Protective host defense against disseminated candidiasis is impaired in mice expressing human interleukin-37

Frank L. van de Veerdonk1,2,3 *, Mark S. Gresnigt2, Marije Oosting2, Jos W. M. van der Meer2, Leo A. B. Joosten2,3, Mihai G. Netea2,3 and Charles A. Dinarello1,2

1 Department of Medicine, University of Colorado Denver, Denver, CO, USA
2 Department of Medicine, Radboud University Nijmegen Medical Center, Nijmegen, Netherlands
3 Radboud Center for Infection, Nijmegen, Netherlands

Edited by:
Annelies Sophie Zinkernagel, University Hospital Zurich–University of Zurich, Switzerland

Reviewed by:
Thomas Tsaganos, University of Athens Medical School, Greece

*Correspondence:
Frank L. van de Veerdonk, Department of Medicine, Radboud University Nijmegen Medical Center, Geert Grooteplein Zuid 8, 6525 GA Nijmegen, Netherlands
email: f.van.deveerdonk@aig.umcn.nl

INTRODUCTION
The interleukin-1 (IL-1) family includes inflammatory cytokines (such as IL-1α, IL-1β, IL-18, and IL-33) that activate target cells through a receptor-mediated mechanism; anti-inflammatory cytokine antagonists (such as IL-1Ra) block IL-1-dependent activation by competing for binding to the IL-1 receptors (Dinarello, 2011). Twelve years ago, using in silico searches, additional members of the IL-1 family namely IL-36, IL-37, and IL-38 were discovered, but only recently have their properties been studied (Dinarello et al., 2013). The case of IL-37, this cytokine has emerged as fundamental inhibitor of innate inflammation using mice transgenic for human IL-37 as well as reducing endogenous IL-37 in mice transgenic for human IL-37 are protected against systemic endotoxemia, chemical induced colitis, ConA hepatitis, and ischemic toxemia, chemical induced colitis, ConA hepatitis, and ischemic hepatic injury, as reviewed in Dinarello and Butler (2013). The mechanism by which IL-37 affords anti-inflammatory protection can be via a caspase-1-dependent nuclear translocation or by an extracellular mechanism engaging the IL-18 receptor (Bulau et al., 2014). It is important however, to recognize that anti-inflammatory strategies based upon IL-37 could have a negative impact on susceptibility to infections by inhibiting host defense. Since in models of live infection blocking inflammation mediated by cytokines such as IL-1 or TNFα can be either detrimental or beneficial for the outcome of the host, we therefore carried-out studies of disseminated candidiasis in mice expressing human IL-37.

MATERIALS AND METHODS

ANIMALS
Transgenic mice expressing human IL-37 (hIL-37Tg) have been previously described Nold et al. (2010). Control C57BL/6J (WT) mice were purchased from the Jackson Laboratory and maintained under specific-pathogen free conditions. The mice were fed sterilized laboratory chow (Hope Farms, Woerden, The Netherlands) and water ad libitum. The experiments were approved by the Ethics Committee on Animal Experiments of Radboud University Nijmegen.

Candida albicans AND GROWTH CONDITIONS
Candida albicans ATCC MYA-3573 (UC 820), a strain well described elsewhere (Lehrer and Cline, 1969), was used in all experiments. Candida was grown overnight in Sabouraud broth at 37°C, cells were harvested by centrifugation, washed twice, and resuspended in culture medium (RPMI-1640 Dutch modification, ICN Biomedicals, Aurora, OH, USA; van der Graaf et al., 2005). To generate pseudohyphae, C. albicans blastocandida were grown at 37°C in culture medium, adjusted to pH 6.4 by using hydrochloric acid. Pseudohyphae were killed at 100°C for 1 h and resuspended in culture medium to a hyphal inoculum size that originated from 10⁶ blastocandida per ml (referred to as 10⁶ pseudohyphae per ml).

CYTOKINE RESPONSES OF C. ALBICANS-STIMULATED MACROPHAGES AND SPLENOCYTES
Resident peritoneal macrophages were harvested from groups of five hIL-37Tg and wild-type (WT) mice by injecting 4 ml of sterile phosphate-buffered saline (PBS) intraperitoneally containing 0.38% sodium citrate (Kullberg et al., 1993). After washing, the cells were resuspended in culture medium in 96-well microtiter plates (Greiner, Alphen, The Netherlands) at 10⁵ cells/well, in a final volume of 200 μl. The cells were stimulated with either control medium or heat killed C. albicans at 1 × 10⁷ microorganisms/ml. After 24 h of incubation at 37°C,
the plates were centrifuged (500 g, 10 min), and the supernatants were removed. The cells were lysed with three freeze-thaw cycles. Samples were stored at -80°C until cytokine assays were performed.

To assess cytokine production in splenocytes, spleen were gently squeezed into a sterile 200 mm filter chamber. The cells were washed and resuspended in RPMI 1640, counted in a Bürker chamber and adjusted to 5 × 10^6/ml. 200 μL of the cell suspension was stimulated with 1 × 10^7 heat-killed C. albicans/ml. Measurement of TNFα and IL-6 concentrations was performed in supernatants collected after 48 h of incubation at 37°C in 5% CO₂ in 48-well plate.

**CYTOKINE ASSAYS**

TNFα was determined by specific radioimmunoassay (detection limit 20 pg/ml), as previously described Netea et al. (1996). IL-6 concentrations were determined by a commercial ELISA (Biosource, Camarillo, CA, USA, detection limit 16 pg/ml), as previously described Netea et al. (1996). The number of viable counts. Subsequently, the mice were sacrificed by cervical dislocation and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and conidia. After 2 h the mice were anesthetized with isoflurane and blood samples were obtained for measurement of blood cells and condia...
mice had died by day 10 in the hIL-37Tg group (Figure 1A). The fungal burden in the kidneys, the target organ of disseminated candidiasis in mice (Spellberg et al., 2005), was not significantly different at day 3 (mean ± SD; WT: 3.6 ± 0.83, IL-37Tg 3.8 ± 0.44 log CFU/g kidney), and 1-log higher in the hIL-37Tg mice than in WT mice on day 7 of infection ($p < 0.05$; Figure 1B). Histology revealed an accumulation of Candida in the pyelum of the kidneys of hIL-37Tg mice which was not observed in the WT mice (Figure 1C).

**NEUTROPHIL RECRUITMENT AND PHAGOCYTOSIS AND KILLING OF C. albicans**

In order to understand the enhanced lethality and greater fungal burden of the hIL-37Tg mice, we investigated the dynamics of the influx and function of neutrophils. Peritoneal cells were harvested and counted 4 h after intraperitoneal injection of heat-killed Candida. A significant lower influx of neutrophils was apparent 4 h after challenge with heat killed Candida in the hIL-37Tg mice compared to WT mice (Figure 2A). Phagocytosis of C. albicans by hIL-37Tg cells was similar to that by cells of WT mice (37 vs. 39% phagocytized in 15 min; $p > 0.05$). hIL-37Tg cells killed 92% of phagocytosed Candida blastoconidia after 3 h, which was not different from the killing activity of cells from WT cells (88%, $p > 0.05$, Figure 2B).

To assess whether the decrease of neutrophils within the first hours has a significant biological effect, we investigated the difference of fungal burden between neutrophil depleted mice and non-neutrophil depleted mice in a short in vivo Candida infection model. The lack of neutrophils at the site of infection resulted in a log increase in fungal growth within 2 h compared to mice in which neutrophil influx was normal (Figure 2C). These differences support the importance of early influx of neutrophils in restricting Candida growth in vivo.

**IL-37 INHIBITS PROINFLAMMATORY CYTOKINE PRODUCTION BY MACROPHAGES AND SPLENOCYTES STIMULATED WITH C. albicans**

To investigate the inhibitory effect of IL-37 at the level of cytokine production, resident peritoneal macrophages, or naïve splenocytes of hIL-37Tg and WT mice were exposed to heat-killed C. albicans blastoconidia and pseudohyphae in vitro. Cytokine production by unstimulated macrophages of each mouse strain was below the detection limit for TNFα and IL-6. However, after stimulation with C. albicans pseudohyphae, the production of TNFα was significantly lower in macrophages from the hIL-37Tg mice compared to cells from WT mice. There were no differences in the production of IL-6 in the same cultures (Figure 3).

**hIL-37Tg MICE DISPLAY INCREASED Th17 AND IL-10 RESPONSES**

Proinflammatory T helper responses such as Th1 and Th17 responses play an important role in fungal host defense (Gow et al., 2012). The Th17 response during disseminated fungal infection can be both protective and detrimental (Huang et al., 2004; Zelante et al., 2007; Lin et al., 2009). To study the impact of IL-37 on proinflammatory adaptive immune responses, we investigated the Th1 and Th17 characteristic cytokines IFNγ and IL-17. Splenocytes isolated from hIL-37Tg mice with a higher fungal burden at day 7 produced significant more IL-17 in response to C. albicans pseudohyphae (Figure 4). IFNγ production in response to C. albicans pseudohyphae was undetectable in WT and hIL-37Tg splenocytes at day 7 (Figure 4). Since IL-37 mainly has anti-inflammatory effects (Nold et al., 2010; Boraschi et al., 2011), we investigated levels of IL-10 in cells from IL-37Tg There was no significant difference in IL-10 production in splenocytes from hIL-37Tg compared to WT cells in response to C. albicans, although hIL-37Tg mice showed a trend toward an increased IL-10 production (Figure 4).

**DISCUSSION**

In the present study, we demonstrate that overexpression of IL-37 is detrimental for the early host defense against C. albicans in a murine model of disseminated candidiasis. This conclusion is based on the increased fungal load in the kidney, the target organ of disseminated candidiasis, in hIL-37Tg mice compared to WT mice. The greater outgrowth of the fungus in the tissues is most probably due to impaired early influx of neutrophils into the infected tissues, which in turn may be due to lower production of neutrophil-inducing cytokines, such as TNF. Therefore, the...
presence of IL-37 in the early stages of infection results in an impaired innate immune response that is essential to limit fungal dissemination.

Recently, several biological functions of the cytokine IL-37 have been described. IL-37 has a protective role in a murine model of lethal endotoxemia (Nold et al., 2010; Bulau et al., 2011), and it has been reported that mice overexpressing IL-37 are protected from DSS colitis (McNamee et al., 2011). These reports point to significant anti-inflammatory properties of IL-37. In the present study we extend these findings to a live infection...
model, the murine model of disseminated candidiasis, in which we assessed whether IL-37 hampers the innate immune defense against a fungal infection. We observed that mice overexpressing IL-37 were more susceptible to invasive candidiasis, due to the inability to control fungal growth in the kidney during infection. This effect is at least partly due to a defective neutrophil recruitment, a cell population central for the local antifungal host defense (Kullberg et al., 1990), and this supports the previously reported finding that leukocyte recruitment to the site of inflammation is decreased in hIL-37Tg mice (McNamee et al., 2011). The importance of neutrophils in the control of Candida outgrowth in vivo is further supported in this study by the observation that neutrophil-depleted mice have a log increase within 2 h in fungal burden compared to mice that have a normal neutrophil influx. In addition, macrophages and splenocytes overexpressing IL-37 produced significantly less TNFα than WT macrophages when exposed to C. albicans. This is in line with other studies, showing that macrophages from hIL-37Tg mice produce less TNF and that IL-37 overexpression reduces TNF-dependent inflammation in a murine model of colitis (McNamee et al., 2011). An involvement of defective TNF production in the increased susceptibility of hIL-37Tg mice to disseminated candidiasis is also consistent with earlier studies showing that mice lacking TNF or the TNF receptor are highly susceptible to disseminated candidiasis (Netea et al., 1999).

Another observation of this study is that neutrophils from hIL-37Tg mice do not display an intrinsic defect in phagocytosis and killing, suggesting that IL-37 does not directly impair neutrophil function. The increased Th17 response in hIL-37Tg mice present on day 7 most likely reflects an increased cellular immune response due to higher fungal burden (antigen) exposure. Whether this increased Th17 response has directly contributed to the higher susceptibility of hIL-37Tg mice to disseminated candidiasis remains to be determined. Interestingly, hIL-37Tg splenocytes showed a consistent trend at day 7 toward an increased production of the anti-inflammatory cytokine IL-10 when exposed to C. albicans. This observation is consistent with the increased IL-10 production found in hIL-37Tg mice with experimental colitis, and supports the concept that IL-37 can contribute to systemic anti-inflammatory effects (McNamee et al., 2011).

In conclusion, IL-37 reduces proinflammatory cytokine production induced by Candida in macrophages, and decreases neutrophil recruitment in vivo in response to C. albicans. These data highlight the potent anti-inflammatory effects of IL-37, and underline that the timing of IL-37 expression in the tissue at the site of inflammation is critical for the outcome of the host during inflammatory processes.

ACKNOWLEDGMENTS
This study was supported by the Niels Stensen Foundation and a Veni Grant of the Netherlands Foundation for Scientific Research to Frank L. van de Veerdonk. Charles A. Dinarello was supported by NIH grant AI-15614.

REFERENCES
double knock-out mice to systemic candidiasis is due to defective recruitment and phagocytosis by neutrophils. *J. Immunol.* 163, 1498–1505.


**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 28 October 2014; accepted: 15 December 2014; published online: 07 January 2015.


This article was submitted to Infectious Diseases, a section of the journal *Frontiers in Microbiology.*

Copyright © 2015 van de Veerdonk, Gresnigt, Oosting, van der Meer, Joosten, Netea and Dinarello. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.