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NLRP3 Inflammasome in Cancer and Metabolic Diseases

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Abstract

The NLRP3 inflammasome is a multimeric cytosolic protein complex which assembles in response to cellular perturbations. This assembly leads to the activation of caspase-1, which promotes maturation and release of inflammatory cytokines, interleukin (IL)-1 β and IL-18, and inflammatory cell death, pyroptosis. The inflammatory cytokines contribute to the development of systemic low-grade inflammation, and aberrant NLRP3 activation can drive a chronic inflammatory state in the body to modulate the pathogenesis of inflammation-associated diseases. Therefore, targeting NLRP3 or other signaling molecules downstream, such as caspase-1, IL-1 β , or IL-18, has the potential for great therapeutic benefit. However, NLRP3 inflammasome-mediated inflammatory cytokines play dual roles in mediating human disease. While they are detrimental in the pathogenesis of inflammatory and metabolic diseases, they have a beneficial role in numerous infectious diseases. Therefore, fine tuning of NLRP3 inflammasome activity is essential for maintaining proper cellular homeostasis and health. In this review, we will cover the mechanisms of NLRP3 inflammasome activation and its divergent roles in the pathogenesis of inflammation-associated diseases such as cancer, atherosclerosis, diabetes, and obesity, highlighting the therapeutic potential of targeting this pathway.

Keywords

NLRP3; inflammasome; cytokines; IL-18; IL-1 β ; inflammation; cancer; metabolic diseases; diabetes; obesity; atherosclerosis; pyroptosis; apoptosis; necroptosis; PANoptosis

1. Overview

The innate immune system recognizes pathogenic insults as well as dead and defective cells in the body to initiate protective responses¹. This recognition occurs through a set of germline-encoded pattern recognition receptors (PRRs) that sense pathogen-associated molecular patterns (PAMPs) and damage-associated molecular patterns (DAMPs)². The membrane-bound PRRs are classified into Toll-like receptors (TLRs) and C-type lectin receptors. The cytoplasmic PRRs include the NOD-like receptors (NLRs), the RIG-I-like receptors (retinoic acid-inducible gene-I-like receptors, or RLRs) and absent in melanoma 2

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(AIM2). The NLRs recognize ligands from various microbial pathogens, host cells, and environmental sources. Based on their domain architecture, NLRs are subdivided into NLRPs and NLRCs. Among these, NLRP1 (mouse NLRP1b), NLRP3, and NLR family apoptosis inhibitory protein (NAIP)-NLRC4 are well established NLRs for their ability to assemble inflammasomes³.

Inflammasomes are multimeric cytosolic protein complexes that assemble in response to DAMPs and PAMPs, leading to the activation of inflammatory responses. Inflammasome assembly initiates an inflammatory form of cell death known as pyroptosis, triggering the release of proinflammatory cytokines, IL-1 β and IL-18. The NLRP3 inflammasome responds to cellular perturbations and a wide variety of microbes^{4, 5, 6, 7, 8, 9, 10}.

The role of NLRP3 varies depending upon whether it responds to sterile or microbial triggers. For example, during many infectious diseases, the NLRP3 inflammasome is protective to the host^{4, 5, 6, 7} mainly via modulating the release of inflammasome effector cytokines. However, NLRP3 has been directly associated with several inflammatory diseases and can play a dual role in the pathogenesis of metabolic diseases and cancer. Additionally, inflammasome-mediated cytokines produced mainly from the hematopoietic compartment also contribute by acting in autocrine and paracrine manners to form an inflammatory microenvironment¹¹, recruit immune cells, and interfere with insulin signaling⁹, processes that promote the development of disease. Our understanding of the mechanistic connections between NLRP3 and metabolic diseases and cancer has grown tremendously in recent years, but there remain many unanswered questions with critical therapeutic implications. This review will focus on the current understanding of the role of NLRP3 in the pathogenesis of different forms of cancer and metabolic diseases such as diabetes, obesity, and atherosclerosis.

2. Mechanism of NLRP3 inflammasome activation

NLRP3 is a cytosolic protein with three domains: a leucine-rich repeat (LRR) at the C-terminal, a central nucleotide-binding and oligomerization domain NACHT which possesses ATPase activity, and a pyrin domain (PYD) at the N-terminal¹². The basal levels of NLRP3 expression are not sufficient for NLRP3 inflammasome activation. Therefore, a two-step process of priming and activation is required for its activation^{13, 14}. The priming step is induced by TLRs and cytokine receptors such as the TNF receptor or IL-1 receptor, which recognize PAMPs or DAMPs and upregulate the transcription of *NLRP3* and *IL1B*. PAMPs and DAMPs promote NLRP3 inflammasome assembly thereby leading to caspase-1 (CASP1)-mediated inflammatory cytokine maturation and release, and pyroptosis^{15, 16}. These PAMPs and DAMPs can include either microbial activators from Gram-positive and Gram-negative bacteria, viruses, fungal, or protozoan pathogens or host-derived moieties such as extracellular ATP, uric acid crystals, calcium phosphate dihydrate, cholesterol crystals, or glucose^{4, 5, 6, 7, 8, 9, 10, 17}(Figure 1). However, in human monocytes, the priming step alone is sufficient to mediate caspase-1 activation and IL-1 β release^{18, 19}. In these cells, LPS induces the release of endogenous ATP, which then activates the P2X7 receptor to trigger NLRP3 inflammasome activation and IL-1 β maturation. An alternative NLRP3 inflammasome pathway is also activated in human monocytes in response to LPS in which

RIPK1, FADD, and CASP8 are required downstream of TLR4-TRIF signaling²⁰. However, more studies are required to fully understand the similarities and differences between NLRP3 activation in humans and mice.

Several mechanisms have been proposed for how NLRP3 inflammasome assembly is activated, and disturbances in cellular homeostasis due to diverse triggers have been suggested to cause oligomerization of NLRP3 monomers through their NACHT domains. This leads to the recruitment of apoptosis-associated speck-like protein containing a CARD (ASC) via interaction between the PYD domain of NLRP3 and the PYD of ASC²¹. The CARD domain of ASC then recruits the CARD domain of pro-CASP1 to form the NLRP3-ASC-pro-CASP1 complex, or the inflammasome²². This facilitates pro-CASP1 cleavage to form active CASP1, which then goes on to cleave IL-1 β and IL-18 into their biologically active forms. The active form of CASP1 also cleaves gasdermin D (GSDMD), which forms pores on the plasma membrane through which the biologically active forms of the inflammasome effector cytokines (IL-1 β and IL-18) are released, leading to the inflammatory form of cell death known as pyroptosis^{23, 24}. An alternative form of NLRP3 activation occurs during influenza A virus (IAV) infection. Z-DNA-binding protein 1 (ZBP1)-mediated pyroptosis and caspase-1 cleavage require the assembly of a particular form of the NLRP3 inflammasome, called the ZBP1-NLRP3 inflammasome⁶. ZBP1 recruits RIPK3 and caspase-8 to assemble the ZBP1-NLRP3 inflammasome after sensing Z-RNA during IAV infection⁶. The assembly of this inflammasome in response to IAV is crucial for host protection and is regulated by several host proteins, including molecules associated with IFN signaling and caspase-6^{5, 6}. Additionally, NLRP3 can be activated through non-canonical pathways by murine caspase-11 (CASP11) or the human homologs caspases-4 and -5. CASP11 senses intracellular LPS and cleaves GSDMD directly²⁵ (Figure 1), and the pore formation provides the signal necessary for the NLRP3 inflammasome activation.

The process of NLRP3 inflammasome activation is tightly regulated by several innate immune molecules during infection and inflammation^{26, 27, 28, 29}. Numerous positive regulators have been identified that promote NLRP3 inflammasome formation and activation. The adaptors MyD88 and TRIF contribute to the priming of the NLRP3 inflammasome³⁰. Additionally, caspase-8 and FADD mediate the priming and activation of the canonical and non-canonical NLRP3 inflammasome³¹. Also, the stress granule protein DDX3X interacts with NLRP3 to promote its activation³². Our recent studies also found that CASP6 facilitates ZBP1-NLRP3 inflammasome activation during IAV infection^{5, 6}. Several other upstream regulators that are necessary for optimal NLRP3 inflammasome activation, including SHARPIN, IRGB10, and IRF8, have also been identified^{26, 28, 29}. On the other hand, negative regulators of the NLRP3 inflammasome are also critical to prevent excessive activation and inflammation. The E3 ligase A20/TNFAIP3, which has been shown to suppress inflammation in macrophages and in a mouse model of inflammatory arthritis³³, has been reported to act as a negative regulator of the NLRP3 inflammasome. In addition, the negative regulator TGF- β activated kinase-1 (TAK1) maintains NLRP3 inflammasome quiescence and preserves cellular homeostasis²⁷ (Figure 1).

In addition to the role of innate immune molecules in regulation, the NLRP3 inflammasome is also controlled by cellular processes, such as ribosome stalling and translation

inhibition³⁴, and post-translational modifications (PTMs) of NLRP3, such as phosphorylation³⁵ and ubiquitination³⁶. PTMs are critical during the priming step to facilitate NLRP3 inflammasome activation. Additionally, recent work discovered that NEK7, a serine/threonine kinase, is also required for NLRP3 inflammasome activation^{37, 38, 39}. A cryo-electron microscopy structure of human NEK7 and inactive NLRP3 shows that NEK7 binds to the LRR and nucleotide-binding domains of NLRP3³⁹. Future studies regarding the molecular mechanism of NLRP3 activation during various infectious and inflammatory conditions are warranted to fully understand its activation mechanism.

3. NLRP3 inflammasome in cancer

Inflammation is a leading hallmark for the development and progression of cancer⁴⁰. Strong connections have been identified between inflammation and tumorigenesis, including proliferation, invasion, angiogenesis, and metastasis⁴¹. More importantly, inflammation-mediated cytokine release orchestrated by various cells within the tumor microenvironment plays a critical role in these processes⁴². Since the NLRP3 inflammasome is a central hub of innate immunity that mediates the secretion of proinflammatory cytokines, it plays a major role in the modulation of inflammatory responses by cross-talking with other cellular compartments⁴³. NLRP3 can have opposing roles in tumorigenesis. It can be tumor suppressive, which has mostly been shown in the context of colitis-associated colorectal cancer (CAC), but it can also be tumor-promoting, with these effects being more evident in other forms of cancer such as gastric and skin cancer⁴¹.

3.1 NLRP3 and human cancer

While much of our mechanistic understanding of NLRP3's roles in cancer has come from studies in mice, there is clear evidence for its physiological role in human cancers. A recent study showed that out of 24 cancers, 15 had significantly altered expression of NLRP3 inflammasome-related genes⁴⁴. NLRP3 expression is increased in cancerous plasmacytoid dendritic cells (pDCs) isolated from human lung samples of patients who had non-small cell lung cancer compared with its expression in healthy controls⁴⁵. In addition, NLRP3 is constitutively expressed and activated in human melanoma cells. These cells mediate autoinflammation via CASP1 processing and biologically active IL-1 β secretion without the presence of exogenous stimuli at the later stage of disease⁴⁶. Moreover, patients with pancreatic cancer have the rs35829419-Nlrp3 polymorphism at a greater frequency than individuals without cancer. This polymorphism may lead to excessive enzymatic cleavage of pro-IL-1 β into its active form⁴⁷. Another study found the association of the rs10733113-Nlrp3 polymorphism with sporadic malignant melanoma in Swedish patients⁴⁸. Likewise, the rs10754558 variant of NLRP3 is significantly associated with gastric cancer⁴⁹. In addition, the genetic polymorphisms IL-1 β -rs16944 and IL-18-rs1946518 were associated with pathophysiological characteristics in patients with chronic myeloid leukemia⁵⁰. Together, these findings strongly suggest that the NLRP3 inflammasome has a key role in cancer.

3.2 NLRP3 in tumor suppression

NLRP3 is expressed in both immune cells and colonic epithelial cells, suggesting a possible association of NLRP3 with colon cancer⁵¹. Several *in vivo* mouse models of colon cancer have demonstrated that NLRP3-deficient mice are hypersusceptible to azoxymethane (AOM)/dextran sulfate sodium (DSS)-induced colitis-associated colorectal cancer (CAC)^{52, 53, 54}. CAC is induced by the DNA-damaging agent AOM and the colitogenic chemical DSS. The combination of AOM with DSS accelerates tumor development and is commonly used to study inflammation-mediated colorectal cancer (CRC)⁵⁵. The protective effect of the NLRP3 inflammasome in CRC is further supported by the increased prevalence of tumors in mice lacking the adaptor ASC and CASP1 as compared with wild type (WT) mice^{52, 53, 56, 57}. However, in contrast to these findings, another study found similar tumor burden between WT and NLRP3-deficient mice in response to AOM/DSS⁵⁸. CASP1-deficient mice have increased colonic epithelial and tumor cell proliferation, which is dependent on NLRC4, but not on NLRP3. Additionally, NLRP3 inhibition via mitophagy using small molecule inhibitors prevents CAC, suggesting a detrimental role for NLRP3 in CAC⁵⁹. The differences between studies finding positive and negative effects for NLRP3 in tumorigenesis during colon cancer could be due to differences in the gut microbiota between animal facilities, differences in the genetic background of the mouse lines, and differences in experimental techniques used that affect the actual phenotype of these mice^{60, 61}. Besides these factors, nutrition and diet could also play a major role to modulating the outcome of CAC^{62, 63}. NLRP3 senses high fat diet-induced danger signals and promotes inflammation-induced obesity and insulin resistance^{64, 65}. It could be possible that NLRP3 inflammasome activation during high-fat diet feeding creates low-grade systemic inflammation that promotes the development of CAC. Indeed, NLRP3 signaling was found to be detrimental in the presence of nutritional factors, such as high-cholesterol and high-fat diet, which increases the inflammatory response and tumor burden in an AOM-DSS-induced mouse model of CAC⁶⁶.

The residual production of inflammasome effector cytokine IL-18 in NLRP3-deficient mice during CAC suggests that other inflammasome sensors are likely involved in this IL-18 release^{53, 67}. Moreover, the injection of recombinant IL-18 into NLRP3-deficient mice reduces the number of tumors formed in response to AOM and DSS, suggesting that NLRP3 mediated IL-18 have protective role during CAC^{53, 67}(Figure 2A). Additionally, NLRP3-mediated IL-18 signaling was found to be important in restricting CRC metastatic growth in the liver. Mice deficient in NLRP3 have increased liver CRC metastatic growth which is mediated by impaired IL-18 signaling that negatively affects hepatic NK cells by interfering with their maturation, surface expression of the death ligand FasL, and capacity to kill FasL-sensitive tumors⁴³. Furthermore, IL-18 downregulates IL-22BP during DSS-induced damage to maintain the IL-22/IL-22BP axis, which is critically important to regulate intestinal tissue repair and tumorigenesis⁶⁸ (Figure 2A). It is important to note that cryopyrin-associated periodic syndrome (CAPS) mice carrying the R258W mutation in the third exon of *Nlrp3* in C57BL/6 mice (*Nlrp3*^{R258W})—which corresponds to the R260W mutation frequently found in humans with Muckle-Wells syndrome⁶⁹—maintain homeostasis in the gut and are strongly resistant to experimental colitis and CAC. Mechanistically, *Nlrp3*^{R258W} enhances IL-1 β secretion in mononuclear phagocytes of the lamina propria to improve the production

of local anti-microbial peptides and facilitate microbiota remodeling, leading to the induction of regulatory T cells (Tregs) that compensate for detrimental inflammation⁷⁰. Additionally, IL-1 signaling can have cell type-specific responses to set the inflammatory tone of the tumor microenvironment that determines tumorigenesis. Indeed, IL-1R signaling in T cells and epithelial cells is pro-tumorigenic, and this effect is counteracted by anti-tumorigenic IL-1R signaling in myeloid cells, particularly neutrophils. Mechanistically, IL-1R deletion in neutrophils results in bacterial invasion into tumors, leading to increased inflammation and aggressive CRC progression⁷¹.

NLRP3 also has protective roles in hepatic cancer. The liver tumor burden from CRC metastasis is elevated in *Nlrp3*^{-/-} mice⁴³. Additionally, the expression of NLRP3 inflammasome components is significantly downregulated or even lost in human hepatic cancer tissues⁷². Moreover, the upregulation of NLRP3 by 17 β -estradiol (E2) suppresses growth of hepatocellular carcinoma cells⁷³, further suggesting a protective role of NLRP3 in hepatic cancer. Additional indirect evidence has also suggested a protective role for the NLRP3 inflammasome during tumorigenesis. Inhibiting an ion channel protein, TRE176B, which is mainly expressed in myeloid cells, activates the inflammasome and leads to the potentiation of CD8⁺ T cell-dependent antitumor immunity⁷⁴. Overall, these findings suggest that NLRP3 has a tumor suppressing role most often in colorectal cancer.

3.3 NLRP3 in tumor promotion

Despite acting as a tumor suppressor in CRC⁵³, the NLRP3 inflammasome promotes tumor formation in other forms of cancer. Mice deficient in CASP1 or NLRP3 have fewer lung metastases and reduced IL-1 β production in an orthotopic mammary gland tumor model in which E70771 murine breast cancer cells were injected orthotopically into the 4th fat pads (murine mammary glands)¹¹. Blocking IL-1R with its antagonist inhibits tumor growth and metastasis, suggesting that the activation of inflammasomes and the subsequent production of IL-1 β in primary tumors creates a favorable microenvironment for tumor metastasis via the recruitment of myeloid-derived suppressor cells (MDSCs) and tumor-associated macrophages into tumor tissues¹¹. It is known that IL-1 signaling drives the accumulation of MDSCs and promotes primary and metastatic mammary tumors⁷⁵. The role for the IL-1 pathway in the recruitment of MDSCs in cancer progression is further supported by a study that found a transgenic mouse strain overexpressing human IL-1 β in the stomach is susceptible to gastric cancer development after colonization of *Helicobacter felis*, a model organism for *H. pylori* that activates NF- κ B pathways in both *in vitro* and *in vivo* system⁷⁶.

Beyond gastric cancer, the NLRP3 inflammasome is also detrimental in a mouse model of fibrosarcoma and is dispensable for asbestos-induced mesothelioma⁷⁷ (Figure 2B). Moreover, although the direct role of NLRP3 in head and neck squamous cell carcinoma (HNSCC) is not clearly understood⁷⁸, patients with HNSCC have an increased concentration of IL-1 β in their peripheral blood. Additionally, blocking the NLRP3 inflammasome using the inhibitor MCC950 in Tgfb β 1/Pten 2cKO HNSCC mice leads to the inhibition of tumor growth, a decrease in immunosuppressive cell accumulation, and an increase in the number of effector T cells present. Together, these data suggest that NLRP3 plays a detrimental role in HNSCC⁷⁹. Moreover, NLRP3-mediated IL-18 production in lymphoma cells reduces

dexamethasone-induced apoptosis, thereby promoting the proliferation of lymphoma cells into the S phase⁸⁰ suggesting a carcinogenic role of NLRP3-mediated IL-18 in lymphoma.

NLRP3 can also interact with the adaptive immune system to drive carcinogenesis in other tumor types. NLRP3 signaling in macrophages drives the differentiation of CD4⁺ T cells into tumor-promoting T helper type 2 (Th2), Th17, and Treg cell populations in pancreatic carcinoma and suppresses Th1 cell polarization and cytotoxic CD8⁺ T-cell activation, suggesting that NLRP3 could be an attractive target for novel immunotherapies to reprogram the tumor microenvironment towards an immunogenic innate and adaptive inflammatory phenotype⁸¹. NLRP3 restricts antitumor T-cell immunity after dendritic cell vaccination, suggesting that novel approaches are needed to improve response to antitumor vaccines by limiting NLRP3 signaling⁸². It is possible that the expression of NLRP3 in the tumor microenvironment diminishes antitumor immunity and vaccine efficacy by promoting the migration of MDSCs to the tumor site. The activation of the NLRP3 inflammasome in MDSCs by 5-fluorouracil and gemcitabine after cathepsin B release limits the antitumor efficacy of these chemotherapeutic agents⁸³. IL-1 β regulates CD4⁺ T helper cell polarization in neighboring cells and drives the formation of Th17 subsets producing IL-17, which play an active role in tumor pathogenesis and progression by enhancing the emergence of immunosuppressor MDSCs to the tumor site and reducing the tumor infiltration by cytotoxic T cells. In line with this study, a recent study found that NLRP3-mediated IL-1 β production in tumor cells creates the pro-tumorigenic pancreatic ductal adenocarcinoma (PDA) microenvironment via establishing immunosuppressive milieu mediated by M2 macrophages, MDSCs, CD45+ regulatory B cells and Th17 cells⁸⁴ (Figure 2B). NLRP3 may also modulate tumor responses by blocking the efficacy of immunotherapy. A recent study found that the genetic and pharmacologic inhibition of NLRP3 blocks the recruitment of granulocytic subsets of MDSCs (PMN-MDSC) and enhances the efficacy of anti-PD-1 antibody immunotherapy⁸⁵. Overall, these findings suggest that NLRP3 can have a pathogenic role in tumorigenesis by interacting with neighboring cells and other immune compartments.

4. NLRP3 inflammasome in metabolic diseases

The interconnection between the immune and metabolic systems is important to balance metabolic homeostasis. Imbalances between these systems leads to chronic, low-grade systemic inflammation that results in the development of metabolic disorders⁸⁶. Molecularly, the NLRP3 inflammasome-mediated inflammatory cytokines can act in both autocrine and paracrine manners in various cells within the metabolic tissues and contribute to metabolic disorders such as diabetes⁶⁴, obesity⁶⁵, atherosclerosis¹⁰ cardiovascular disease⁸⁷ gout¹⁷, and neurodegenerative diseases⁸⁸. Here, we discuss the role of NLRP3 in diabetes, obesity, and atherosclerosis.

4.1 NLRP3 in diabetes and obesity

Obesity is characterized by excess fat accumulation when an energy intake exceeds energy expenditure, leading to the pathological expansion and fundamental changes in cellular metabolism with immune modulation in the adipose tissue (AT)⁸⁹. Ectopic fat accumulation

in muscle and liver with low-grade inflammation instigates insulin resistance (IR) with the elevation of glucose in the blood^{86, 90}. The first study that reported the overexpression of TNF in the AT of obese mice provided a link between diabetes, obesity, and the immune response⁹¹. Since then, several studies have reported that inflammasome components including NLRP3 are upregulated in subcutaneous adipose tissue (SAT) or visceral adipose tissue (VAT) of obese patients compared with lean controls^{92, 93, 94, 95, 96}. Likewise, calorie restriction- and weight loss-induced insulin sensitivity are associated with reduced NLRP3 and IL-1 β expression in SAT⁹⁷, further suggesting that NLRP3 is associated with diabetes and obesity.

Mice deficient in NLRP3 are protected from high fat diet (HFD)-induced obesity and IR⁹⁷. These mice have smaller adipocytes with reduced macrophage infiltration in the VAT when compared with control mice. Moreover, HFD-fed *Nlrp3*^{-/-} mice have reduced inflammasome activation in the fat and liver and have improved insulin signaling. Similarly, another study found that HFD-fed *Nlrp3*^{-/-} mice have reduced weight gain and hypertrophy. Upregulation of CASP1 after HFD feeding regulates both insulin sensitivity and differentiation of adipocytes⁶⁴. Additionally, the preadipocytes derived from *Casp1*^{-/-} or *Nlrp3*^{-/-} mice display higher insulin sensitivity and higher fat oxidation rates. Moreover, treatment with recombinant IL-1 β and recombinant IL-1 receptor antagonist showed that the effects of CASP1 are mediated by the processing of IL-1 β ⁶⁴.

The hematopoietic compartment may play a predominant role in the recognition of obesity-related DAMPs and subsequent production of IL-1 β and IL-18^{9, 97}. The blood glucose and insulin levels are significantly reduced in *Nlrp3*^{-/-} mice fed with HFD for 3 months when compared with WT mice⁹. In contrast to these finding, one study has shown that *Nlrp3*^{-/-} mice are not protected from weight gain, AT inflammation, or glucose intolerance after 6 months of being fed with 45% fat and 1% cholesterol⁹⁸. The discrepancies observed in these studies could be due to differences in the composition of dietary intake, genetic background of the mice used in the study, composition of the microbiota, and differences in animal facilities.

A key question regarding the role of NLRP3 in diabetes and obesity is what triggers are sensed by NLRP3 to induce CASP1 activation and the release of inflammatory cytokines over the course of weight gain. Several endogenous ligands have been reported to be required for the activation of the NLRP3 inflammasome and IL-1 β maturation. One key example is islet amyloid polypeptide (IAPP), which is co-secreted with insulin to form an amyloid deposit in the pancreas. IAPP leads to NLRP3 inflammasome activation and IL-1 β maturation via lysosome destabilization in mouse macrophages⁹⁹. Additionally, the transgenic expression of human IAPP in mice leads to spontaneous development of diabetes, further highlighting the pathogenic role of IAPP⁹⁹. During HFD feeding, changes in gut microbial composition or reduced gut permeability lead to increased circulating levels of LPS, which can provide the primary signal for the upregulation of NLRP3 and IL-1 β ¹⁰⁰. Additionally, ceramides, saturated fatty acids, reactive oxygen species (ROS), mitochondrial dysfunction, and ATP released from necrotic adipocytes can act as the secondary signal for NLRP3 inflammasome activation via a autocrine or paracrine signaling mechanism¹⁰¹. For example, palmitic acid regulates AMPK activation which diminishes autophagy and

promotes the accumulation of mitochondrial ROS, leading to inflammasome activation as well as IL-1 β -mediated IR⁹. Similarly, another study found that obesity-related lipotoxic ceramides induce CASP1 activation in an NLRP3-dependent manner^{97, 102}. Palmitic acid induces the activation of a stress response element, IRE1 α , which enhances chronic low-grade inflammation and NLRP3 inflammasome activation during HFD feeding¹⁰³. However, oleic acid, which is an unsaturated fatty acid, negatively regulates NLRP3 via AMPK activation, and mice fed with oleic acid exhibit reduced adipose IL-1 β and improved IR¹⁰⁴. Additionally, the amino acid homocysteine can act as a DAMP, and lysophosphatidylcholine (Lyso-PC) provides the secondary signal to activate the inflammasome in both adipocytes and AT macrophages to induce IR¹⁰⁵. One of the inflammasome-dependent cytokines IL-1 β reduces glucose uptake in adipocytes by reducing the mRNA expression of insulin receptor substrate (IRS1) and blocking its downstream events, which are essential for glucose mobilization¹⁰⁶ (Figure 3). The detrimental role of IL-1 β in inducing AT inflammation and IR is further supported by a study in which the lack of IL-1R protects mice from HFD-induced AT inflammation coincident with improved glucose homeostasis¹⁰⁷. In contrast, the acute physiological elevation of IL-1 β after feeding stimulates glucose disposal and reduces AT inflammation¹⁰⁸. Overall, these data suggest that NLRP3 is a molecular sensor of obesity-associated danger signals, and that NLRP3-mediated, CASP1-dependent IL-1 β secretion and inflammation in key metabolic tissues, including liver, fat, and muscle, promote obesity-induced inflammation and IR (Figure 3).

The NLRP3 inflammasome has also been associated with age-related metabolic complications. Mechanistically, NLRP3 mediates age-related chronic inflammation and controls catecholamine-induced lipolysis in AT macrophages, resulting in increased visceral obesity and defective free fatty acid mobilization¹⁰⁹. Furthermore, NLRP3-mediated IL-1 β and IL-18 contribute to the expansion of adipose B cells in VAT, which impairs metabolic homeostasis¹¹⁰. Hence, inhibiting NLRP3-dependent B cell accumulation could be targeted to reverse metabolic impairment in aging.

4.2 NLRP3 in atherosclerosis

Atherosclerosis is a chronic inflammatory disease in which extensive immune cell infiltration, lipid deposition, and vascular smooth muscle cell proliferation lead to the formation of atherosclerotic plaques in the arterial wall. In particular, higher expression of NLRP3 inflammasome components such as NLRP3, ASC, CASP1, IL-1 β , and IL-18 in carotid atherosclerosis plaques suggest an association of NLRP3 with the pathogenesis of atherosclerosis¹¹¹. Additionally, a high level of NLRP3 expression is strongly correlated with the severity of coronary artery stenosis¹¹².

The direct function of NLRP3 in the pathogenesis of atherosclerosis has been investigated using different in vivo mouse models. The detrimental role of NLRP3 in atherosclerosis is mostly dependent on its effector cytokine, IL-1 β ^{113, 114}. Bone marrow transplantations of *Ldlr*^{-/-} mice with bone marrow derived from *Nlrp3*^{-/-}, *Asc*^{-/-}, *Il1a*^{-/-}, or *Il1b*^{-/-} mice followed by feeding with a Western-type high cholesterol diet (Teklad Adjusted Calories 88137; 21% fat [wt/wt], 0.15% cholesterol [wt/wt] and 19.5% casein [wt/wt]; no sodium cholate) for 8 weeks results in significantly reduced atherosclerosis and inflammasome-

dependent IL-18 levels as compared to *Ldlr*^{-/-} mice transplanted with WT bone marrow¹⁰, providing genetic evidence for the role of the NLRP3 inflammasome in atherosclerosis. In line with this, a more recent study reported that the bone marrow transplantation from *Casp1/11*^{-/-} mice to *Ldlr*^{-/-} mice leads to the development of significantly smaller atherosclerotic plaques than *Ldlr*^{-/-} mice transplanted with WT bone marrow¹¹⁵. However, another study demonstrated that there was no reduction in the progression of atherosclerosis in *ApoE*^{-/-}*Nlrp3*^{-/-}, *ApoE*^{-/-}*Asc*^{-/-}, or *ApoE*^{-/-}*Casp1*^{-/-} mice with respect to *ApoE*^{-/-}, after feeding with a high-fat diet (KlibaNafag 3200 supplemented with 1.25% w/w cholesterol and 15% w/w cacao butter; Kliba Nafag, Kaiseraugst, Switzerland) for 11 weeks, suggesting that atherosclerosis can progress independent of the NLRP3 inflammasome¹¹⁶. The discrepancy observed in these studies could be due to the differences in the mouse models, time of diet feeding, and the type of atherogenic diet used. It is possible that an overabundance of dietary cholesterol in combination with the longer feeding might bypass the NLRP3 inflammasome and activate other inflammatory pathways. Inflammasome-independent cytokines IL-1 α and HMGB1 also promote atherosclerosis and are able to induce strong inflammatory immune responses¹¹⁷. *Ldlr*^{-/-} mice transplanted with bone marrow from *Il1a*^{-/-} mice showed significantly reduced atherosclerosis compared with *Ldlr*^{-/-} mice transplanted with bone marrow from *Il1b*^{-/-} mice after 16 weeks of atherogenic diet feeding¹¹⁸. These findings suggest that IL-1 α has a predominant role in the progression of vascular inflammation and atherosclerosis during prolonged atherogenic diet feeding.

Mechanistically, low density lipoprotein (LDL), cholesterol crystals, and calcium phosphate crystals are the major drivers of NLRP3 inflammasome activation in atherosclerosis (Figure 4). Cholesterol crystals activate the NLRP3 inflammasome in macrophages *in vitro* in a process that involves phagolysosomal damage. The phagocytosed crystals cannot be engulfed or digested, resulting in the leakage of the lysosomal enzyme cathepsin B, which activates the NLRP3 inflammasome¹⁰. Intraperitoneal injection of cholesterol crystals induces acute inflammation in WT mice which is absent in mice deficient in the components of the NLRP3 inflammasome, cathepsin B, cathepsin L, or IL-1¹⁰. Altogether, these *in vitro* and *in vivo* data suggest that crystalline cholesterol acts as an endogenous danger signal, and its deposition is an early cause of inflammation, not the consequence of inflammation. Additionally, oxidized LDL leads to cholesterol crystallization and the activation of priming signals to induce NLRP3 and pro-IL-1 β expression¹¹⁹. Similar findings describe that oxidized LDL mediates the endocytic pathway via the PRR CD36 and forms crystals or fibrils which result in lysosomal disruption and NLRP3 activation¹¹⁹. Macrophages that lack CD36 fail to release IL-1 β , which is dependent on the NLRP3 inflammasome¹¹⁹. In summary, endogenous danger signals produced during atherosclerosis provide both the priming signal to upregulate expression of inflammasome components and the activation signal to activate the NLRP3 inflammasome, which provokes the pathogenesis of atherosclerosis.

5. Summary and future perspectives

The association of NLRP3 with cancer and metabolic diseases has been reported from both animal and human studies. NLRP3 has contrasting roles in tumorigenesis, demonstrating both detrimental and beneficial effects. The beneficial effect is well reported only in the

context of CAC^{52, 53, 56, 57} and some forms of liver cancer⁴³. However, detrimental effects are observed in other cancers and metabolic diseases including diabetes, obesity, atherosclerosis etc. Inflammasome effector cytokines, IL-1 β and IL-18, which are produced as a result of NLRP3 activation are major effector molecules aggravating these diseases. These cytokines generate and maintain an inflammatory micro-environment which supports the pathogenesis of inflammatory diseases. The inflammatory micro-environment surrounding cancer cells inhibits the effect of NK and T cell-mediated immune surveillance, aggravating the pathogenesis of cancer. Specifically, the detrimental role of IL-1 β for the initiation and progression of inflammation-associated metabolic disease and cancer has recently been reported in patients enrolled in the Canakinumab Anti-inflammatory Thrombosis Outcomes Study (CANTOS)¹²⁰. In this study, patients who received canakinumab, an anti-IL-1 β antibody, had reduced levels of high-sensitivity C-reactive protein as compared with the placebo group, suggesting that the inhibition of IL-1 β reduces cardiovascular burden¹²¹. These clinical data are further supported by a mouse study in which the inhibition of NLRP3 or IL-1 β has been shown to reduce the incidence of atherosclerosis¹⁰. Additionally, CANTOS found a 77% reduction in lung cancer fatality and a 67% reduction in lung cancer incidence, although the reduction was not statistically significant for non-lung cancers¹²⁰. Overall, the findings from CANTOS suggest that IL-1 β has a detrimental role in lung cancer, where inflammation is the major driver of tumorigenesis. The pathogenic role of IL-1 β has been further observed during NLRP3 sensing of metabolic perturbations, where IL-1 β acts in both an autocrine and paracrine manner to interfere with insulin signaling, leading to the development of metabolic diseases^{64, 65}. Overall, modulating NLRP3 or its downstream inflammatory cytokines could have promising therapeutic effects in the development of metabolic diseases or cancer.

Inflammasome-mediated inflammatory cytokine release depends upon gasdermin family proteins. GSDMD has been identified as an executioner of pyroptosis that forms pores on the membrane^{23, 24}. Pyroptosis in gasdermin E-positive cancer cells has also been observed due to caspase-3 activation in response to chemotherapeutic drugs^{122, 123}. Additionally, PD-L1-mediated gasdermin C expression switches apoptosis to pyroptosis in cancer cells and facilitates tumor necrosis¹²⁴, suggesting a cross talk between major cell death pathways in cancer¹²⁵. Indeed, recent studies have shown crosstalk between pyroptosis, apoptosis, and necroptosis, defining PANoptosis as a unique, physiologically relevant, inflammatory programmed cell death pathway activated by specific triggers and regulated by the PANoptosome complex, which provides a molecular scaffold for contemporaneous engagement of key molecules from pyroptosis, apoptosis, and necroptosis^{126, 127, 128, 129}. PANoptosis has been implicated in infectious and autoinflammatory diseases, cancer, and beyond^{6, 130}, and PANoptosis prevents tumorigenesis in both spontaneous and inflammation-induced mouse models of CAC¹²⁷. In the context of metabolic disease, proinflammatory cytokines and DAMPs released from both immune and non-immune cells activate inflammatory cell death in various metabolic tissues, including liver and pancreas, leading to IR^{131, 132}. The combination of TNF and IFN γ specifically has been reported to induce pancreatic beta cell death¹³³, which may be linked to the ability of these cytokines to drive PANoptosis¹³⁴. It would be interesting to investigate whether NLRP3 can form unique

PANoptosome complexes to regulate PANoptosis in the context of metabolic and inflammatory diseases and cancer.

The divergent roles of NLRP3 in the pathogenesis of cancer raises new opportunities and challenges to fully understand how it carries out both the pro-tumorigenic as well as anti-tumorigenic functions. These diverse functions could be affected by the tumor microenvironment influencing the activation of NLRP3. Additionally, the differential expression of NLRP3 in various cells and tissues suggests it has distinct roles in the pathogenesis of tumors originating in specific tissues. For example, NLRP3 expression is upregulated in lung adenocarcinoma and small cell lung cancer, where the role of NLRP3 is pathogenic¹³⁵. Likewise, the expression of NLRP3 is downregulated in hepatic cancer cells, where the role of NLRP3 appears to be beneficial⁷². The function of NLRP3 in particular cancers could also depend on the effects of other mutations on its expression, the tumor type, the stage of tumor development, and the effector molecules downstream of NLRP3. Therefore, NLRP3 signaling has complex effects on tumor initiation and progression through its modulation of antitumor immunity, cell death, proliferation, angiogenesis and metastasis. Given that the outcomes of inflammasome signaling are diverse across tumor types, gaining insight on how to manage this diversity will also be an important area for future investigations.

Overall, it is critical to continue to improve our mechanistic understanding of NLRP3 and its divergent functions across diseases. It is possible that NLRP3 may undergo different forms of activation in response to DAMPs vs PAMPs. Hence, examining the highest resolution structure of NLRP3 in response to inflammatory and infectious triggers could improve our understanding of the specific functions of NLRP3 in the context of these diseases. Moreover, one possible mechanism driving the divergent roles of NLRP3 in cancers could be cell- and tissue-specific functions of NLRP3 in different stages of tumorigenesis. Thus, the use of cell- and tissue-specific NLRP3 deletions, the use of mice with similar genetic backgrounds, and the use of littermates will provide valuable insight to understand the differential functions of NLRP3 in inflammatory and infectious diseases. Identifying the specific functions of the NLRP3 inflammasome, along with the pathways and regulatory mechanisms that control its activation, in disease-specific contexts will support evidence-based therapeutic design and drastically improve our ability to balance the beneficial and detrimental functions of this critical innate immune molecule to benefit patients.

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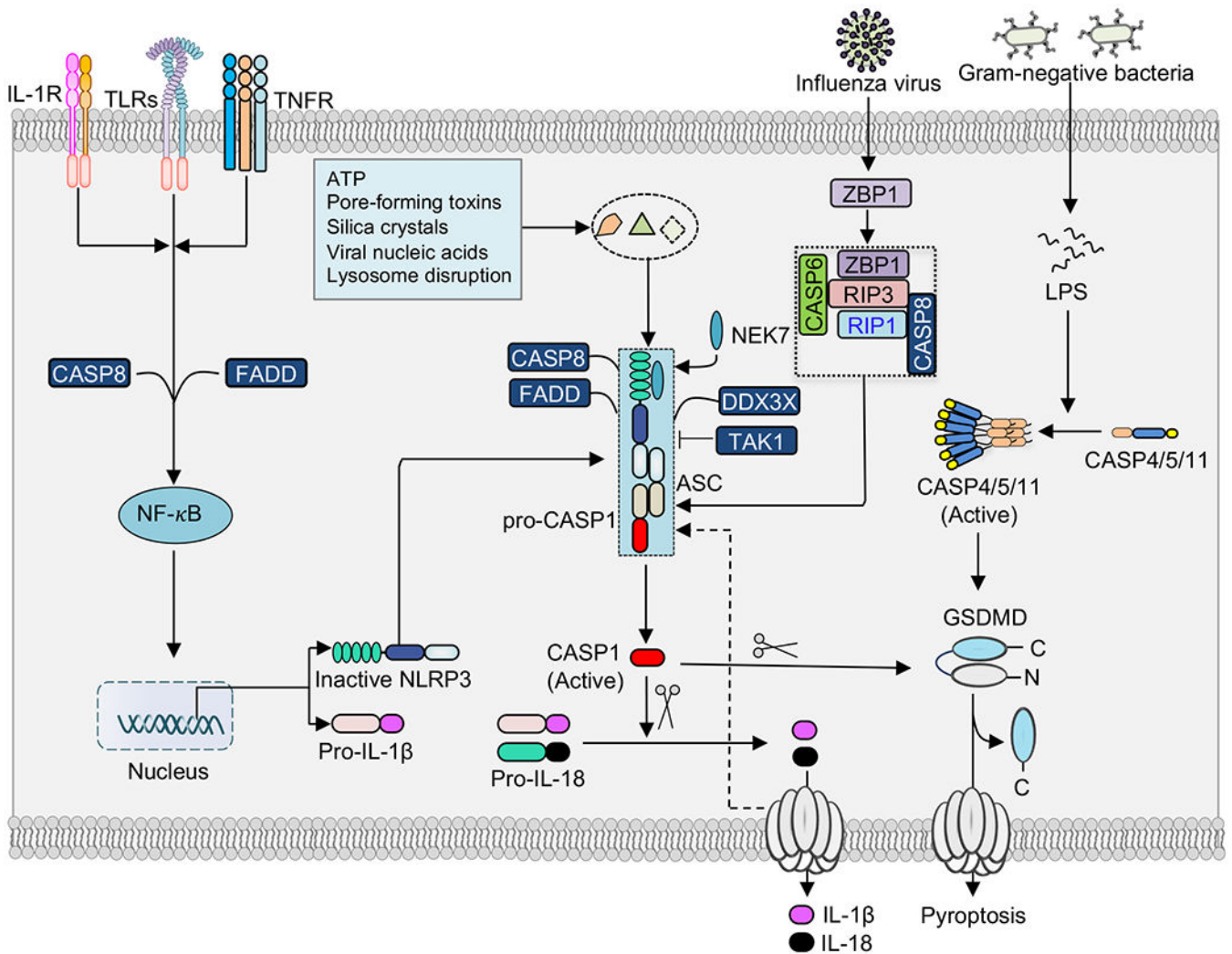


Figure 1. Mechanism of NLRP3 inflammasome activation.

The canonical NLRP3 inflammasome activation requires two steps. The priming step occurs when inflammatory stimuli are sensed by Toll-like receptors (TLRs), the interleukin-1 receptor (IL-1R), and the TNF receptor (TNFR). The activation step is provided by a wide range of stimuli including ATP, pore forming toxins, particulate matter, silica crystals, ion flux, etc. FADD and caspase-8 (CASP8) promote the transcription of NLRP3 and IL-1 β . CASP8, FADD, transforming growth factor β -activated kinase 1 (TAK1), DDX3X, and NEK7 are all reported to regulate the activation of the NLRP3 inflammasome. Z-DNA-binding protein 1 (ZBP1)-dependent NLRP3 inflammasome activation occurs in response to influenza virus. Non-canonical NLRP3 inflammasome activation occurs in response to cytosolic lipopolysaccharide (LPS) and is dependent on CASP11, which is the mouse homolog of human CASP4 and CASP5. Activated CASP1 or CASP11 cleaves gasdermin D (GSDMD), which then forms pores in the plasma membrane causing cell lysis (pyroptosis). GSDMD pores also facilitate the release of the mature forms of IL-1 β and IL-18.

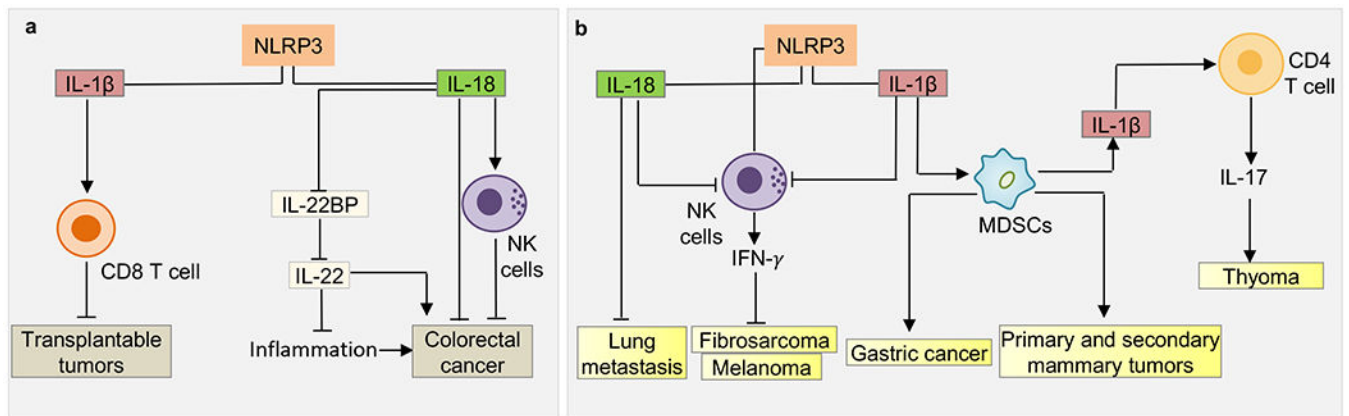


Figure 2. NLRP3 inflammasome in cancer.

(A) NLRP3 mediates the production of IL-18, which contributes to protection against colitis-associated colorectal cancer. IL-18 increases the tumoricidal activity of natural killer (NK) cells against metastasized colonic tumor cells in the mouse liver⁴³. IL-18 also downregulates IL-22BP which modulates colorectal cancer⁶⁸. NLRP3 also drives T-cell responses via IL-1 β to inhibit transplantable tumor cells¹³⁶. (B) The NLRP3/IL-1 β /IL-18 axis suppresses the tumoricidal activity of NK cells to promote methylcholanthrene (MCA)-induced fibrosarcoma¹³⁷. Overexpression of IL-1 β mobilizes myeloid-derived suppressor cells (MDSCs) to the stomach and induces gastric cancer⁷⁶. In primary and metastatic mammary tumors, IL-1 signaling drives the accumulation of MDSCs and promotes the tumors⁷⁵. IL-1 β also induces the secretion of IL-17 by CD4⁺ T cells and dampens the antitumor efficacy of chemotherapeutic agents in thyoma⁸³. Inflammation-independent activity of NLRP3 suppresses NK cells and increases lung metastasis in certain models of melanoma^{82, 137}.

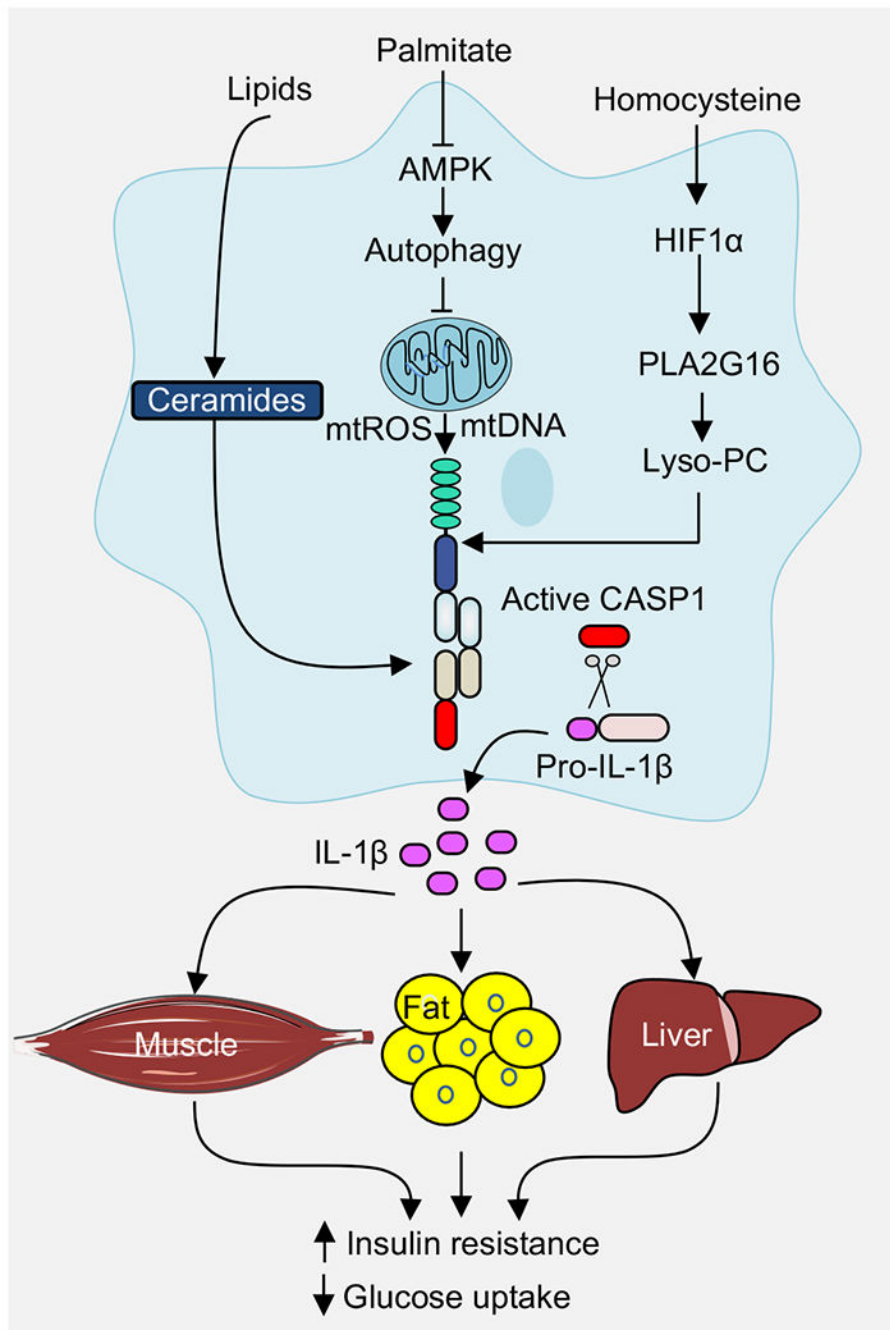


Figure 3. NLRP3 inflammasome in diabetes and obesity.

Obesity-related danger signals such as palmitate, lipids, and ceramides promote the activation of the NLRP3 inflammasome. Ceramides are generated from the endoplasmic reticulum and/or through the conversion of sphingomyelins located in the plasma membrane. Saturated fatty acids such as palmitate increase mitochondrial reactive oxygen species (mtROS) by reducing autophagy through the blockade of 5' adenosine monophosphate-activated protein kinase (AMPK) signaling. Elevated homocysteine levels can also activate the NLRP3 inflammasome through the induction of the hypoxia-inducible factor 1 α .

(HIF1 α)/phospholipase A2 group 16 (PLA2G16) axis by generating adipocyte-derived lysophosphatidyl choline (Lyso-PC). The release of IL-1 β downstream of NLRP3 activation causes insulin resistance and reduces glucose uptake in insulin target tissues such as muscle, liver, and adipose tissues, leading to the pathogenesis of diabetes and obesity.

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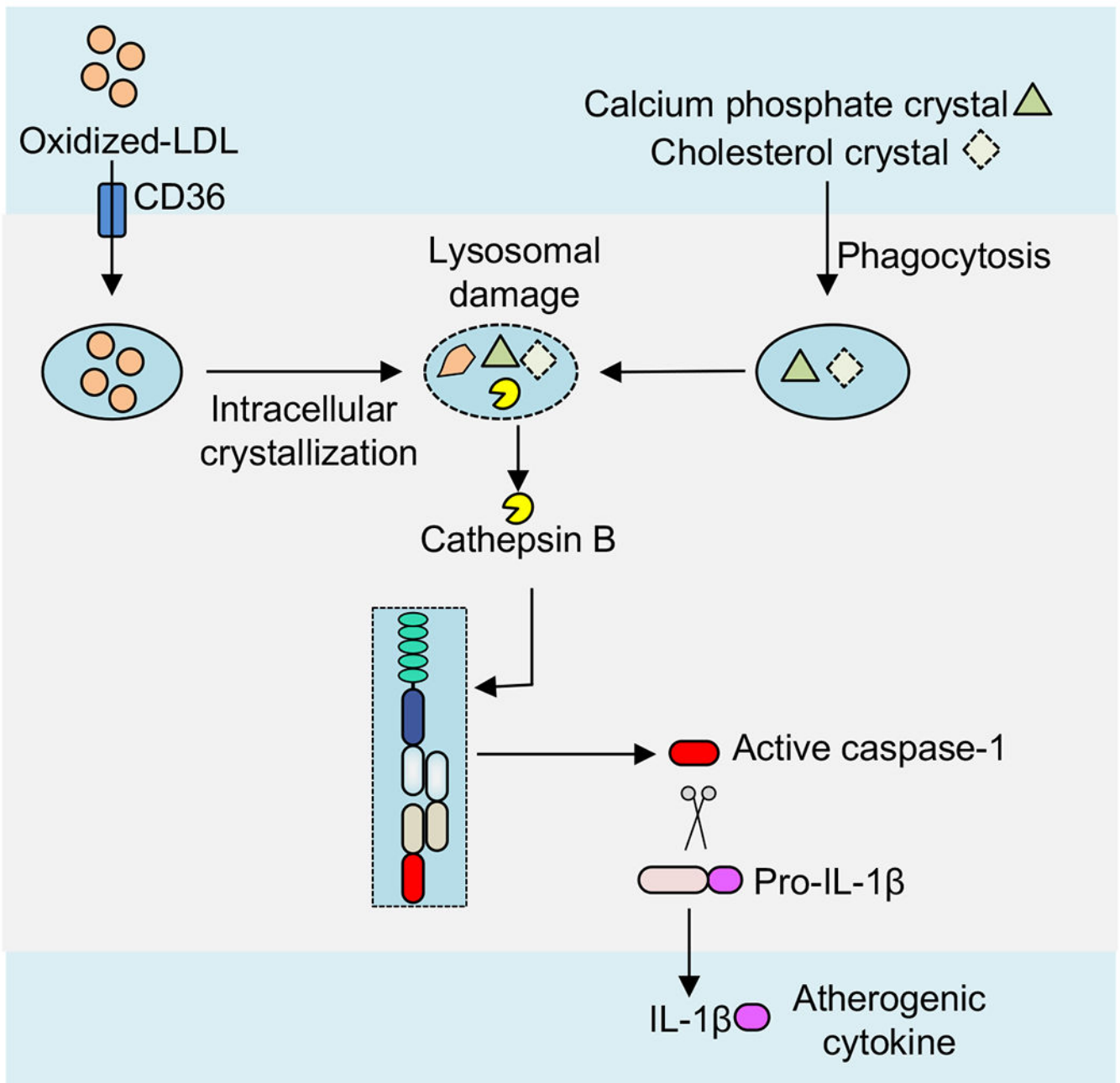


Figure 4. NLRP3 inflammasome in atherosclerosis.

Calcium phosphate crystals and cholesterol crystals are taken into the lysosome by phagocytosis, or intracellular cholesterol crystals are formed when oxidized low-density lipoprotein (oxidized-LDL) is taken up by the scavenger receptor CD36. An excess of crystals in atherosclerosis causes lysosomal destabilization and rupture. Rupturing of lysosomes leads to the leakage of the lysosomal enzyme cathepsin B, resulting in NLRP3 inflammasome activation. The release of IL-1 β downstream of NLRP3 activation signals to

neighboring monocytes/macrophages, endothelial cells, and smooth muscle cells to promote the pathogenesis of atherosclerosis.

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