P2X₄ Assembles with P2X₇ and Pannexin-1 in Gingival Epithelial Cells and Modulates ATP-induced Reactive Oxygen Species Production and Inflammasome Activation

Shu-Chen Hung¹², Chul Hee Choi³⁹, Najwane Said-Sadier¹², Larry Johnson¹², Kalina Rosenova Atanasova³, Hanen Sellami¹²⁵, Özlem Yılmaz³⁴, David M. Ojcius¹²⁶

¹ Department of Molecular Cell Biology, University of California Merced, Merced, California, United States of America, ² Health Sciences Research Institute, University of California Merced, Merced, California, United States of America, ³ Department of Periodontology, University of Florida, Gainesville, Florida, United States of America, ⁴ Emerging Pathogens Institute, University of Florida, Gainesville, Florida, United States of America, ⁵ Department of Microbiology, Habib Bourguiba University Hospital, Medical School of Sfax, University of Sfax, Sfax, Tunisia

Abstract

We have previously reported that Porphyromonas gingivalis infection of gingival epithelial cells (GEC) requires an exogenous danger signal such as ATP to activate an inflammasome and caspase-1, thereby inducing secretion of interleukin (IL)-1β. Stimulation with extracellular ATP also stimulates production of reactive oxygen species (ROS) in GEC. However, the mechanism by which ROS is generated in response to ATP, and the role that different purinergic receptors may play in inflammasome activation, is still unclear. In this study, we revealed that the purinergic receptor P2X₄ is assembled with the receptor P2X₇ and its associated pore, pannexin-1. ATP induces ROS production through a complex consisting of the P2X₄, P2X₇, and pannexin-1. P2X₄-mediated ROS production can activate the NLRP3 inflammasome and caspase-1. Furthermore, separate depletion or inhibition of P2X₄, P2X₇, or pannexin-1 complex blocks IL-1β secretion in P. gingivalis-infected GEC following ATP treatment. However, activation via P2X₇ alone induces ROS generation but not inflammasome activation. These results suggest that ROS is generated through stimulation of a P2X₄/P2X₇/pannexin-1 complex, and reveal an unexpected role for P2X₄, which acts as a positive regulator of inflammasome activation during microbial infection.

Introduction

Innate immunity is the first line of defense used by the host against microbial infection. In human tissues, epithelial cells play a major role in innate immunity. Epithelial cells can not only form physical barriers, but also secrete inflammatory cytokines and chemokines in response to infection following recognition of microbial products by pattern-recognition receptors (PRRs), such as Toll-like receptors (TLR) and Nod-like receptors (NLR) [1–4]. These PRRs, also known as danger-sensing receptors (DSR), recognize pathogen-associated molecular patterns (PAMPs) and danger signals [5–7]. Some PAMPs like lipopolysaccharide (LPS), peptidoglycan, lipoteichoic acid, flagellin, and microbial nucleic acids induce pro-IL-1β and pro-IL-18 expression and intracellular accumulation [8,9]. However, the maturation and secretion of these cytokines requires a danger signal like ATP or uric acid crystal, which comes from stressed or infected cell and leads to the activation of inflammasomes [10–13].

Inflammasomes are large multiprotein complexes that act as a caspase-1-activating platform for IL-1β and IL-18 maturation. They can be categorized by the composition of their integral PRR family member, which acts as a scaffold protein that contributes to caspase-1 recruitment, clustering, and auto-activation [12–17]. The best characterized inflammasome is the NLRP3 inflammasome. It contains NLRP3 as a scaffold protein, an apoptosis-associated speck-like protein containing a caspase recruitment domain (ASC) adaptor, and caspase-1 [18,19]. Danger-associated molecular patterns (DAMPs), such as extracellular ATP, can activate the NLRP3 inflammasome through ATP-gated P2X₇ ion channels [11,12,20]. Upon ATP stimulation, the P2X₇ receptor opens a cation channel, which permits K⁺ efflux, and gradually forms a larger pore on the membrane by recruiting the hemichannel pannexin-1 to activate the NLRP3 inflammasome [21–23]. Although P2X₄ is also an ATP-gated ion channel, it has
not been previously described to participate in ATP-mediated caspase-1 activation.

Several downstream mechanisms have been proposed to induce NLRP3 inflammasome activation, including reactive oxygen species (ROS) production, lysosomal destabilization, K+ efflux, and apoptosis [12,24–26]. In particular, ATP stimulation of cells has been shown to induce caspase-1 activation following ROS production, and treatment with the P2X7 antagonist, oxATP, attenuates ATP-induced ROS generation [12,27–32]. In addition to P2X7 agonists, agonists of other purinergic receptors also promote ROS generation, implying that other purinergic receptors may also contribute to ATP-induced ROS production [31,33,34]. However, until now, no other purinergic receptor has been implicated in ATP-induced activation of the NLRP3 inflammasome other than P2X7.

Gingival epithelial cells (GEC) represent the first barrier to infection and are a prominent component of the innate immune system in the oral cavity. The GEC are also targets of infection, and can be infected by common periodontopathogens such as Porphyromonas gingivalis, Tannerella forsythia, and Actinobacillus actinomycetemcomitans [35–38]. Previously, we showed that P. gingivalis-infected GEC overexpress pro-IL-1β, but secretion of the cytokine requires a second stimulus, such as treatment with exogenous ATP, to activate caspase-1 through the NLRP3 inflammasome [34,39]. Characterizing the cell signaling events activated by pathogens in GEC provides potential candidates to control inflammatory responses associated with periodontal disease. However, the molecular mechanisms by which the GEC respond to bacterial infections remain to be elucidated. Thus, we here investigate which purinergic receptors contribute to ATP-induced ROS production and inflammasome activation in GEC, and reveal an unexpected modulatory role for P2X4.

Materials and Methods

Cells and Chemical Reagents

Porphyromonas gingivalis ATCC 33277 was cultured anaerobically for 24 h at 37°C in trypticase soy broth (TSB) supplemented with yeast extract (1 mg/ml), hemin (5 µg/ml) and menadione (1 µg/ml) and used for infection as described [34]. The human immortalized gingival keratinocyte (HIGK) cell line [40], was obtained as previously described [40,41]. Cells were cultured in serum-free defined keratinocyte-SFM (Gibco) at 37°C in a humidified incubator containing 5% CO₂.

Primary GEC were obtained after oral surgery from healthy gingival tissue as previously described [42]. Cells were cultured as monolayers in serum-free keratinocyte growth medium (KGM) (Lonza) at 37°C in 5% CO₂. Primary GEC were used for experimentation at ~75–80% confluence and cultured for 24 h or...
48 h before infection with *P. gingivalis* at a multiplicity of infection (M.O.I.) of 100 [34].

ATP, ADP, UTP, oxATP, PPADS, and probenecid were from Sigma-Aldrich. AMP was from Santa Cruz Biotech. 5-BDBD was from Tocris Bioscience. All primers were purchased from Fisher Scientific. Antibodies against P2X4 (APR-002) and P2X7 (APR-008) were obtained from Alomone Labs.

**RNA Extraction, Reverse Transcription PCR, and Quantitative PCR**

Total RNA was isolated from 10⁶ HIGK cells using RNeasy Mini kit (Qiagen) according to the manufacturer's protocol. cDNA was amplified from 2 µg RNA by random hexamers using TagMan Reverse Transcription Reagents kit (Applied Biosystems). The following primers were used in PCR: 5'-GGGCTTTTCTCTCTGAGTATGA-3' and 5'-AGA- TAAAGCCCCCACCTTTTTTACG-3' for P2X1; 5'-GCCCTACCCGATCCGCAT- TCGGCTGAAC-3' for P2X2; 5'-GCTGGACCATTGAGG- GATCA-3' and 5'-GAAAACCCACCTACAAAGTAGGA-3' for P2X3; 5'-CCTTGCTTGTCCACCT- CAGGTACTC-3' and 5'-CCAGGAGATACGTTGTGCTCAA-3' for P2X4; 5'-CTGGCTTGTCCATTCGA-3' and 5'-GCAGGCCC- CACCTTTTGT-3' for P2X5; 5'-AGGC- CAGTGTGTGGTGTTCA-3' and 5'-TCTCCACTGGGAC- CAACTC-3' for P2X6; 5'-

![Figure 2. Synergistic effects of NADPH oxidase and mitochondria in ROS production.](image-url)
Figure 3. Involvement of P2X$_4$, P2X$_7$, and pannexin-1 in ATP-mediated ROS generation. (A) Total RNA from immortalized GEC was extracted and reversed transcribed (RT) to cDNA. The cDNA was used to perform PCR with the primers specific for the indicated genes, and the PCR products were finally visualized by EtBr staining. (B) GEC were treated with 100 μM or 3 mM ATP as indicated for 1 hour, and ROS production was measured with DCF staining and visualized by fluorescence microscopy. Quantification of the fluorescence in three independent experiments with SD is shown in (C). (D–E) ROS production was measured by DCF staining in GEC stimulated under different conditions. GEC were left untreated or stimulated with 20 μM nigericin or 3 mM ATP for 1 hour followed by fluorescence microscopy. Diminished ROS generation by different receptor antagonists was examined by pretreating cells with 100 μM oxATP for 30 minutes, 1 mM probenecid for 10 minutes, or 50 μM 5-BDBD or 100 μM PPADS for 15 minutes, followed by 3 mM ATP stimulation for 1 hour.

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Figure 4. Diminished ATP-induced ROS production due to depletion of P2X$_4$ or P2X$_7$ by RNA interference. (A) Immortalized GEC were transduced with lentiviruses carrying the indicated shRNA-expressing plasmid for 1 day and selected with puromycin. After selection, cells were collected and total RNA was analyzed by qPCR to confirm knockdown efficiency. (B) DCF staining of ROS production after 3 mM ATP stimulation for 1 hour in different cell lines. The fluorescence shown in (C) was quantified as in Figure 1 and normalized to shCtrl, which was transduced with control, non-mammalian shRNA.

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method, as described by the manufacturer (Stratagene). The primers for the genes coding P2X4, P2X7, and pannexin-1 were as above. For GAPDH, the primers were: 5'-TTAAG-CACGCCCTGTGAC-3' and 5'-CTCTGTCFTCTCCTGTTCGAC-3'.

**Lentiviral Infection of HIGK Cells**

Immortalized GEC (HIGK) stably expressing shRNA against P2X4 (TRCN0000044960 and TRCN0000044962), P2X7 (TRCN0000045095 and TRCN0000045097), and pannexin-1 (TRCN0000156046 and TRCN0000155348) were generated by transducing the cells with lentiviral particles purchased from Sigma-Aldrich. Transduction was performed following the manufacturer’s instructions. Nontarget shRNA control cells were also generated using an irrelevant sequence (SHC002V, Sigma). Briefly, GEC were plated at 70% confluency 24 h prior to transduction, and the corresponding lentiviral transduction particles were added at M.O.I. of 3 overnight. Fresh media was added the next day, and stably infected cells were selected by addition of media containing 5 μg/ml puromycin (Sigma-Aldrich).

**Transient RNA Depletion with Sirna in Primary GEC**

Expression of P2X4 and P2X7 in primary GEC was repressed with different siRNA sequences as previously described [43]. The siRNA sequences were: 5'-GCUUUCAACGGGUCUGUCATT-3’ and 5'-UGACAGACCCGUUGAGGCTA-3’ for P2X4 (Ambion, LifeCell Technologies, S9957, Cat. #: 4392420); and 5'-ACAAUUGUAGAAACGACUCUGAT-3’ for P2X7 (27 mer siRNA duplexes OriGene Technologies, Cat. #: SR303325). Briefly, cells were treated with siRNA using Glycofect Transfection Reagent (Kerafast) mixed with 10 nM siRNA (stock concentration of siRNA was 20 nM) in a total volume of 100 μl. Four hours later, new cell-medium was added to the cells without removal of the transfection mixture, and cells were incubated for 36 hours. qPCR was performed to confirm the knockdown efficiency and specificity, as previously shown [44].

**ROS Measurement**

ROS measurement was assayed with the ROS indicator dyes, CM-H2DCFDA DCF and MitoSOX (Invitrogen), as described previously [43,45]. In brief, cells were loaded with 2.5 μM DCF or 5 μM MitoSOX in PBS for 30 min at 37°C, washed with PBS, and treated with 100 μM or 3 mM ATP for 1 h at 37°C. Cells were counter-stained with Hoechst33342 in order to reveal the nucleus. Finally, the cells were observed by wide-field fluorescence microscope (Leica, Deerfield, IL).

**Measurement of Caspase-1 Activation by ELISA**

GEC were treated with 100 μM or 3 mM ATP for 3 h and supernatants were collected and subjected to human caspase-1 immunoassay (R&D) according to manufacturer’s instructions. In brief, the caspase-1 ELISA uses monoclonal and polyclonal antibodies specific for the caspase-1 p20 subunit as capture and detection antibodies, respectively. One hundred μl of supernatant were first mixed with 50 μl of RD1W buffer and loaded onto caspase-1 monoclonal antibody coated-wells for 1.5 hrs. One hundred μl of caspase-1 antiserum was then used as detection antibodies. Anti-rabbit IgG-HRP conjugate was used for quantification. Activated caspase-1 was measured using a plate reader at 450 nm with wavelength correction at 540 nm.
Figure 6. Abrogation of ATP-induced IL-1β secretion in *P. gingivalis*-infected GEC by inhibition of P2X4, P2X7, or pannexin-1. Primary GEC (C and D) and immortalized GEC (A and B) were infected with or without *P. gingivalis* (*P.g.* ) at an M.O.I. of 100 for 6 hours, followed by treatment with different pharmaceutical agents. Infected cells were treated with 100 μM ATP, 3 mM ATP, 3 mM ADP, 3 mM AMP, or 3 mM UTP individually for 1...
Measurement of IL-1β Secretion by ELISA

Secretion of IL-1β was measured using a commercial cytokine ELISA kit (BD Biosciences Pharmingen) as described [39].

Co-Immunoprecipitation of Purinergic Receptors

Co-immunoprecipitation was performed with Dynabeads (Invitrogen) according to the manufacturer’s instructions. Cells were lysed with the extraction buffer, and cell extracts were incubated for 3 h at 4°C with beads pre-coupled overnight with P2X4 antibody. Precipitates were washed with extraction buffer and LWB with the use of a magnet and were subjected to 2X sample buffer and heated to 99°C for 10 min. The eluted proteins were analyzed by Western blot as previously described [46].

Results

ATP Induces ROS Generation in GEC

It has been shown stimulation with ATP results in high levels of ROS generated in alveolar macrophages and primary GEC [27,34]. In order to characterize ATP-induced ROS production in GEC, we used a stable GEC cell line, the human immortalized gingival keratinocyte cell line (HIGK) [40], stained with carboxy-H2DCFDA (DCF), which remains nonfluorescent until its deacetylation and oxidation. Fluorescence microscopy images showed a significant increase of DCF fluorescence in 3 mM ATP stimulated HIGK cells (Figure 1A). Quantitative analysis of fluorescence microscopy data showed that the fluorescence in ATP-treated cells was about 9 times higher than in cells without treatment. Furthermore, the cells responded quickly to ATP stimulation within 5 minutes and reached a steady state from 30 minutes to at least 3 hours (Figure 1, B and C). Treatment with other extracellular nucleotides such as ADP, AMP, or UTP was unable to induce significant ROS generation in the cells (Figure 1C). These results suggest that stimulation with ATP, unlike other nucleotides, can induce ROS production in GECs.

Synergetic Effects of NADPH Oxidase and Mitochondria During ROS Generation

Two possible sources of ROS that activate the inflammasome have been described. One may be due to activation of nicotinamide adenine dinucleotide phosphate (NADPH) oxidase, triggered by frustrated phagocytosis [47]. The other may due to the main intracellular source of ROS, the mitochondria [30]. Recent studies have uncovered the existence of cross-talk between the NADPH oxidase and mitochondria [48]. In GECs, it was demonstrated that ATP induces both cytosolic and mROS production (Choi, 2013). To verify whether NADPH oxidase-induced ROS by ATP may modulate mROS production in GECs, we measured ATP-induced mROS generation after inhibiting NADPH oxidase with diphenyleneiodonium chloride (DPI), which was previously shown to block caspase-1 activation [49]. As shown in Figure 2A and B, DPI profoundly attenuated ATP-triggered cytosolic ROS production, as detected by DCF, confirming that ATP treatment induces ROS through NADPH oxidase. To examine if NADPH oxidase could also modulate ATP-induced mROS production, we used MitoSOX to detect superoxide in mitochondria. Quantitative analysis of fluorescence micrographs confirmed that ATP treatment also triggers mROS production, in agreement with previous results [45]. The increase of mROS can be partially inhibited by DPI, implying that NADPH oxidase plays a significant role in mROS generation (Figure 2, A and B). Taken together, these results suggest that ATP-induced NADPH activation can synergistically promote mROS production in GECs.

Figure 7. Model showing the role of P2X4 and P2X7 in ROS production and inflammasome activation in GEC stimulated with extracellular ATP.

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Purinergic Receptors Involved in ATP-induced ROS Generation

It has been proposed that extracellular ATP induces ROS production through ligation of the ATP-gated P2X7 ion channel, in association with the pore-forming hemi-channel, pannexin-1, in macrophages and neurons [19,21,50]. To investigate whether ATP-induced ROS production in GEC takes place through P2X7, we examined the gene expression levels of purinergic receptors in HIGK cells. In agreement with our previous description of primary GEC [51], the HIGK cells express P2X7 through P2X4. In addition, the HIGK cells express pannexin-1 (Figure 3A).

P2X7- and pannexin-1-dependent responses in HIGK cells were next examined by fluorescence microscopy (Figure 3B). Consistent with previous results, 3 mM ATP stimulated a large level of ROS production, suggesting that ATP mediates ROS production through P2X7 ligation (Figure 3, B and C). A role for P2X7 was further confirmed by showing that ATP-induced ROS production was inhibited by pretreatment with the potently P2X7 antagonist, 5-BDBD. As shown in Figure 3E, pretreatment with 5-BDBD significantly blocked ATP-induced ROS generation. Taken together, these results suggest that P2X7 may be involved in ATP-induced ROS generation in GEC.

Unexpectedly, treatment with 100 μM ATP also elicited ROS generation but to a lower extent than with 3 mM ATP (Figure 3, A and B). P2X4 is considered to mediate high affinity responses to ATP stimulation, at lower concentrations than for P2X7 [31,33,32,33]. Thus, these results suggested that P2X4 may be involved in ATP-mediated ROS production. To test this possibility, we pretreated cells with the potent P2X4 antagonist, probenecid, also abrogated IL-1β secretion by infected cells (Figure 6C). We further confirmed a role for P2X4 in IL-1β secretion, even though the cells were treated with 3 mM ATP, which stimulates signaling via P2X7 (Figure 6B and D).

Confirmation by RNA Interference for Role of P2X4 and Pannexin-1 in ATP-Mediated ROS Production

As inhibitor studies suggested that P2X4 may be involved in ATP-dependent ROS responses, we examined this unexpected result by stably depleting P2X4, P2X7, and pannexin-1 by lentiviral delivery of specific siRNA. Specific depletion efficiency in each cell line was validated individually by qPCR, as we have previously shown with this concentration of ATP was not sufficient to activate the inflammasome. However, 100 μM ATP stimulation induced ROS generation through P2X7 ligation, but stimulation with this concentration of ATP was not sufficient to activate the inflammasome.

The non-redundant roles of P2X4 and P2X7 in ATP-induced ROS generation led us to hypothesize that P2X4 and P2X7 may be associated in the membrane and function as a physical complex in ATP-mediated responses in GEC. Therefore, we examined physical associations between P2X4 and P2X7 in GEC by performing co-immunoprecipitation experiments. As expected, in endogenous P2X4 using an anti-P2X4 antibody, we observed that P2X7 and pannexin-1 were detected in the immunoprecipitate (Figure 5B). Taken together, these data indicate that P2X4, P2X7, and pannexin-1 form a heterocomplex in GEC, and play non-redundant roles in ATP-induced ROS generation.

ATP Ligation by P2X4/P2X7/Pannexin-1 Complex Leads to Inflammasome Activation in GEC

We previously showed that ATP treatment of GEC leads to NLRP3 inflammasome activation [39]. As ROS production has been associated with inflammasome and caspase-1 activation [12,27,29,30], we evaluated whether ATP-mediated caspase-1 activation in GEC takes place through P2X4/P2X7 ligation. Using ELISA to measure secretion of activated caspase-1, we observed that treatment of GEC with 100 μM ATP was insufficient for caspase-1 activation, even though ROS generation was induced. In contrast, 3 mM ATP treatment resulted in high levels of caspase-1 activation in GEC stably-expressing the control siRNA (Figure 5A); but the activation of caspase-1 by 3 mM ATP treatment was abrogated when either P2X4 or P2X7 were depleted in GEC (Figure 5A). Thus, treatment with 5 mM ATP induced ROS production via the P2X7/P2X7 complex and activated the NLRP3 inflammasome. However, 100 μM ATP stimulation induced ROS generation through P2X7 ligation, but stimulation with this concentration of ATP was not sufficient to activate the inflammasome.

P2X4 Modulates ATP-Induced Inflammasome Activation

Previously we had reported that infection of GEC with P. gingivalis leads to expression of pro-IL-1β and its accumulation within the infected cell. However, secretion of IL-1β requires a second signal, such as the danger signal ATP, in order to activate the NLRP3 inflammasome and caspase-1, allowing processing and secretion of IL-1β [39].

Given the unexpected observation that P2X4 can modulate ATP-dependent caspase-1 activation in the immortalized HIGK cells, we examined whether a similar effect could be observed in immortalized (HIGK) cells and primary GEC during infection with P. gingivalis. As in our previous studies, neither P. gingivalis infection alone nor infection combined with 100 μM ATP treatment could induce IL-1β secretion by HIGK cells. Only infected cells treated with 3 mM ATP, but not other nucleotides, could promote IL-1β secretion (Figure 6A). Similarly, using primary GEC, we found that ATP, but not other nucleotides, could promote IL-1β secretion by infected cells (Figure 6C). We also consistently observed that primary GEC produce and secrete higher levels of IL-1β than HIGK cells (Figure 6).

Furthermore, pretreatment of infected HIGK or primary GEC with the P2X7 antagonists, PAMP4 and oxATP, blocked ATP-dependent IL-1β secretion. In addition, the pannexin-1 inhibitor, probenecid, also abrogated IL-1β secretion. Finally, inhibition of P2X4 by 5-BDBD reduced the amount of IL-1β secretion, even though the cells were treated with 3 mM ATP, which stimulates signaling via P2X7 (Figure 6B and D).

To further confirm a role for P2X4 and P2X7 in IL-1β, we used siRNA to deplete P2X4 and P2X7 in primary GEC individually. (In our hands, siRNA treatment is more effective than shRNA delivery for RNA interference in primary GEC.) Figure 6E showed that P2X4 or P2X7 mRNA levels were depleted with an efficiency of over 80% in primary GEC. Similarly to our previous results [39], P. gingivalis infection followed by 3 mM ATP treatment caused IL-1β secretion by the primary GEC that had been treated with control siRNA. However, depletion of P2X4 or
P2X4 reduced significantly IL-1β secretion, which again showed a non-redundant role for P2X4 and P2X7 in ATP-dependent IL-1β secretion. Probenecid treatment prior to ATP stimulation repressed even further the IL-1β secretion in P2X4 and P2X7 knockdown cells, consistent with a role for pannexin-1 in IL-1β secretion by primary GEC. All these results imply that a P2X4/P2X7/pannexin-1 complex is required for IL-1β secretion in response to ATP treatment of P. gingivalis-infected cells.

Discussion

Our results show that P2X4, P2X7, and pannexin-1 contribute to ROS generation and are associated with inflammasome activation in GEC. Consistent with this possibility, previous studies have suggested that P2X4 and P2X7 may behave as heterometric receptors on bone marrow derived macrophages (BMDM) [54,55]. Similarly, ATP-induced cell death of mouse macrophages was shown to involve the P2X7 receptor, initiating Ca2+ influx upon stimulation with ATP and contributing to pore formation by activation of the P2X7 receptor [56,57]. These findings suggest the functionality and dependence of the P2X4 and P2X7 receptors on each other.

In GEC, we found that extracellular nucleotide-induced ROS production occurred within a few minutes and was specific for ATP stimulation. We then characterized expression of possible target receptors and tested whether specific inhibitors for these receptors could block ROS generation. Inhibitors of P2X4, P2X7, and pannexin-1 reduced significantly ATP-dependent production of ROS. To further evaluate the functionality of the receptors, we depleted either purinergic receptor or pannexin-1 by RNA interference, and find that both purinergic receptors and pannexin-1 are required for efficient ATP-induced ROS production in primary or immortalized GEC. Our findings differ from another study, which showed that depletion of the P2X4 receptor increased ATP-mediated ROS production in the macrophage cell line, RAW264.7 cells [56,57]. The conflicting results may be attributed to different cell lines, but we also used primary GEC and found similar results as with the HIGK cells. It has been proposed that either DAMPs or PAMPs could trigger ROS production, which leads to NLRP3 inflammasome activation [19]. However, the intracellular origin of ROS remains debated. Previous studies demonstrated that inhibiting NADPH oxidases with pharmacological inhibitors such as DPI or depletion by siRNA significantly decreased caspase-1 activity and IL-1β in matured macrophages stimulated with DAMPs or PAMPS, indicating that NADPH oxidase-elicited ROS play a role in inflammasome activation [47,58-60]. Subsequently, another intracellular source of ROS, mitochondria, was also reported to activate NLRP3 in response to DAMPs or PAMPS by inducing oxidation and release of mitochondrial DNA [30,61,62]. In GECs, a recent study demonstrated that ATP stimulation results in NADPH-induced ROS generation via P2X7 ligation which also promotes mROS generation, indicating that NADPH oxidase and mitochondria produce ROS synergistically [45]. Consistent with these findings, we showed that inhibition of NADPH oxidase also decreased oATP-induced mROS generation.

Our studies show that pannexin-1 is indispensable for ATP-induced NLRP3 activation in GECs. However, recent genetic evidence showed normal NLRP3 inflammasome function in macrophages derived from Panx1-deficient mice [63,64]. This discrepancy may be explained by assuming that pannexin-1 plays a different role in different cell types. For example, in neurons, pannexin-1 is involved in inflammasome-induced cell death, as shown through the use of pannexin-1 depletion and Panx1-deficient mice [65-67].

We have previously reported that treatment of GEC with ATP concentrations that stimulate P2X4 leads to activation of the inflammasome and caspase-1 [39]. However, we now find that depletion of either P2X4 or P2X7 results in decreased caspase-1 activation in GEC. ROS is produced when either P2X4 or P2X7 are stimulated, but caspase-1 is activated only when GEC are treated with ATP concentrations that activate P2X7. Similarly, IL-1β secretion from P. gingivalis-infected cells, which requires caspase-1 activation, could be induced by treatment of the infected cells with ATP concentrations that stimulate P2X7, but inhibiting or depleting either P2X4 or P2X7 resulted in significantly lower levels of IL-1β secretion.

Taken together, these results suggested that P2X4 stimulation may not be sufficient for activation of caspase-1, but P2X7 may form a complex with P2X7, which could explain why P2X4 depletion results in loss of P2X7-mediated signaling. We confirmed this hypothesis by demonstrating by co-immunoprecipitation experiments that P2X4 is physically associated with P2X7 and pannexin-1 in GEC. P2X4 and P2X7 have been previously shown to also form heterometric receptors in BMDM [54]. Thus, these results suggest that P2X4 stimulation is required for caspase-1 activation, but P2X7, through its presence in the P2X4/P2X7/pannexin-1 complex, modulates the activity of P2X7 (Figure 7). Here, we provide an initial insight into how signaling through P2X4, P2X7, and pannexin-1 may activate caspase-1 in GEC. The same complex is involved in secretion of IL-1β from GEC that had been primed by P. gingivalis infection. Thus, understanding the triggers for P2X4-dependent ROS generation and caspase-1 activation could aid in drug discovery and development of therapeutic approaches for diseases associated with P. gingivalis, such as periodontal disease and cardiovascular disease.

An obvious question is the intracellular source of ROS in GEC following P2X4 or P2X7 stimulation, which could be from mitochondria and/or the NADPH oxidase on the plasma membrane [34]. A larger challenge may be to identify the molecular mechanisms that allow caspase-1 to be activated only after P2X7 stimulation, even though both P2X4 and P2X7 ligation leads to ROS production.

Author Contributions

Conceived and designed the experiments: OY DMO. Performed the experiments: SCH CHC NSS LJ KRA HS. Analyzed the data: SCH CHC. Contributed reagents/materials/analysis tools: OY DMO. Wrote the paper: SCH DMO.

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