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WP1066 suppresses macrophage cell death induced by inflammasome agonists independently of its inhibitory effect on STAT3

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The compound WP1066 was originally synthesized by modifying the structure of AG490, which inhibits the activation of signal transducer and activator of transcription 3 (STAT3) by directly targeting Janus kinases (JAKs). WP1066 exhibits stronger anti-cancer activity than AG490 against malignant glioma and other cancer cells and is regarded as a promising therapeutic agent. By screening a small library of target-known compounds, we identified WP1066 as an inhibitor of macrophage cell death induced by agonists of the NLRP3 inflammasome, an intracellular protein complex required for the processing of the proinflammatory cytokine interleukin (IL)-1β. WP1066 strongly inhibited cell death as well as extracellular release of IL-1β induced by inflammasome agonists in mouse peritoneal exudate cells and human leukemia monocyctic THP-1 cells that were differentiated into macrophagic cells by treatment with PMA. However, inflammasome agonists did not increase STAT3 phosphorylation, and another JAK inhibitor, ruxolitinib, did not inhibit cell death, although it strongly inhibited basal STAT3 phosphorylation. Thus, WP1066 appears to suppress macrophage cell death independently of its inhibitory effect on STAT3. In contrast, WP1066 itself induced the death of undifferentiated THP-1 cells, suggesting that WP1066 differentially modulates cell death in a context-dependent manner. Consistent with previous findings, WP1066 induced the death of human glioma A172 and T98G cells. However, neither ruxolitinib nor AG490, the former of which completely suppressed STAT3 phosphorylation, induced the death of these glioma cells. These results suggest that WP1066 targets cell death-modulating molecules other than those involved in JAK-STAT3 signaling.
induced by NLRP3 inflammasome agonists. We further examined the effects of WP1066 on cell death in various contexts, with a particular focus on the relationship between its cell death-modulating activity and its inhibitory effect against STAT3.

Materials and Methods

Reagents. Nigericin was purchased from Wako Chemical (Osaka, Japan). R837/imiquimod was purchased from InvivoGen (San Diego, CA, USA) and Tokyo Chemical Industry (Tokyo, Japan). WP1066, AG490 and ruxolitinib were purchased from Cayman Chemical (Ann Arbor, MI, USA). Lipopolysaccharide (LPS) and phorbol 12-myristate 13-acetate (PMA) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ac-YVAD-CMK was purchased from Peptide Institute, Osaka (Tokyo, Japan). WP1066, AG490 and ruxolitinib were purchased from Adipogen, San Diego, CA, USA. HRP-conjugated anti-mouse IgG (GE Healthcare) and HRP-conjugated anti-rabbit IgG (Cell Signaling) were used as secondary antibodies.

Cell culture. Human leukemia monocytic THP-1 cells (American Type Culture Collection, Manassas, VA, USA) were cultured in RPMI 1640 medium supplemented with 100 units/mL penicillin G and 0.1 mg/mL streptomycin containing 8% fetal bovine serum (FBS) under a 5% CO2 atmosphere at 37°C. THP-1 cells were differentiated into macrophagic cells by overnight treatment with 0.1 MC PMA. Human glioma A172 cells and T98G cells (American Type Culture Collection) were cultured in Dulbecco’s modified Eagle’s medium (DMEM) containing 8% FBS and supplemented with 100 units/mL penicillin G and 0.1 mg/mL streptomycin under a 5% CO2 atmosphere at 37°C. Mouse peritoneal exudate cells (PECs) were isolated from the peritoneal cavity of 8- to 12-week-old mice 2 days after the intraperitoneal injection of 2 mL of 4% fluid thioglycollate medium (BD Diagnostic Systems, Heidelberg, Germany) and were further cultured in RPMI 1640 medium containing 8% FBS and supplemented with 100 units/mL penicillin G and 0.1 mg/mL streptomycin under a 5% CO2 atmosphere at 37°C for overnight. Prior to stimulation with inflammasome agonists, cells were washed twice with PBS and further cultured for 4 h in Opti-MEM I Reduced-Serum Medium (Thermo Fisher Scientific, Tewksbury, MA, USA) containing 100 ng/mL LPS, which was the “priming” stimulus to induce the transcription of pro-IL-1β.

Immunoblot analysis. For immunoblot analysis of culture supernatants, culture medium was collected and centrifuged for 1 min at 1500 g before cell harvest. For adherent cells, cells were dissociated with trypsin and suspended into single cells by pipetting or passing through 23G needles. The suspended cells were centrifuged at 860 g for 3 min and resuspended in PBS. The fluorescence emitted by cells was analyzed using a BD Accuri C6 flow cytometer (BD Bioscience, Franklin Lakes, NJ, USA). To detect the level of lactate dehydrogenase (LDH) released from the cells, the Cytotoxicity LDH Assay Kit-WST (Dojindo, Kumamoto, Japan) was used according to the manufacturer’s instructions.

Cytotoxicity LDH Assay. For propidium iodide (PI) staining, 2 μg/mL PI was added to the culture medium 10 min before cell harvest. For adherent cells, cells were dissociated with trypsin and suspended in single cells by pipetting or passing through 23G needles. The suspended cells were centrifuged at 860 g for 3 min and resuspended in PBS. The fluorescence emitted by cells was analyzed using a BD Accuri C6 flow cytometer (BD Bioscience, Franklin Lakes, NJ, USA). To detect the level of lactate dehydrogenase (LDH) released from the cells, the Cytotoxicity LDH Assay Kit-WST (Dojindo, Kumamoto, Japan) was used according to the manufacturer’s instructions.

Results

WP1066 suppresses IL-1β release from macrophages. To explore the mechanism of IL-1β release from macrophages, we sought to identify target-known low-molecular-weight compounds that inhibit IL-1β release. We expected that this would be a fast approach to identify important molecules that regulate IL-1β release. We screened the effects of 365 compounds on the release of IL-1β from human leukemia monocytic THP-1 cells treated with the chemical NLRP3 inflammasome agonist R837/imiquimod. Prior to treatment with R837, THP-1 cells were differentiated into macrophagic cells by PMA treatment and then primed with LPS to efficiently induce the transcription of pro-IL-1β. We found that WP1066 was among the strongest compounds that inhibited R837-induced IL-1β release from THP-1 cells (Fig. 1a). While IL-1β was continuously released from THP-1 cells after R837 stimulation, 10 μM WP1066 completely suppressed IL-1β release during the 120-min treatment with R837 (Fig. 1b), and as little as 1 μM WP1066 suppressed IL-1β release 60 min after stimulation (Fig. 1c). Immunoblot (IB) analysis of IL-1β released into the culture supernatant of THP-1 cells revealed that WP1066 also strongly suppressed the release of IL-1β and unprocessed pro-IL-1β. Our results demonstrated that WP1066 inhibited the release of IL-1β and prevented apoptosis in macrophages.
urea (MSU) crystals and low osmolarity (treatment with 2:5 diluted Opti-MEM I Reduced-Serum Medium), all of which have been shown to act as strong NLRP3 inflammasome agonists (14–16) (Fig. 1d). These results suggest that WP1066 suppresses IL-1β release upon NLRP3 inflammasome activation from THP-1 cells.

We next examined the effect of WP1066 on PECs. WP1066 suppressed IL-1β release upon NLRP3 inflammasome activation from THP-1 cells.

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stimulation (Fig. 2a). This raised the possibility that cell death was induced by inflammasome agonists, as has been shown in the case of pyroptosis, a form of cell death mediated by the activation of caspase-1.\(^{17}\) In fact, the LDH release assay revealed that R837 strongly induced the death of THP-1 cells, an effect that was suppressed by pretreatment with WP1066 (Fig. 2b). When dead cells were detected through the cellular incorporation of propidium iodide (PI) assay, R837-induced death and the strong inhibitory effect of WP1066 on it were confirmed in THP-1 cells (Fig. 2c, upper graph). This R837-induced death was strongly inhibited by the addition of high KCl to the culture medium. High KCl is known to inhibit NLRP3 inflammasome activation and cell death by blocking K\(^+\) efflux, a common trigger of NLRP3 inflammasome activation, as confirmed by the considerable reduction in released IL-1\(\beta\) in the culture supernatant.\(^{18,19}\) (Fig. 2c, lower panel). On the other hand, the inhibition of cell death by the caspase-1 inhibitor Ac-YVAD-CMK was limited, although it effectively suppressed caspase-1 activation, as confirmed by the reduction in cleaved IL-1\(\beta\) in the supernatant (Fig. 2c). We found similar results when THP-1 cells were stimulated with nigericin (Fig. 2d). Furthermore, the R837-induced death of PECs was suppressed by WP1066, whereas it was not suppressed but rather enhanced by Ac-YVAD-CMK (Fig. 2e). These results suggest that the site of action of WP1066 is not limited to NLRP3 inflammasome activation, i.e., caspase-1 activation and that WP1066 targets the cell death-inducing machinery that does not rely on caspase-1 activity in macrophages.

**Inflammasome agonists do not induce STAT3 activation.** Because WP1066 has been characterized as a STAT3 inhibitor, we examined the activation state of STAT3 by monitoring its phosphorylation at Y705 in THP-1 cells. Whereas the basal phosphorylation of Y705 (P-Y705) was quite low in undifferentiated THP-1 cells, P-Y705 increased in a time-dependent manner in response to PMA and increased further by 4-h priming with LPS (Fig. 3a). The PMA/LPS-induced P-Y705 was attenuated by treatment with WP1066. The phosphorylation of STAT3 at S727, which has been reported to be required for the mitochondrial translocation of STAT3,\(^{20}\) did not change throughout treatment with PMA and LPS, in contrast to P-Y705. We first expected that inflammasome agonists would further activate STAT3 to facilitate NLRP3 inflammasome activation and cell death, but quite the contrary, R837

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Fig. 2. WP1066 suppresses cell death induced by inflammasome agonists. (a) Differentiated THP-1 cells were treated with 10 \(\mu\)g/mL R837 for the indicated periods. The culture supernatants (Sup) were subjected to IB analysis. (b) Differentiated THP-1 cells were pretreated with 10 \(\mu\)M WP1066 for 30 min and treated with 10 \(\mu\)g/mL R837 for 2 h. Cells were subjected to an lactate dehydrogenase (LDH) release assay. Data are shown as the mean ± SEM (n = 3). **P < 0.01, Student’s t-test, compared with the cells treated with R837 but not with WP1066. (c, d) Differentiated THP-1 cells were pretreated with 10 \(\mu\)M WP1066 (WP), 20 \(\mu\)M Ac-YVAD-CMK (YV), or 60 mM KCl for 30 min and treated with 10 \(\mu\)g/mL R837 (c) or 5 \(\mu\)M nigericin (d) for 2 h. Cells were subjected to a propidium iodide (PI) assay, and the culture supernatants were subjected to IB analysis. Data are shown as the mean ± SEM (n = 3). **P < 0.01, ***P < 0.001, Dunnett’s multiple comparison test, compared with the cells treated with R837 but not with any inhibitors. (e) Peritoneal exudate cells (PECs) were pretreated with 10 \(\mu\)M WP1066 (WP), 20 \(\mu\)M Ac-YVAD-CMK (YV), or 60 mM KCl for 30 min and treated with 10 \(\mu\)g/mL R837 for 2 h. Cells were subjected to a PI assay. Data are shown as the mean ± SEM (n = 3). **P < 0.01, ***P < 0.001, Dunnett’s multiple comparison test, compared with the cells treated with R837 but not with any inhibitors.
time-dependently decreased P-Y705 that had been induced by pretreatment with PMA and LPS (Fig. 3b). Moreover, none of other NLRP3 inflammasome agonists examined increased STAT3 P-Y705 (Fig. 3c).

WP1066 suppresses inflammasome agonist-induced cell death independently of its inhibitory effect on STAT3. We then examined the involvement of STAT3 in IL-1β release and cell death using different JAK inhibitors that have previously been shown to inhibit STAT3 activation. Ruxolitinib (INCBO18424), a well-characterized inhibitor of JAK1 and JAK2, strongly suppressed STAT3 P-Y705 but unexpectedly did not suppress IL-1β release from THP-1 cells treated with R837 (Fig. 4a). The inhibitory effect of AG490, the predecessor compound of WP1066, on R837-induced IL-1β release was much weaker than that of WP1066 (Fig. 4b). Consistent with these results, neither ruxolitinib nor AG490 suppressed the R837-induced death of THP-1 cells (Fig. 4c). Thus, the inhibitory effect of WP1066 on inflammasome agonist-induced cell death does not appear to depend on its inhibitory effect on STAT3, and WP1066 may target cell death-inducing molecules other than those involved in JAK-STAT3 signaling.

WP1066 induces the death of undifferentiated THP-1 cells. As described above, WP1066 has been shown to induce apoptosis...
in a variety of malignant cells. We thus examined whether WP1066 itself affected the viability of THP-1 cells. Whereas WP1066 exhibited no obvious toxicity on PMA-differentiated THP-1 cells, it clearly induced the death of undifferentiated THP-1 cells 6 h after stimulation (Fig. 5a). More prolonged treatment with WP1066 (for 12 h) still did not induce the death of differentiated THP-1 cells but strongly induced the death of undifferentiated THP-1 cells (Fig. 5b). These results suggest that the sensitivity of THP-1 cells to WP1066 largely depends on their differentiation state. Similar to the inhibitory effects on inflammatory agonist-induced cell death, neither AG490 nor ruxolitinib induced the death of undifferentiated THP-1 cells (Fig. 5a,b), and cell viability was not correlated with the phosphorylation state of STAT3 (Fig. 5c). Thus, the cell death-inducing activity of WP1066 may also not depend on its inhibitory effect on STAT3.

**WP1066 induces the death of glioma cells independently of its inhibitory effect on STAT3.** Given that WP1066 likely induces the death of undifferentiated THP-1 cells by targeting molecules other than those involved in JAK-STAT3 signaling, we examined whether the well-characterized cell death-inducing effects of WP1066 on glioma cells indeed were dependent on its inhibitory effect on STAT3. Whereas WP1066 consistently induced death and inhibited STAT3-P-Y705 in A172 glioma cells (Fig. 6a), it induced death but did not inhibit STAT3-P-Y705 in another glioma cell line, T98G (Fig. 6b). In addition, neither AG490 nor ruxolitinib, the latter of which completely suppressed STAT3-P-Y705, induced death in both cell lines. These results suggest that, contrary to previous findings, WP1066 induces the death of glioma cells independently of its inhibitory effect on STAT3.

**Discussion**

In this study, we found that WP1066 strongly suppressed macrophage cell death and the extracellular release of IL-1β.
induced by NLRP3 inflammasome agonists in two models of macrophages, mouse primary PECs and PMA-differentiated human THP-1 cells. IL-1β is essential for an appropriate acute inflammatory response to various pathogens and injury, but its dysregulated excess release leads to sepsis and septic shock or to chronic inflammation. Thus, the NLRP3 inflammasome is a fascinating drug target for controlling IL-1β production. It has indeed been reported that a small-molecule inhibitor of the NLRP3 inflammasome is effective in treating various autoinflammatory and autoimmune diseases. However, considering that the extracellular release of IL-1β upon cell death does not totally depend on the activation state of the NLRP3 inflammasome, regulating cell death may be the ultimate way to control IL-1β production, particularly in the case of severe inflammatory conditions, such as septic shock. In this regard, it would be interesting to see if WP1066 could also effectively suppress IL-1β production in in vivo models of inflammation.

Although cell death appears to be one of the potential ways to release IL-1β from cells, the mechanisms by which macrophage cell death is induced by various inflammatory stimuli, including NLRP3 inflammasome agonists, are still elusive. It has recently been reported that R837 activates the NLRP3 inflammasome by inducing robust reactive oxygen species through disturbing the quinone oxidoreductase NQO2 and mitochondrial complex I, but how R837 induces cell death has not been clarified. In our experiments, the caspase-1 inhibitor Ac-YVAD-CMK did not suppress the R837- or nigericin-induced death of THP-1 cells or the R837-induced death of PECs, suggesting that pyroptosis, which depends largely on caspase-1, is not a major type of cell death in these conditions. In fact, it has recently been reported that necrosis mostly contributes to IL-1β release at least from THP-1 cells. Nevertheless, caspase-1 has been proposed to induce necrosis independently of its catalytic activity, which may indeed be induced in our experiments particularly in the presence of Ac-YVAD-CMK (Fig. 2). Thus, we should further carefully examine the role of caspase-1 in macrophage cell death induced by various inflammatory stimuli. Although we concluded in this study that WP1066 suppresses inflammasome agonist-induced macrophage cell death independently of its effect on JAK-STAT3 signaling, identification of the molecules targeted by WP1066 in stimulated macrophages will shed new light on the mechanism regulating inflammatory cell death in macrophages.

The induction of death in THP-1 cells only in their undifferentiated state was an unexpected effect of WP1066. Interestingly, this cell death-promoting effect of WP1066 on undifferentiated THP-1 cells was also independent of its effect on JAK-STAT3 signaling. Although it is unknown at the present time whether the target molecules of WP1066 differ between undifferentiated and differentiated THP-1 cells, WP1066 generally targets molecules critical for the regulation of cell death regardless of cellular conditions. This difference in sensitivity to WP1066 between the two differentiation states of THP-1 cells suggests that the range of cell death-inducing stimuli differs depending on the differentiation state of the THP-1 cells. This might account for the mechanism by which activated macrophages are prone to inflammatory death when they should release intracellular cytokines such as IL-1β. WP1066 would also be a strong tool to use in exploring this issue.

The results that WP1066 induced death in two glioma cell lines, A172 and T98G, apparently independently of the activation state of STAT3 were unexpected. Of course, we need to examine many more cell types, including those other than glioma cells, to confirm our conclusion. However, this appears to provide an important caution with regard to the clinical use of this compound. In this case, neither the phosphorylation level of STAT3 nor the activity of JAKs may be suitable markers for the use of WP1066, at least in malignant glioma. Thus, identification of the WP1066 target molecules that are critical for cell death regulation would be a rather difficult but reliable approach to ensure the appropriate clinical use of this compound.

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Disclosure

The authors have no conflict of interest.