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*J Immunol* 2011; 186:19-23; Prepublished online 6 December 2010;
doi: 10.4049/jimmunol.1002735

http://www.jimmunol.org/content/186/1/19

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**Supplementary Material**

http://www.jimmunol.org/content/suppl/2010/12/06/jimmunol.1002735.DC1

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Cutting Edge: Critical Role of Intracellular Osteopontin in Antifungal Innate Immune Responses

Makoto Inoue,* Yasuhiro Moriwaki,*,† Tomohiro Arikawa,*‡ Yu-Hsun Chen,* Young Joo Oh,* Timothy Oliver,§ and Mari L. Shinohara*†

We found that absence of osteopontin (OPN) in immunocompromised Rag2−/− mice, which lack T and B cells, made the mice extremely susceptible to an opportunistic fungus Pneumocystis, although immunocompetent OPN-deficient mice could clear Pneumocystis as well as wild-type mice. OPN has been studied as an extracellular protein, and the role of an intracellular isoform of OPN (iOPN) is still largely unknown. In this study, we elucidated the mechanism by which iOPN was involved in antifungal innate immunity. First, iOPN was essential for cluster formation of fungal receptors that detect Pneumocystis, including dectin-1, TLR2, and mannose receptor. Second, iOPN played a role as an adaptor molecule in TLR2 and dectin-1 signaling pathways and mediated ERK activation and cytokine production by zymosan, which simultaneously activates TLR2 and dectin-1 pathways. Third, iOPN enhanced phagocytosis and clearance of Pneumocystis. Our study suggests the critical involvement of iOPN in antifungal innate immunity. The Journal of Immunology, 2011, 186: 19–23.

Pneumocystis is an opportunistic fungal pathogen that causes serious morbidity and mortality in immunocompromised individuals. Host cells recognize Pneumocystis via pattern recognition receptors (PRRs), such as dectin-1, TLR2, and mannose receptor (MR), followed by phagocytosis, cytokine production, and killing the pathogen (1–3). These PRRs are recruited in proximity on the cell surface and cooperatively integrate their signals (4–7). However, the molecular mechanisms by which these PRRs collaborate are largely unknown.

Osteopontin (OPN) is a protein that is expressed by a variety of tissues and cell types, including macrophages, dendritic cells (DCs), NK cells, neutrophils, and T and B lymphocytes. The role of OPN in innate immunity is reflected by its protective role in infectious diseases, but only limited numbers of reports are available on the involvement of OPN in host responses against fungi (8, 9). A recent microarray study, however, showed that Opn mRNA was one of the most highly expressed transcripts 8 wk after Pneumocystis infection in alveolar macrophages from immunosuppressed rats (10). OPN has two types of isoform; secreted OPN (sOPN) and intracellular OPN (iOPN) that was recently characterized (11–17). Opn−/− mice showed attenuated resistance to a low-dose Candida albicans infection (9), but depletion of OPN by Ab in wild-type (WT) mice did not attenuate the resistance to C. albicans (9). The finding suggested that the host resistance to C. albicans is attributed to iOPN, but not sOPN, because OPN Ab only depletes sOPN.

OPN has been studied as an extracellular protein (i.e., as sOPN), and the role of iOPN is much less characterized compared with that of sOPN. Thus, current understanding on iOPN is limited, but it is known that innate immune phagocytes, such as macrophages and DCs, constitutively express high levels of iOPN (and sOPN), but T cells prefer to express sOPN (12, 14, 18). Currently, iOPN is known to participate in TLR9 signaling by interacting with MyD88 and enhances IFN-α production by plasmacytoid DCs (14). These results suggested that iOPN plays a role as a adaptor molecule in innate immune signaling pathways.

Our study demonstrated that OPN in Rag2−/− mice, which lack adaptive immunity, makes a significant difference in host resistance against opportunistic Pneumocystis fungal infection. In contrast, OPN-deficient immunocompetent mice can clear Pneumocystis, suggesting that OPN is not essential in the presence of adaptive immunity. Yet, OPN still matters in immunocompromised hosts: Patients who contract opportunistic fungal infections are immunocompromised. In this study, we demonstrated that iOPN plays a critical role in formation of fungal PRR clusters on the cell surface, in addition to iOPN’s involvement in TLR2 and in dectin-1 signaling transduction pathways as an adaptor molecule.

Materials and Methods

Animals and Pneumocystis

C57BL/6 background mice were used in this study. Opn−/− mice were a gift from D. Denhardt and S. Rittling (Rutgers University, Piscataway, NJ), and the online version of this article contains supplemental material.

Abbreviations used in this paper: DC, dendritic cell; DKO, double knockout; iOPN, intracellular osteopontin; IRAK1, IL-1R–associated kinase 1; MR, mannose receptor; OPN, osteopontin; PRR, pattern recognition receptor; ROS, reactive oxygen species; sOPN, secreted osteopontin; WT, wild-type.

Received for publication August 16, 2010. Accepted for publication November 4, 2010.

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www.jimmunol.org/cgi/doi/10.4049/jimmunol.1002735
backcrossed to C57BL/6 mice for 15 generations. *Rag2*^−/−^ mice (The Jackson Laboratory, Bar Harbor, ME) were crossed to *Opn*^−/−^ mice to generate *Opn*^−/−^ *Rag2*^−/−^ mice. All of the mice were kept in a barrier facility. This study was approved by the Duke University Institutional Animal Care and Use Committee (Durham, NC). *Pneumocystis* was obtained from American Type Culture Collection (*Pneumocystis murina*, PRA-111; Manassas, VA), propagated in vivo by infecting *Rag2*^−/−^ mice, and harvested from lungs as previously described (19).

Quantitative PCR conditions and primer sequences

mRNA expression levels were determined by using the −ΔΔCt method of real-time PCR. Quantitative PCR primers/TagMan probe for *Pneumocystis* rRNA (20) and *PCMei2* (19) are previously described. *Actb* mRNA (encoding β-actin) was used as an internal control (14).

Confocal microscopy

To evaluate colocalization of *Pneumocystis*-recognition receptors and iOPN, we stained cells with Abs against *Pneumocystis* (2A1, Santa Cruz Biotechnology, Santa Cruz, CA), MR (Biologend, San Diego, CA), dextrin-1 (Biologend), and TLR2 (Molecular Probes, Eugene, OR) with fluorophore-conjugated secondary Abs. The frequency (percentage) of cells that show clustering of iOPN and PRRs was calculated by enumerating cells that formed the cluster from at least 50 cells, which were either attached to *Pneumocystis* or had phagocytosed *Pneumocystis*.

**Immunoprecipitation, immunoblotting, and ELISA**

Immunoprecipitation was carried out with OPN Ab (2A1), followed by immunoblotting with IL-1R–associated kinase 1 (IRAK1) Ab (Assay Designs, Plymouth Meeting, PA) or Syk Ab (Biologend) with Pam3CSK4 (TLR2 ligand), respectively. To evaluate ERK activation by zymosan, peritonal macrophages from WT and *Opn*^−/−^ mice were used. To neutralize secreted OPN, we treated cells with a neutralizing Ab, AF808 phospho-ERK were detected by immunoblotting. Levels of IL-1 were evaluated by detecting CD11b and Alexa 647 double-positive cells. To evaluate ERK activation previously described (19).

Statistical analysis

Statistical analysis was evaluated using Student t tests. The criterion of significance was set as *p* < 0.05. All results are expressed as mean ± SEM.

**Results and Discussion**

**OPN-deficient *Rag2*^−/−^ mice are susceptible to spontaneous Pneumocystis infection**

Immunocompromised *Rag2*^−/−^ mice, which lack T and B cells, are susceptible to opportunistic fungal infection by *Pneumocystis*. *Opn*^−/−^ *Rag2*^−/−^ mice became sick, and under the environment that *Opn*^−/−^ *Rag2*^−/−^ mice were healthy and showing no signs of disease. *Opn*^−/−^ *Rag2*^−/−^ mice were clearly smaller in size compared with the *Opn*^+/−^ *Rag2*^−/−^ mice at 13 wk old (Supplemental Fig. 1A) and started dying at ∼10 wk of age (Fig. 1A). We performed pathology analyses on 14-wk-old mice. Although the lungs from *Opn*^+/−^ *Rag2*^−/−^ mice appeared normal (Fig. 1B, left panel), those from the *Opn*^−/−^ *Rag2*^−/−^ mice indicated typical *Pneumocystis* histopathology (i.e., foamy exudates), stained in pink with H&E, which were filling alveolar spaces (Fig. 1B, center and right panels). Lung sections of *Opn*^−/−^ *Rag2*^−/−^ mice also showed extensive inflammatory cell infiltration and lack of airway spaces (Fig. 1B). *Opn*^−/−^ *Rag2*^−/−^ mice could recruit cells into lungs (Fig. 1B), but the ability of cell recruitment did not appear to be a decisive factor to clear *Pneumocystis*, because of the high loads of *Pneumocystis* in the lungs of *Opn*^−/−^ *Rag2*^−/−^ mice (Fig. 1C).

*Pneumocystis* cannot be cultured; therefore, it is not possible to assess the fungal loads by CFU. We confirmed *Pneumocystis* loads by detecting the expression of the mitochondrial large subunit rRNA of *Pneumocystis* (22) and *Pneumocystis*-specific gene *PCMei2* (19). Four-week-old *Opn*^−/−^ *Rag2*^−/−^ (double knockout [DKO]) mice looked healthy, and the levels of the large subunit *Pneumocystis* rRNA and *PCMei2* mRNA were around the detection limit in their lungs (Fig. 1C, Supplemental Fig. 1B). However, 14-wk-old *Opn*^−/−^ *Rag2*^−/−^ mice showed much higher expression levels of both transcripts than the 4-wk-old *Opn*^−/−^ *Rag2*^−/−^ mice. This suggested that the mice developed intensive *Pneumocystis* infection. In addition to lungs, the presence of *Pneumocystis* was also detected in mediastinal (lung draining) lymph nodes from the 14-wk-old *Opn*^−/−^ *Rag2*^−/−^ mice. In contrast, lungs from single gene-deficient mice (i.e., *Opn*^−/−^ *Rag2*^−/−^ and *Opn*^+/−^ *Rag2*^−/−^ mice) at the age of 14 wk did not have detectable levels of *Pneumocystis* rRNA and *PCMei2* transcripts (Fig. 1C, Supplemental Fig. 1B), suggesting that single knockouts remained highly resistant to opportunistic *Pneumocystis* infection. The *Opn*^−/−^ *Rag2*^−/−^ mouse data suggested that OPN is not essential to protect hosts against opportunistic *Pneumocystis* when adaptive immunity is equipped. In summary, OPN plays a role to protect hosts against opportunistic *Pneumocystis* infection in immunocompromised hosts, but OPN is dispensable in the presence of adaptive immunity.

![FIGURE 1.](http://www.jimmunol.org/FIGURE1.png)

*FIGURE 1.* OPN-deficient *Rag2*^−/−^ mice are extremely susceptible to spontaneous *Pneumocystis*. A, Survival ratio of *Opn*^+/−^ *Rag2*^−/−^ mice and *Opn*^−/−^ *Rag2*^−/−^ mice. *n* = 10. B, Representative H&E staining in the lungs of 13-wk-old *Opn*^+/−^ *Rag2*^−/−^ mice and *Opn*^−/−^ *Rag2*^−/−^ mice. The image in a yellow square in the middle panel is enlarged in the right panel. Scale bars, 50 μm. Original magnification ×60. C, *Pneumocystis* rRNA was detected by quantitative PCR, normalized with β-actin mRNA. The first column (not seen) denotes *Pneumocystis* rRNA levels in lungs of 4-wk-old *Opn*^−/−^ *Rag2*^−/−^ (DKO) mice; otherwise, all the samples were from 14-wk-old mice of DKO and single KO of *Rag2*^−/−^ or *Opn*^−/−^. The last column denotes values from lung draining lymph nodes from 14-wk-old DKO mice.
Colocalization of iOPN and fungal PRRs in macrophages stimulated by Pneumocystis

Macrophages contribute to the host immune responses to Pneumocystis by phagocytosis and subsequent killing of the fungus. TLR2, dectin-1, and MR are known to play a critical role in detection and clearance of Pneumocystis (1, 3, 6, 23). Previous studies showed colocalization of the PRRs, and such physical proximity of the PRRs makes their signals integrated and synergized to enhance host responses (4–7). To evaluate involvement of iOPN in the association of fungal PRRs, we detected iOPN, TLR2, and dectin-1 or MR in WT macrophages stimulated with Pneumocystis. Thirty minutes after Pneumocystis treatment, cells showed colocalization of iOPN, TLR2, dectin-1, and MR upon contact with Pneumocystis (Fig. 2A, 2B, Supplemental Fig. 2A). In contrast, Opn<sup>−/−</sup> macrophages failed to colocalize the PRR cluster (Fig. 2C, 2D, Supplemental Fig. 2B), suggesting that iOPN is essential for PRR clustering.

To elucidate a role of iOPN in downstream signaling pathway from TLR2, we first tested whether iOPN associates with IRAK1, which is one of downstream kinases of the TLR2 signaling pathway. IRAK1 was selected because of possible interdependence between iOPN and IRAK1 from previous studies, demonstrating that iOPN and IRAK1 are required for TLR9-mediated IRF7 activation (14, 24). TLR2 stimulation with Pam<sub>2</sub>CSK<sub>4</sub>, a TLR2 ligand, induced OPN–IRAK1 association (Fig. 2E). This finding suggested the involvement of iOPN in TLR2 signaling. We also found that iOPN is involved in a dectin-1 signaling pathway by associating with Syk after stimulation with curdlan (Fig. 2F). It should be noted that whole-cell lysates include both iOPN and sOPN (i.e., OPN that are to be secreted). Yet, OPN that associates with IRAK1 and Syk is iOPN, because iOPN, IRAK1, and Syk are cytosolic proteins, but sOPN is segregated in secretory vesicles. In summary, we found that iOPN is essential for fungal PRR cluster formation and involved in signaling downstream of TLR2 and dectin-1 pathways by associating with IRAK1 and Syk, respectively.

**iOPN facilitates phagocytosis and clearance of Pneumocystis**

We next tested the requirement of iOPN in the phagocytosis of Pneumocystis. Pneumocystis labeled with Alexa 647 was cultured with WT or Opn<sup>−/−</sup> macrophages, and phagocytosis of Pneumocystis by macrophages was detected by flow cytometry. Phagocytosis was significantly reduced in Opn<sup>−/−</sup> macrophages compared with WT macrophages (Fig. 3A). We next evaluated which OPN, sOPN or iOPN, is involved in phagocytosis of Pneumocystis by Ab-mediated sOPN depletion in WT macrophages and lentivirus-mediated iOPN expression in Opn<sup>−/−</sup> macrophages. sOPN depletion with OPN Ab (AF808; 10 μg/ml) in WT cell culture treatment did not reduce phagocytic activity (Fig. 3B, left panel), but expression of iOPN in Opn<sup>−/−</sup> macrophages rescued the OPN-deficient phenotype of decreased phagocytic ability (Fig. 3B, right panel). These findings strongly suggested that iOPN, but not sOPN, was critical for the phagocytosis of Pneumocystis by macrophages.

Once pathogen is phagocytosed, ROS production is critical for its killing (25). It was reported that ROS generation is impaired in dectin-1–deficient macrophages upon stimulation with Pneumocystis (2). We found that Opn<sup>−/−</sup> macrophages had significantly reduced ROS generation (Fig. 3C, Supplemental Fig. 3B). In addition, ROS activity was not affected by treatment with OPN Ab (Fig. 3D, left panel), but lentiviral reconstitution of iOPN expression in Opn<sup>−/−</sup> macrophages induced ROS generation (Fig. 3D, right panel). The result suggests that iOPN, not sOPN, is involved in ROS generation in macrophages that phagocytosed Pneumocystis. A previous study showed that deficiency of p91<sub>phox</sub> (Nox2), a component of the Nox2 NADPH oxidase that produces ROS, did not affect tissue damage in Pneumocystis-infected CD4<sup>+</sup> T cell-depleted mice (26). Because Sasaki et al. (27)
demonstrated that Nox1 could compensate ROS generation in Nox2-deficient bone marrow macrophages/monocytes, the Nox1 NADPH oxidase may compensate resistance against Pneumocystis in Nox2-deficient mice.

We also found that Pneumocystis was not effectively killed in Opn−/− macrophages as in WT macrophages. Deficiency in killing was demonstrated by the high levels of Pneumocystis rRNA and PCM1 mRNA expression, which was detected in Opn−/− macrophages after phagocytosing Pneumocystis (Fig. 3E, Supplemental Fig. 3C). Collectively, our findings strongly suggested that iOPN in macrophages played a critical role to clear Pneumocystis by enhancing phagocytosis, ROS generation, and fungal killing.

iOPN enhances zymosan-induced cytokine production in macrophages

We next tested the requirement of iOPN in the cytokine production by macrophages stimulated with Pneumocystis. Although Opn−/− macrophages appeared to produce less IL-1β and IL-10 than WT macrophages when stimulated with Pneumocystis (Supplemental Fig. 3D), the levels of cytokines were not high enough by ELISA detection. To better assess the consequence of simultaneous stimulation of multiple receptors that detect Pneumocystis, we used zymosan, a glucan from fungal cell walls. Zymosan simultaneously ligates dectin-1 and TLR2, which are essential for the detection of Pneumocystis by host cells (5, 28–30). Although the expression levels of TNF-α and IFN-γ were not altered (Supplemental Fig. 3E), Opn−/− macrophages had significantly reduced production of both IL-1β and IL-10 (Fig. 4A) upon zymosan stimulation. Because iOPN is essential for clustering of dectin-1 and TLR2, and involved in PRR signaling as an adaptor molecule (Fig. 2), we asked whether iOPN induces the production of IL-1β and IL-10 by zymosan stimulation. iOPN expression successfully restored the production of IL-1β and IL-10 in Opn−/− macrophages (Fig. 4B), suggesting the involvement of iOPN in signal transduction pathways activated by zymosan. It is known that zymosan induces IL-10 production through ERK activation (29). Opn−/− macrophages had reduced ERK activation compared with WT macrophages (Fig. 4C), and iOPN expression in Opn−/− macrophages restored ERK activation (Fig. 4D). Collectively, our findings demonstrated that iOPN mediated signal transduction of dectin-1 and TLR2 by interacting with IRAK1 and Syk, leading to ERK-dependent cytokine production.

In conclusion, we have shown that Opn−/−Rag−/− mice are extremely susceptible to spontaneous Pneumocystis infection. iOPN is essential for generating antifungal innate immune responses in pathogen recognition, signal transduction, phagocytosis, and clearance of Pneumocystis, and cytokine production. It appears that iOPN not only clusters fungal PRRs together, but iOPN also functions as an adaptor molecule that transduces signals from PRRs (Supplemental Fig. 4). This study demonstrated a new mechanism, to our knowledge, by which a novel OPN isotype, iOPN, plays a critical role in anti-fungal responses. Lack of iOPN in the innate immune system may explain the extremely susceptible phenotype of Opn−/−Rag−/− mice to opportunistic Pneumocystis infection.

Acknowledgments

We thank Drs. Minghua Zhu, Weiguo Zhang, Xiaoping Zhong, and Hongjie Pan for technical comments and reagents, Drs. John Perfect and Joseph Heitman for discussion, and Dr. Joshua Burgess for technical comments on handling Pneumocystis.

Disclosures

The authors have no financial conflicts of interest.
References


Supplemental Fig. 1 – Involvement of OPN in resistance against Pneumocystis infection in innate immunity.

(A) Body weight of four- and 13-week old $Opn^{+/+}Rag2^{-/-}$ mice (white columns) and $Opn^{-/-}Rag2^{-/-}$ mice (black columns). $n=7$. (B) $PCMei2$ mRNA was detected by real-time qPCR, normalized with β-actin mRNA. First column denotes $PCMei2$ levels in the lungs of 4-wk old $Opn^{-/-}Rag2^{-/-}$ (DKO) mice, otherwise all the samples were obtained from 14-wk old mice of DKO, and single KO of $Rag2^{-/-}$ or $Opn^{-/-}$. The last column denotes values from the lung draining LNs from 14-wk old DKO mice.
**Supplemental Fig. 2 – iOPN is essential for PRR co-localization.**

(A) Representative confocal microscopic images of iOPN (magenta), MR (red), TLR2 (green) and DAPI (blue) staining of WT macrophages at indicated time points after co-culture with *Pneumocystis*. Merged images are found in Fig. 2B. (B) Representative confocal microscopic images of dectin-1 or MR (red), TLR2 (green) and DAPI (blue) staining in *Opn−/−* macrophages 30 min after *Pneumocystis* and macrophage co-culture. Merged images are found in Fig. 2C. Scale bars = 5 µm.
Supplemental Fig. 3 – OPN induces phagocytosis of Pneumocystis, ROS generation, and fungal clearance. (A) Phagocytosis of Pneumocystis by macrophages. Macrophages (CD11b-labeled) were co-cultured with Pneumocystis (Alexa-647-labeled) for indicated duration. CD11b-gated cells were analyzed for phagocytosis of Pneumocystis by detecting Alexa-647. Alexa-647/CD11b double-positive cells over total CD11b positive cells were indicated with horizontal bars in flow cytometry panels. (B) ROS production by macrophages was evaluated 0 min (solid lines) and 60 min (broken lines) after co-culture with Pneumocystis. Cells gated on CD11b positive were analyzed with DHE staining to detect ROS. Increase of ROS activity from 0 min to 60 min is indicated in Fig. 3C as a percentage increase of MFI values. (C) Pneumocystis clearance was detected with PCMei2 mRNA in macrophages by real-time qPCR. (D) Cytokine expression detected in culture supernatants of peritoneal macrophage (1x10^7 cells/ml) stimulated with (shown as “P”) or without (indicated as “N”) Pneumocystis (5x10^6 cysts/ml). (E) Expression of TNFα and IFNγ detected in culture supernatants of WT and Opn^-/- macrophages stimulated with (indicated as “Z”) or without (indicated as “N”) 100 µg/ml zymosan for 24 hr. Macrophage culture supernatants were analyzed by ELISA. n.s.: not significant.
Supplemental Fig. 4 – Schematic model of iOPN fungal PRR clustering and signal transduction to MAPK activation. *Pneumocystis* is simultaneously detected by dectin-1, MR, and TLR2. iOPN is essential for colocalization of dectin-1, TLR2, and MR. (It is likely that TLR2 is dimerized with TLR6, but we did not include TLR6 here for simplification.) In this figure, three PRRs co-localize and detect *Pneumocystis* for efficient detection and synergistic signal transduction. iOPN associates with IRAK1 (and MyD88 (14)) and Syk when TLR2 and dectin-1 are ligated, respectively. Simultaneous stimulation of TLR2 and dectin-1 requires the presence of iOPN for ERK MAPK activation to produce cytokines.