Prevention and Early Treatment of Invasive Fungal Infection in Patients with Cancer and Neutropenia and in Stem Cell Transplant Recipients in the Era of Newer Broad-Spectrum Antifungal Agents and Diagnostic Adjuncts

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Invasive fungal infection (IFI) is a leading cause of infection-related mortality among patients with cancer and prolonged neutropenia and among allogeneic hematopoietic stem cell transplant recipients with graft-versus-host disease. Invasive candidiasis was the principal IFI in the period predating fluconazole prophylaxis, whereas today, invasive aspergillosis and other mold infections cause the majority of deaths from fungal infection in this patient population. The changing epidemiology of IFI, in addition to advances made in antifungal therapeutics and early diagnosis of IFI, warrant a reevaluation of earlier strategies aimed at prevention and early treatment of IFI that were developed several years ago. Here, we propose that persistent neutropenic fever is nonspecific for an IFI and should not be used as the sole criterion for empirical modification in the antifungal regimen in a patient receiving mold-active prophylaxis. We explore the potential benefits and gaps in knowledge associated with employing chest CT scans and laboratory markers as diagnostic adjuncts for IFI. Finally, we discuss the implications of newer antifungal agents and diagnostic adjuncts in the design of future clinical trials to evaluate prophylaxis and early prevention strategies.

Invasive fungal infection (IFI) is a major cause of morbidity and mortality among patients with acute leukemia and receipt of an allogeneic hematopoietic stem cell transplant (HSCT). Four strategies for prevention and treatment of IFI include (1) prophylaxis, (2) empirical antifungal therapy, (3) preemptive antifungal therapy, and (4) treatment of established fungal infection (table 1). Even among highly immunocompromised patients, most will not develop an IFI. Therefore, any prevention strategy entails administering an antifungal agent to a prespecified patient population in which only a minority would be expected to benefit (table 2).

Prophylactic fluconazole has led to a decrease in the frequency of invasive candidiasis among patients with leukemia and among HSCT recipients. However, invasive aspergillosis (IA) [1–3] and less common molds, including zygomycetes [4], Fusarium species, [5–7], and Scedosporium species, have become increasingly important causes of IFI-related mortality relative to invasive candidiasis among patients with leukemia and among allogeneic HSCT recipients [3, 8, 9]. Some centers have noted an increased frequency of zygomycosis in patients receiving prophylactic voriconazole [10–12]; it is controversial whether a causal relationship exists or whether this finding reflects a larger pool of highly immunocompromised patients. Modern prophylactic and early-treatment strategies are required that encompass the changing epidemiology of IFI, advances in antifungal agents, and improved diagnostic tools (e.g., chest CT scans and laboratory markers) that facilitate early detection of IFI.

Empirical antifungal therapy for neutropenic fever has been studied in >3000 patients and has been codified in authoritative guidelines [13, 14]. Its use was justifiably supported because of the combination of inadequate diagnostic testing, the need for early antifungal drug treat-
ment of IFI, uncertain prophylactic regimens, and high-level morbidity and mortality from IFI.

Although fever in a neutropenic patient should prompt a meticulous evaluation, we challenge the principle of using fever alone as a specific entry point for clinical decisions regarding patients receiving mold-active prophylaxis when we have diagnostic tools that allow us to make a more precise diagnosis. Challenges and pitfalls in prevention trials involving non-neutropenic allogeneic HSCT recipients at high risk for IFI are discussed. We also discuss significant gaps in knowledge that may be the basis for future clinical trials.

**HISTORICAL PERSPECTIVE**

In the 1960s and 1970s, the development of antipseudomonal β-lactams and the routine use of empirical antibacterial therapy at the onset of neutropic fever reduced mortality from bacterial infections [15]. More patients were treated with potent cytotoxic regimens (e.g., for acute leukemia), and IFI became a frequent cause of mortality in these patients. Before the use of empirical antifungal therapy, IFIs were frequently diagnosed at autopsy in patients with leukemia and unexplained persistent neutropic fever; *Candida* and *Aspergillus* species were the principal pathogens [16, 17]. Thus, the rationale for empirical antifungal therapy is that clinical examination and cultures are not sufficiently sensitive for early detection of IFI and that early treatment of IFI can be life saving [18].

Two randomized prospective studies in the 1980s showed that empirical amphotericin B deoxycholate (AmB-D) was associated with a trend toward fewer IFIs in antibiotic-treated neutropic patients with persistent fever [16, 19]. In the larger study, no deaths from IFI occurred in patients receiving empirical AmB-D, compared with 4 deaths from IFI in the control group ($P = .05$). The benefit of empirical AmB-D therapy primarily occurred in patients who did not receive antifungal prophylaxis [19]. Because both studies were underpowered and neither showed a statistically significant benefit of empirical antifungal therapy in preventing IFIs or overall mortality, some investigators argue that a placebo arm in empirical antifungal therapy studies could be justified in future trials, particularly if prophylaxis against candidiasis were included [20].

**FLUCONAZOLE VERSUS AMPHOTERICIN B (EARLY VS. LATE) PARADIGM**

Because of its toxicity, AmB-D was more likely to be used as empirical therapy for neutropic fever than as prophylaxis, which would entail treating a larger number of patients over a longer period [21]. Fluconazole therapy is effective in preventing invasive candidiasis in HSCT recipients [22–24], although breakthrough fluconazole-sensitive and fluconazole-resistant infections occur [25]. A meta-analysis of randomized studies of azole prophylaxis (fluconazole, ketoconazole, miconazole, and itraconazole) in neutropic patients demonstrated that azoles led to reductions in the use of parenteral antifungal therapy, superficial fungal infections, IFIs, and fungal infection–related mortality [26]. The incidence of IA was unaffected. In a meta-analysis of 16 randomized, controlled trials involving patients who did not receive HSCT and who had chemotherapy-induced neutropenia, fluconazole prophylaxis was beneficial when the incidence of IFI was expected to be >15% [27].

Empirical therapy for neutropic fever initially involved initiation of AmB-D therapy to increase the spectrum of activity to include molds and azole-resistant *Candida* species. The trade-off was straightforward: early administration of a narrow-spectrum but safe agent (fluconazole), compared with later administration of a broader spectrum agent with greater toxicity (AmB-D).

There are many causes of fever in neutropic patients (e.g., bacterial infections, transfusion reactions, drug reactions, tissue necrosis, and growth factors). IFIs are documented in ≤5% of patients enrolled in modern empirical antifungal trials in which antifungal prophylaxis was commonly used [28–31]. Indeed, 2 randomized trials showed that fluconazole was equally effective but safer than AmB-D as empirical therapy for persistently febrile

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**Table 1. Strategies for prevention and treatment of invasive fungal infection (IFI).**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Definition</th>
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<tbody>
<tr>
<td><strong>Prophylaxis</strong></td>
<td>Administration of the antifungal agent is initiated at a period of high risk of infection to prevent fungal infections</td>
</tr>
<tr>
<td><strong>Empirical treatment</strong></td>
<td>Initiation or modification of an existing antifungal regimen in persistently febrile patients with neutropenia (generally 4–7 days in duration) that is without a known source and is unresponsive to appropriate antibacterial agents</td>
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<td><strong>Preemptive therapy</strong></td>
<td>Similar to empirical antifungal therapy, preemptive therapy aims to treat a suspected early IFI but uses radiologic studies, laboratory markers, or both (rather than fever alone) to stratify the likelihood of an IFI; meeting prespecified criteria would trigger preemptive initiation or modification of antifungal therapy</td>
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<tr>
<td><strong>Treatment of established IFI</strong></td>
<td>Corresponds to patients who meet European Organization for Research and Treatment of Cancer/Mycoses Study Group criteria for proven and probable IFI [71]</td>
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* Standardized definitions for what constitutes preemptive antifungal therapy are required. For example, a positive serum galactomannan or β-glucan assay result for a neutropic patient with persistent fever may be used as a trigger to modify the antifungal regimen in a preemptive strategy. Another preemptive strategy may use chest CT findings as a decision node regarding modification of the antifungal regimen. Other preemptive strategies may use laboratory and radiologic studies in different sequences. Triggers for preemptive antifungal therapy must be distinguished from a “probable IFI,” as defined by European Organization for Research and Treatment of Cancer/Mycoses Study Group criteria; antifungal therapy in this situation is aimed at treating a documented IFI rather than at being preemptive.
neutropenic patients [32, 33]. Because of its lack of activity against molds, the authors cautioned that chest radiographs or CT scans be performed prior to initiating empirical fluconazole therapy [32].

**NEWER ANTIFUNGAL AGENTS**

The development of newer antifungal agents with activity against yeasts and molds and with superior safety and tolerability, compared with AmB-D, raised questions about whether the older paradigm of early and safe treatment versus late and potentially toxic treatment should be continued [34]. The improved tolerability of lipid formulations of amphotericin B, azoles, and echinocandins, compared with AmB-D, has prompted many centers to use these agents early, as prophylaxis, rather than later, as empirical therapy for neutropenic fever [14, 35, 36].

Indeed, it is common for agents within the same class and with a similar spectrum to be evaluated as prophylaxis and as empirical therapy in separate trials. The echinocandins provide an instructive example. Caspofungin was at least as effective as and less toxic than liposomal amphotericin B as empirical therapy in persistently febrile patients with neutropenia [30]. The success rate in each arm, using a prespecified composite outcome, was only 34%, with the majority of treatment failures being driven by a lack of resolution of fever during the neutropenic period. In a prophylactic trial of autologous and allogeneic HSCT recipients that compared micafungin with fluconazole, treatment success required the absence of suspected, probable, or proven IFI through the end of therapy [36]. Empirical modification of antifungal therapy on the basis of neutropenic fever was equated with a suspected IFI. The frequency of breakthrough candidemia was similar in both arms, but there was a trend to fewer episodes of IA in allogeneic HSCT recipients receiving micafungin. The superiority of micafungin therapy was principally driven by a lower frequency of persistent neutropenic fever requiring empirical modification of the antifungal regimen.

These trials raise 2 questions. First, should persistent fever without evidence of a breakthrough IFI be a criterion for failure in antifungal prophylactic and empirical trials? Several empirical antifungal studies have employed a composite outcome in which fulfillment of several prespecified criteria were required for a successful outcome [29–31]. These composite outcomes have generally included the following: (1) absence of breakthrough fungal infections, (2) successful treatment of baseline fungal infections, (3) survival, (4) no premature study withdrawal, and (5) resolution of fever during neutropenia.

In studies comparing voriconazole with liposomal amphotericin B and caspofun-
Figure 1. Proposed algorithm for early diagnosis of invasive fungal infection (IFI) and use of antifungal regimens in neutropenic patients with persistent fever of unknown etiology. When mold-active prophylaxis is used, we propose an algorithm in which the initial prophylactic agent is continued with negative diagnostic results. Although this algorithm addresses neutropenic patients, the concepts are applicable to other patients at high risk for IFIs (e.g., allogeneic hematopoietic stem cell transplant recipients). BAL, bronchoalveolar lavage fluid; GMI, galactomannan index.

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The second question relates to whether empirical modification of the antifungal regimen is warranted solely on the basis of persistent neutropenic fever in patients receiving mold-active prophylaxis. No studies specifically address this question. This question has become particularly relevant in light of recent data on posaconazole prophylaxis. Posaconazole has activity in vitro and in animal models against the major pathogenic fungi [38–42]. Posaconazole has been effective as salvage therapy in patients with a broad range of IFIs [41, 43–47]. Posaconazole was effective as primary therapy for mucosal candidiasis [48], but it has not been evaluated as primary therapy for IFI. Prophylaxis with posaconazole led to fewer IFIs and less overall mortality, compared with prophylaxis with fluconazole or itraconazole, in neutropenic patients with acute leukemia or myelodysplastic syndrome in a randomized trial [49]. Results of this trial have been reported in abstract form and require confirmation by peer review. The availability of effective and safe mold-active prophylaxis creates the need for a new paradigm to diagnose breakthrough IFIs early and to modify the antifungal regimen in only those patients who meet prespecified criteria.

**ALLOGENEIC HSCT**

Several studies have reported the predominance of aspergillosis cases occurring in the postengraftment period, rather than in the neutropenic period, among allogeneic HSCT recipients [2, 50–56], with immunosuppressive therapy for graft-versus-host disease (GVHD) and T cell depletion being principal risk factors. Marr et al. [3] noted an increased incidence of infections due to less common fungal pathogens, including zygomycetes and *Fusarium* and *Scedosporium* species, among allogeneic HSCT recipients—particularly among patients with multiple stem cell transplants for relapsed malignancy, who are among the most severely immunocompromised HSCT recipients. In contrast to neutropenic patients, patients with GVHD who are receiving corticosteroids and other immunosuppressive agents commonly do not experience fever during IFI [56].
Until recently, almost all clinical trials of antifungal prophylaxis in patients with cancer focused on neutropenic patients. Two prophylactic trials comparing fluconazole with itraconazole have addressed this changing epidemiology by extending the period of administration of antifungal drugs from the time of the conditioning regimen through at least the first 100 days, corresponding to the period of acute GVHD [57, 58]. Itraconazole prophylaxis was associated with fewer cases of IA, but overall survival rates were similar [57, 58]. Hepatic toxicity and discontinuation of prophylaxis because of gastrointestinal intolerance were more common in itraconazole recipients [57]. Itraconazole led to an increase in cyclophosphamide metabolites, which, in turn, were associated with hyperbilirubinemia and nephrotoxicity during the early posttransplantation period [59]. This finding reinforces a note of caution about itraconazole and newer second-generation triazoles, which are potent inhibitors of cytochrome P450 isoenzymes, regarding the potential for drug-drug interactions.

Posaconazole was compared with fluconazole as prophylaxis in allogeneic HSCT recipients with significant GVHD in a prospective, randomized, double-blind study [60]. Posaconazole prophylaxis led to reductions in the incidence of IA, the total number of IFIs experienced while receiving treatment, and the number of deaths attributed to fungal infection. These results have been reported in abstract from and require confirmation by peer review. If posaconazole is used in allogeneic HSCT recipients with GVHD, breakthrough IFIs would be expected to be uncommon, and conceivably, the proportion of infections due to uncommon drug-resistant pathogens (e.g., Scedosporium species) or azole-resistant yeasts might increase. Development of effective surveillance strategies for use in this patient population that have a high positive predictive value (PPV), to detect breakthrough IFIs early, and a high negative predictive value (NPV), to avoid unnecessary modifications in antifungal prophylaxis, pose an important challenge for future research.

NEED FOR VALIDATED SURROGATE MARKERS

Both the serum Aspergillus galactomannan and β-glucan assays have been accepted as diagnostic adjuncts of IFI in the revised European Organization for Research and Treatment of Cancer/Mycosis Study Group consensus criteria (which is currently in preparation). PCR-based detection is considered to be investigational.

These markers have advantages and limitations. Several variables can affect the performance of the galactomannan assay [61, 62] and may account for differences in the results of prospective studies. The sensitivity of the assay is reduced by concomitant mold-active antifungal agents [63, 64]. False-positive results may be more common among children and allogeneic HSCT recipients [65]. Receipt of concomitant piperacillin-tazobactam can cause false-positive galactomannan assay results [66, 67].

Herbrecht et al. [65] evaluated galactomannan antigenemia in patients at risk for IA. The sensitivity of the assay was 64.5% for cases of definite IA. The PPV of the test varied among different patient groups, and the lowest PPVs occurred when the test was used as a surveillance tool among patients with persistent neutropenic fever (PPV, 7.1%) and in HSCT recipients (PPV, 10%); the NPV was 100% in both groups. A recent meta-analysis showed that the galactomannan assay had a sensitivity of 70% and a specificity of 89% for proven IA and that the accuracy of the test was variable among different patient populations [68]. In populations with a prevalence of IA of 5%–10%, the expected PPV was 23%–53%, whereas the expected NPV was 95%–99% [68].

Detection of β-glucan has received US Food and Drug Administration approval for use for presumptive diagnosis of IFI. Among patients with acute myeloid leukemia and myelodysplastic syndrome, the assay was highly sensitive and specific in detecting early IFIs, including candidiasis, fusariosis, trichosporonosis, and aspergillosis [69]. The NPV was 100%. Experience with use of the β-glucan assay in HSCT recipients is limited [70], and the use of this assay in this population requires additional study.

Although valuable as diagnostic adjuncts to support a diagnosis of a probable...
IFI in patients with compatible host factors and radiological findings as defined in the European Organization for Research and Treatment of Cancer/Mycosis Study Group criteria [71], the value of these laboratory markers as screening tools for IFIs is controversial, and more research is required. In neutropenic patients with fever without localizing symptoms or physical examination findings who have negative blood culture results and negative chest CT findings, a negative galactomannan and/or β-glucan assay result lends additional support for the absence of a breakthrough IFI.

INCORPORATION OF CT SCANS AND LABORATORY DETECTION MARKERS INTO MANAGEMENT ALGORITHMS: GAPS IN KNOWLEDGE

Preemptive antiviral therapy on the basis of surveillance-antigen or PCR detection has become standard for preventing cytomegalovirus disease in allogeneic HSCT recipients [72]. Preemptive antifungal strategies are at an exploratory level and do not have standardized criteria. Laboratory markers, radiological monitoring, or both are used to identify early IFIs before the development of clinically overt disease. This approach differs from preemptive cytomegalovirus therapy, which relies on the detection of viral replication to stratify the risk for developing cytomegalovirus disease.

In an open-label feasibility study, Martens et al. [73] used serial serum galactomannan and chest CT scanning to detect early aspergillosis in high-risk neutropenic patients receiving fluconazole prophylaxis. This strategy reduced the use of empirical antifungal therapy and successfully identified cases of early IA, but it may not be adequate to identify early infection with non-Aspergillus molds.

An ongoing randomized double-blind trial comparing fluconazole with voriconazole as prophylaxis after allogeneic HSCT incorporates some of the elements of preemptive antifungal therapy. The study encompasses both the early neutropenic period and the later posttransplantation period when GVHD occurs. Incorporation of real-time serum galactomannan monitoring aims to permit early detection of IA and modification of the antifungal regimen. Seen in this light, the protocol compares antimold prophylaxis (voriconazole) with the strategy of using a narrower spectrum agent (fluconazole) coupled with galactomannan monitoring and an early switch to a mold-active regimen if prespecified criteria are met [74].

Because the potential benefit of prophylactic voriconazole may be offset by increased toxicity, equipoise exists [74]. In a manner similar to that used in trials of itraconazole prophylaxis, the use of empirical antifungal therapy with amphotericin B for persistent neutropenic fever of unknown etiology was not scored as failure of prophylaxis [57, 58].

Because no study has evaluated empirical modification of antifungal therapy in neutropenic patients receiving mold-active prophylaxis on the basis of persistent fever alone, we propose an algorithm in which the initial prophylactic agent is continued with negative diagnostic results (figure 1). In this algorithm, fever prompts further evaluation, rather than being an automatic trigger to change the antifungal regimen in the absence of evidence of failure prophylaxis. Testing newer early diagnostic algorithms to detect breakthrough IFIs in high-risk patients receiving mold-active prophylaxis would address an important gap in knowledge.

In patients receiving no antifungal prophylaxis or fluconazole prophylaxis, empirical antifungal trials have shown that a small minority have baseline IFIs at the time of study enrollment. For example, in the empirical antifungal trial comparing caspofungin and liposomal amphotericin B, ~5% of patients in both arms had a baseline IFI (almost 90% of these IFIs were invasive candidiasis or IA) [30]. Empirical antifungal therapy initiated prior to diagnosis of IFI would be expected to benefit this small minority of patients. Empirical treatment with caspofungin is not associated with greater toxicity than fluconazole used as prophylaxis, and it represents a viable strategy. Whether it is safe to continue fluconazole prophylaxis in neutropenic patients with persistent fever of unknown etiology who have negative chest CT findings and negative laboratory markers merits further study (figure 2).

Studies that compare competing diagnostic and treatment algorithms, rather than simply comparing one drug with another, are required to delineate optimal strategies tailored to specific patient populations. Such studies should be randomized and aim to demonstrate an improvement in morbidity or mortality over standard approaches, and they should include an analysis of the cost of competing strategies.

CONCLUSIONS

Three factors create the need to reevaluate older paradigms for prophylaxis and early treatment of suspected IFIs. The first is the change in the epidemiology of IFIs, in which mold infections pose a greater threat than invasive candidiasis in patients with acute leukemia and allogeneic HSCT. Among allogeneic HSCT recipients, the predominance of invasive mold infection during GVHD, rather than neutropenia, has led to recent prophylactic trials that encompass the GVHD period. Second, the availability of effective and safe mold-active agents challenges the older paradigm of using fever alone as a trigger to modify antifungal therapy. Third, chest CT findings and laboratory markers as diagnostic adjuncts for IFI may be useful as triggers to initiate or modify antifungal therapy. It is a high priority to validate the application of these tests to antifungal algorithms.

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