3Δ::CHS3 all survived the inoculation of heat-killed cells (Fig. 3A). Conversely, mice that received the HK chs3Δ strain all died at the same rate as observed above for mice that received the live chs3Δ strain (Fig. 2 and 3A), indicating that mortality was not dependent on the virulence of the fungi. Supporting the conclusion that the observed phenotype was due to loss of Chs3 and not introduced by a secondary mutation, we also tested the original chs3Δ strain described by Baker et al. (11) (see Fig. S1 in the supplemental material) and saw the same rapid mortality observed in Fig. 3A, indicating that mortality can be attributed to the loss of Chs3.

Different mouse backgrounds have various susceptibilities to C. neoformans depending on the strain used (11). Due to the strong phenotype observed with chs3Δ in the C57BL/6 mice, we wanted to verify that the rapid rate of mortality was not due to the mouse background. To assess susceptibility in different mouse backgrounds,
BALB/c or CBA/J mice received an intranasal inoculation with 10^7 CFU of HK WT KN99, HK chs3Δ/H9004, or HK chs3Δ/H9004::CHS3 and were monitored for survival. Regardless of the mouse background, mice that received HK WT KN99 or HK chs3Δ/H9004::CHS3 all survived the challenge, whereas mice that received HK chs3Δ/H9004 all died at the same rate as observed in the C57BL/6 mice (Fig. 3A to C), indicating that rapid rate of mortality was not a mouse background phenomenon.

Mortality due to the chs3Δ strain is dose dependent. We previously reported that the chs3Δ strain is avirulent and rapidly cleared from the mice (9). Those studies were performed with a lower inoculum, and in conjunction with our above observations, the results suggest that chs3Δ-associated mortality may be dose dependent. To test this, we inoculated C57BL/6 mice with 10^6, 2.5 × 10^6, or 10^7 CFU HK chs3Δ, and mice were monitored for survival. The mice that received 10^7 CFU all died as observed above. In contrast, mice that received 10^6 CFU all survived, and although they displayed signs of morbidity, they recovered. Mice that received 2.5 × 10^6 CFU had a 50% mortality rate where half the animals had succumbed within 24 h postinoculation (Fig. S2). These data suggest that mortality due to chs3Δ is dose dependent and whatever component(s) that triggers the overabundant immune response needs to be at a certain concentration to elicit the response.

A massive inflammatory response is triggered by chs3Δ inoculation. The above data indicate that mice are not dying due to the fungal burden, as death was not...
dependent on viable fungi in multiple mouse backgrounds (Fig. 3). These data suggest that the mortality associated with chs3Δ/H9004 may be host mediated (12). To test this, C57BL/6 mice received an intranasal inoculation with 10^7 CFU HK WT KN99, HK chs3Δ, or HK chs3Δ::CHS3, and the lungs were processed for histology. For all immune studies, we chose to use heat-killed fungi to control for fungal burden as the WT KN99 and chs3Δ/H9004 strains would rapidly outgrow the chs3Δ strain and potentially skew our results. Lungs were processed at 8 h postinoculation, as we could not keep the mice inoculated with the chs3Δ strain (chs3Δ-inoculated mice) alive for the full 24 h. The 8-h time point was chosen, as this was the time the animal started to show signs of morbidity. The paraffin-embedded lungs were sectioned and processed for hematoxylin and eosin (H&E) staining. Histological analysis of the infected lung show little pathology in the lungs of the mice inoculated with either HK KN99 or HK chs3Δ::CHS3 compared to the strong inflammatory response in the lungs of the chs3Δ-inoculated mice at 8 h (Fig. 4). The lungs from mice inoculated with chs3Δ exhibit abundant foci of inflammation spread across the whole lung section (Fig. 4C) consisting of a profound amount of mixed inflammatory infiltrates with enhanced presence of neutrophils (green arrows). Such severe pneumonia and lung damage could explain the mortality observed in chs3Δ-inoculated mice and indicate that the immune response in the lungs, albeit robust, is nonprotective and detrimental.

Mortality due to chs3Δ is not dependent on the signaling components involving Card9 or MyD88. Other cryptococcal mutants that have defects in the cell wall, like rim101Δ, have been found to induce a strong proinflammatory response and lead to granulocyte recruitment (13). In addition, it was found that proinflammatory cytokine
production was dependent on the adapter proteins caspase recruitment domain family member 9 (Card9) and myeloid differentiation primary response 88 (MyD88) (14, 15). Because of these data, we next tested whether Card9 or MyD88 was important in the response to chs3Δ infection. To test this, C57BL/6, Card9−/−, or MyD88−/− mice received an intranasal inoculation with 10^7 CFU of HK chs3Δ and were monitored for survival. We observed no difference in survival with Card9−/− or MyD88−/− mice compared to WT mice infected with chs3Δ (Fig. S3), indicating that rapid rate of mortality was not dependent on these two adapter proteins.

**chs3Δ induces a strong proinflammatory cytokine response.** Because we observed significant infiltration of immune cells in the lungs of chs3Δ-inoculated mice (Fig. 4D and E), we next assessed the cytokine/chemokine produced. To do this, C57BL/6 mice received an intranasal inoculation with 10^7 CFU HK WT KN99, HK chs3Δ, or HK chs3Δ::CHS3, and at 8 h postinoculation, homogenates were prepared from the lungs of each group as well as a phosphate-buffered saline (PBS) control group. Cytokine/chemokine responses were determined from the lung homogenates using the Bio-Plex protein array system. We observed an increase in multiple cytokines (Fig. S4); however, there was a significant increase in the chemokines KC (keratinocyte-derived chemokine) (Fig. 5A) and granulocyte colony-stimulating factor (G-CSF) (Fig. 5B), as well as extremely high levels of interleukin 6 (IL-6) (Fig. 5C) in chs3Δ-inoculated mice compared to PBS-, HK WT KN99-, or HK chs3Δ::CHS3-inoculated mice. This cytokine profile is indicative of a strong neutrophilic response in the lungs, which correlates with the histology data above, indicating an enhanced presence of granulocytes (Fig. 4).

A significant increase in neutrophil recruitment in the lungs of chs3Δ-inoculated mice. Since both the histology and cytokine analysis indicate a strong inflammatory response, we wanted to identify the responding cells. For this, C57BL/6 mice received an intranasal inoculation with 10^7 CFU of HK WT KN99, HK chs3Δ, or HK chs3Δ::CHS3, and at 8 h postinoculation, pulmonary leukocytes were isolated from the lungs of each group of mice by enzymatic digestion and subjected to flow cytometry analysis for leukocyte identity (Fig. S5). Consistent with the above histology data, there was a significant increase in the total number of immune cells in the lungs of chs3Δ-inoculated mice (Fig. 6A). In addition, there was a significant increase in both the total number and percentage of neutrophils in the lungs of chs3Δ-inoculated mice compared to the WT KN99- or HK chs3Δ::CHS3-inoculated mice (Fig. 6B and C). We did not observe a significant change in any of the other cell types assayed (Fig. S6).

Depletion of neutrophils protects chs3Δ-inoculated mice. Due to the significant increase in neutrophil recruitment to the lungs of mice inoculated with the chs3Δ
strain, we sought to determine the role of neutrophils in the rapid mortality observed in these animals. To test this, C57BL/6 mice were injected with 200 μg of anti-Ly6G (1A8), an antibody that specifically depletes neutrophils (16, 17), or an isotype antibody 24 h before intranasal inoculation with 10^7 CFU of HK chs3Δ/H9004 and monitored for survival. Mice were injected with antibody every 24 h for the first 5 days postchallenge. After day 5, the mice were injected every 48 h. This antibody is usually injected every 48 h; however, with the high number of neutrophils recruited (Fig. 6) and the elevated levels of neutrophil growth factors (Fig. 5), we elected to increase the number of the initial injections to ensure neutrophil depletion. Mice that were treated with the isotype antibody all died at the same rate as observed above with HK chs3Δ/H9004 (Fig. 3A and 7A), whereas mice that were treated with anti-Ly6G all survived (Fig. 7A), indicating that death was neutrophil mediated. To confirm this finding, we repeated the experiment in BALB/c and CBA/J mice. Consistent with our findings for C57BL/6 mice, mice that were depleted of neutrophils all survived inoculation with HK chs3Δ, whereas mice treated with the isotype antibody all died regardless of mouse background (Fig. 7B and C). These data demonstrate that the rapid rate of mortality observed in mice inoculated with chs3Δ is neutrophil dependent.

DISCUSSION

We have previously shown that deletion of a specific chitin synthase (CHS3) or deletion of all three chitin deacetylases causes a significant reduction in chitosan in the vegetative cell wall (9). These chitosan-deficient strains of C. neoformans were found to be avirulent and rapidly cleared from the murine lung (9). Moreover, infection with a chitosan-deficient C. neoformans strain lacking three chitin deacetylases (cda1Δ2Δ3Δ) was found to confer protective immunity to a subsequent challenge with a virulent wild-type counterpart (10). These findings suggest that there is an altered host response to chitosan-deficient strains. Surprisingly, we observed that mice inoculated with chitosan-deficient chs3Δ all died within 36 h (Fig. 2 and 3), and death was associated with an aberrant hyperinflammatory immune response, indicating that chitosan is critical in modulating the immune response to Cryptococcus.

While the chs3Δ strain is chitosan deficient like the cda1Δ2Δ3Δ strain, the fact that the immune responses to the two strains are different is not surprising, as there are some key differences in the strains. Both strains have a budding defect that we have associated with the lack of chitosan; however, the lack of chitosan does not explain why the chs3Δ cells are so much larger than the cda1Δ2Δ3Δ or WT cells (Fig. 1) (18). Biochemically, there are significant differences in the amount of total chitinous material.
The two strains. The \textit{cda1\Delta 2\Delta 3\Delta} strain has all the chitin synthases intact, including Chs3, and it makes chitin, but it cannot be deacetylated to chitosan, so it has approximately the same amount of total chitinous material as the wild type, but it is all chitin, with no chitosan. On the other hand, the \textit{chs3/L9004} strain has less total chitinous material than the wild type, but it has slightly increased amounts of chitin and lacks chitosan (8). \textit{CHS3} is a highly expressed chitin synthase and is responsible for the synthesis of the majority of the chitin that is converted to chitosan (18). The reduced amount of total chitinous material found in the \textit{chs3\Delta} strain could explain why it is more sensitive than the \textit{cda1\Delta 2\Delta 3\Delta} strain to some, but not all, of the cell wall stressors like caffeine, Congo red, and calcofluor white (18). The different amounts of total chitinous material could also lead to exposure of other cell wall components that are known to be immunogenic like mannans or glucans. Additionally, the temperature sensitivity observed in the \textit{chs3\Delta} strain (Fig. 1) (18) is not found in the \textit{cda1\Delta 2\Delta 3\Delta} strain, indicating that the lack of chitosan is not linked to the ability to grow at high temperatures. With the multiple defects in the \textit{chs3\Delta} strain, the hyperinflammatory immune response induced by \textit{chs3\Delta} could be due to other factors in addition to the chitosan deficiency.

The immune response to \textit{Cryptococcus}, as well as the magnitude of the response, can play a protective or detrimental role. Our data fit well within the damage-response
framework proposed by Casadevall and Pirofski (12) where host damage or benefit is dependent on the host response. This is represented as a parabolic curve, where too little of a response to a microorganism can lead to damage caused by the microorganism and too strong of a host response can lead to damage caused by the host response. This framework is observed in cryptococcus-infected AIDS patients. Too little of a response can lead to patient death due to the fungus, whereas a hyperactive response can lead to death caused by immunopathology. AIDS patients treated with antiretroviral therapy often develop cryptococcal immune reconstitution inflammatory syndrome (IRIS), which is an exaggerated and frequently deadly inflammatory reaction that complicates recovery from immunodeficiency (19). Cryptococcal IRIS emphasizes the potential role of the host immune system in mediating host damage and disease symptoms.

There is reason to study mutants that induce an aberrant hyperinflammatory immune response, as similar responses like increased cytokine levels and strong neutrophil responses have been observed with fungal IRIS (19–22). Cryptococcal IRIS develops in 8 to 49% of patients with known cryptococcal disease before antiretroviral therapy (23). Neutropenia from chemotherapy or stem cell transplant is a risk factor for invasive aspergillosis (IPA). However, fast recovery of neutrophils in patients with IPA has been associated with the induction of IRIS in about one quarter of these patients (21, 22). The pathogenesis of IRIS is poorly understood, and prediction of IRIS is not currently possible. Innate immune cells, such as monocytes and neutrophils, are of increasing interest in IRIS pathophysiology, since granuloma appears to be frequently found in IRIS lesions (19). Additionally, at the time of IRIS onset, multiple proinflammatory cytokine are detected, including IL-6 (20). Further study of the chs3Δ immune response could advance our understanding of host immune mechanisms involved in an inappropriately strong immune response to Cryptococcus, like those seen in immune reconstitution inflammatory syndrome. These studies have the potential to advance our understanding of a significant problem in the management of cryptococcal patients.

Other cryptococcal mutants that have defects in the cell wall, like rim101Δ and mar1Δ, have been found to induce a strong proinflammatory response and lead to neutrophil recruitment (13–15) but not to the order of magnitude observed with chs3Δ. Neutrophils have a complicated role in the cryptococcal immune response. While neutrophils can kill C. neoformans, the fungus can modulate the neutrophil response. Cryptococcal capsular and cell wall components can inhibit neutrophil migration (24, 25) and the production of neutrophil extracellular traps (26). In the brain, neutrophils have been shown to be important in clearance of the fungus from the microvasculature (27, 28). Neutrophil depletion in a protective immunization model did not affect pulmonary fungal burden, indicating that neutrophils are not required for clearance (16) or for the secondary response (17). These data further support the observation by Mednick et al. that neutropenic mice given a pulmonary C. neoformans infection survived significantly longer than control mice that had an intact neutrophil compartment (29), therefore indicating that neutrophils are not necessary for protective responses against cryptococcal infection. We observed a significant increase in neutrophil recruitment to the lungs of mice inoculated with the chs3Δ strain (Fig. 6B and C). Mice inoculated with HK chs3Δ and depleted of neutrophils all survived, whereas the isotype-treated mice all died (Fig. 7), indicating a detrimental role for neutrophils. Further supporting a harmful role for neutrophils, mice with genetically induced neutrophilia appear to have increased susceptibility to cryptococcal disease (30). More work is needed to elucidate our understanding the cryptococcus-neutrophil interactions.

We have shown that chs3Δ induces massive production of IL-6, KC, and G-CSF as well as a strong neutrophilic response. However, the source of these cytokines, as well as their role in the pathology, of chs3Δ is not known. It is likely that the cytokines are produced by the lung epithelium and/or resident immune cells, since the response is so fast, but other immune cells, such as the recruited neutrophils, could play a role. We plan to assay this by utilizing knockout and depletion strategies. Additionally, as mortality due to chs3Δ is dose dependent and associated with a highly inflamed lung, we hypothesize that there are cellular components from chs3Δ that elicit the rapid
onset of death. We plan to test this by fractionating WT, chs3Δ, and chs3Δ::CHS3 cryptococcal cells to identify the immune activating components.

In summary, we have shown that inoculation with either live or dead cells from the chs3Δ strain leads to death of the mice within 36 h. The rapid onset of death is likely due to an aberrant hyperinflammatory immune response, as mortality was not dependent on viable fungi. Histology, cytokine profiling, and flow cytometry indicate a massive influx of neutrophils in the mice inoculated with chs3Δ. Depletion studies show a damaging role for neutrophils in the response to chs3Δ. Altogether, chitosan may play a major role in the immune response to C. neoformans. In addition, the response to chitosan-deficient C. neoformans seems to depend on the type of genes deleted, as not all chitosan-deficient strains induce the same immune response.

MATERIALS AND METHODS

Fungal strains and media. C. neoformans strain KN99α was used as the wild-type strain and as progenitor of mutant strains. Strains were grown in YPD broth (1% yeast extract, 2% Bacto peptone, and 2% dextrose) or on YPD solid medium containing 2% Bacto agar. Selective YPD medium was supplemented with 200 μg/ml nourseothricin (NAT) (Werner BioAgents, Germany).

Strain construction. Gene-specific deletion construct of the chitin synthase 3 gene (CNAG_05581) was generated using overlap PCR gene technology described previously (31, 32) and included the nourseothricin resistance cassette. The primers used to disrupt the genes are shown in Table S1 in the supplemental material. The Chs3 deletion cassette contained the nourseothricin resistance cassette, resulting in a 1,539-bp replacement of the genomic sequence between the regions of primers 3-Chs3 and 6-Chs3 shown in uppercase in Table S1. The construct was introduced into the KN99α strain using biolistic techniques (33). To generate a CHS3 complemented strain, we replaced the NAT resistance cassette in the chs3 deletion strain with the native CHS3 gene sequence by electroporation (34) and screened for NAT sensitivity.

Morphological analysis. Cells were incubated for 2 days in YPD medium at 30°C with shaking and diluted to an optical density at 650 nm (OD650) of 0.2 with phosphate-buffered saline (PBS). Five microliters of each cell solution was spotted onto a clean glass slide and photographed using an Olympus BX61 microscope.

Evaluation of temperature sensitivity. Wild-type, chs3 deletion, and chs3Δ::CHS3 complemented strains were grown in liquid YPD for 2 days at 30°C with shaking. Cells were diluted to an OD650 of 1.0, and 10-fold serial dilutions were made. Five microliters of each dilution were spotted onto YPD plates, and the plates were incubated for 2 or 3 days at 30°C and 39°C and photographed.

Cellular chitosan measurement. As previously described, MBTH (3-methyl-2-benzothiazolinone hydrazone)-based chemical method was used to determine the chitin and chitosan content (35). In brief, cells were grown in liquid YPD for 2 days at 30°C with shaking collected by centrifugation. Cell pellets were washed two times with PBS (pH 7.4) and lyophilized. The dried samples were resuspended in water and then washed with PBS (pH 7.4) to a concentration of 10 mg/ml in PBS (by dry weight), and 0.1 ml of each sample was used in the MBTH assay (36).

Mice. BALB/c (catalog no. 000651), CBA/J (catalog no. 000656), C57BL/6 (catalog no. 000664), Card9−/− (catalog no. 028652), and MyD88−/− (catalog no. 009088) mice were obtained from Jackson Laboratory (Bar Harbor, ME). BALB/c and C57BL/6 mice obtained from Jackson Laboratory are also known as BALB/cJ and C57/6J mice, respectively. All mice were 6 to 8 weeks old at the time of inoculation. All animal protocols were reviewed and approved by the Animal Studies Committee of the Washington University School of Medicine and conducted according to National Institutes of Health guidelines for housing and care of laboratory animals.

Pulmonary inoculations. Strains were grown at 30°C and 300 rpm for 48 h in 50 ml YPD. The cells were centrifuged, washed in endotoxin-free 1× PBS, and counted with a hemocytometer. For studies utilizing heat-killed organisms, after being diluted to the desired cell number in PBS, the inoculum was heated at 70°C for 15 min. Complete killing was assayed by plating for CFU. Mice were anesthetized with an intraperitoneal injection (200 μl) of ketamine (8 mg/ml)-dexametomidine (0.05 mg/ml) mixture and then given an intranasal inoculation with 1 × 107 CFU of live or heat-killed organism in 50 μl of sterile PBS. Anesthesia was reversed by an intraperitoneal injection of (200 μl) of antipamezole (0.25 mg/ml). The mice were fed ad libitum and monitored daily for symptoms. For survival studies, mice were sacrificed when body weight fell below 80% of weight at the time of inoculation. For cytokine analysis, flow cytometry studies, and histology, mice were euthanized 8 h postinoculation by CO2 inhalation, and the lungs were harvested.

Histology. Mice were sacrificed according to approved protocols and perfused intracardially with sterile PBS, and the lungs were inflated with 10% formalin. Lung tissue was then fixed for 48 h in 10% formalin and submitted to Histowiz Inc. (Brooklyn, NY) for histology using standard operating procedures and fully automated workflow. Samples were processed, embedded in paraffin, cut into 4-μm sections, and stained using hematoxylin and eosin (H&E). After staining, sections were dehydrated and film
were lysed by incubation in NH4Cl buffer (0.859% NH4Cl, 0.1% KHCO3, 0.0372% Na2EDTA [pH 7.4]; 200 μl) and centrifuged. The percentage of cells stained by fluorochrome-labeled antibodies for each cell population analyzed.

Antibodies (clone 2A3; BioXcell) in 100 μl PBS, 0.1% bovine serum albumin (BSA), 0.02% NaN3, 2mM EDTA) and incubated with CD16/CD32 (Fc receptor blocking; BD Biosciences, San Jose, CA) for 5 min. For flow cytometry, 1 × 10^6 cells were incubated for 30 min at 4°C in the dark with optimal concentrations of fluorochrome-conjugated antibodies (see Table S2 for a list of the antibodies, antigens, clones, and sources) diluted in brilliant stain buffer (BD Biosciences). After three washes with FACS buffer, the cells were fixed in 2% ultrapure paraformaldehyde. For data acquisition, >200,000 events were collected on a BD LSRFortessa X-20 flow cytometer (BD Biosciences, San Jose, CA), and the data were analyzed with FlowJo V10 (TreeStar, Ashland, OR). The absolute number of cells in each leukocyte subset was determined by multiplying the absolute number of CD45^+ cells by the percentage of cells stained by fluorochrome-labeled antibodies for each cell population analyzed.

Flow cytometry. Cell populations in the lungs were identified by flow cytometry. Briefly, lungs from individual mice were enzymatically digested at 37°C for 30 min in digestion buffer (RPMI 1640 containing 1 mg/ml of collagenase type IV). The digested tissues were then successively passed through sterile 70- and 40-μm-pore nylon strainers (BD Biosciences, San Jose, CA). Erythrocytes in the strained suspension were lysed by incubation in NH4Cl buffer (0.859% NH4Cl, 0.1% KHCO3, 0.0372% Na2EDTA [pH 7.4]; Sigma-Aldrich) for 3 min on ice, followed by the addition of a twofold excess of PBS. The leukocytes were then collected by centrifugation, resuspended in sterile PBS, and stained using the LIVE/DEAD Fixable Blue Dead Cell Stain kit (1:1,000; Invitrogen, Carlsbad, CA) for 30 min at 4°C in the dark. Following incubation, samples were washed and resuspended in fluorescence-activated cell sorting (FACS) buffer (PBS, 0.1% bovine serum albumin [BSA], 0.02% NaNO3, 2 mM EDTA) and incubated with CD16/CD32 (Fc Block; BD Biosciences, San Jose, CA) for 5 min. For flow cytometry, 1 × 10^6 cells were incubated for 30 min at 4°C in the dark with optimal concentrations of fluorochrome-conjugated antibodies (see Table S2 for a list of the antibodies, antigens, clones, and sources) diluted in brilliant stain buffer (BD Biosciences). After three washes with FACS buffer, the cells were fixed in 2% ultrapure paraformaldehyde. For data acquisition, >200,000 events were collected on a BD LSRFortessa X-20 flow cytometer (BD Biosciences, San Jose, CA), and the data were analyzed with FlowJo V10 (TreeStar, Ashland, OR). The absolute number of cells in each leukocyte subset was determined by multiplying the absolute number of CD45^+ cells by the percentage of cells stained by fluorochrome-labeled antibodies for each cell population analyzed.

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Neutrophil depletion. Mice were depleted of neutrophils via intraperitoneal (i.p.) administration of 200 μg anti-Ly6G (clone 1A8; BioXcell) in 100 μl of control mice received 200 μg IgG2a isotype control antibody (clone 2A3; BioXcell) in 100 μl of control mice received 200 μg IgG2a isotype control antibody (clone 2A3; BioXcell) in 100 μl. Depletions were started 24 h prior to challenge, and the mice were injected every 24 h for the first 5 days postchallenge. After day 5, the mice were injected every 48 h.

Statistics. Data were analyzed using GraphPad Prism, version 8.0 (GraphPad Software, Inc., La Jolla, CA). The one-way analysis of variance (ANOVA) with the Tukey’s multiple-correction test was used to compare more than two groups. Kaplan-Meier survival curves were compared using the Mantel-Cox log rank test. P values of <0.05 were considered significant.

SUPPLEMENTAL MATERIAL
Supplemental material is available online only.

FIG S1, TIF file, 0.1 MB.
FIG S2, TIF file, 0.1 MB.
FIG S3, TIF file, 0.2 MB.
FIG S4, TIF file, 0.6 MB.
FIG S5, TIF file, 2.5 MB.
FIG S6, TIF file, 0.4 MB.
TABLE S1, DOCX file, 0.01 MB.
TABLE S2, DOCX file, 0.01 MB.

ACKNOWLEDGMENTS
This work was funded by National Institutes of Health grants AI072195 and AI1125045 to J.K.L. C.R.H. was partly funded by a National Institute of Allergy and Infectious Diseases training grant (T32 AI007172).

The funders had no role in study design, data collection and interpretation, or the decision to submit the work for publication.

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