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Victoria L. Crotzer and Janice S. Blum

Intracellular degradation by autophagy plays a role in the maintenance of cellular homeostasis under normal conditions and during periods of cellular stress. Autophagy has also been implicated in several other cellular processes including immune recognition and responsiveness. More specifically, autophagy has been identified as a route by which cytoplasmic and nuclear Ag are delivered to MHC class II molecules for presentation to CD4⁺ T cells. Autophagy has also recently been implicated in MHC class I cross-presentation of tumor Ag and the activation of CD8⁺ T cells. This review discusses the role of autophagy in modulating MHC class I and class II Ag presentation as well as its implication in regulating autoimmunity and tolerance, tumor immunity, and host defense against intracellular pathogens. The Journal of Immunology, 2009, 182: 3335–3341.

Autophagy is one mechanism that cells use to degrade cytoplasmic proteins and organelles during the maintenance of cellular homeostasis (1). There are multiple pathways of autophagy. In microautophagy, small portions of the cytosol are internalized via lysosomal membrane invaginations, and proteins are continuously degraded in the lumen of this organelle even under resting conditions (2). Microautophagy is up-regulated under conditions of cellular stress such as nutrient deprivation, but studies of this pathway have been limited to yeast and cell-free systems (3, 4). In mammalian cells, constitutively active autophagy pathways can also be up-regulated as a mechanism to salvage amino acids during periods of cellular stress. Several types of selective autophagy have been identified in mammalian cells including macroautophagy and chaperone-mediated autophagy (CMA)² (Fig. 1), as well as pexophagy and mitophagy (5). A related constitutive biosynthetic pathway, cytoplasmin-to-vacuole targeting, is involved in hydrolase sorting in yeast (6). Another pathway, xenophagy, involves the use of the autophagic machinery for the degradation of intracellular pathogens (7). Macroautophagy and CMA have been implicated in the presentation of Ag by MHC molecules and, thus, are the major focus of this review.

Macroautophagy is also a constitutively active cellular process modulating the degradation of long-lived proteins and organelles (1). During short periods of nutrient deprivation, this pathway is rapidly induced as a mechanism to salvage amino acids. The absence of growth factors or amino acids prevents signaling through PI3K from activating the autophagy regulatory molecule known as mammalian target of rapamycin (mTOR), and thus, macroautophagy is induced (8). In macroautophagy, portions of the cytoplasm are sequestered into double-membrane structures known as autophagosomes. The formation of the autophagosome requires a number of autophagy-related gene (Atg) products that have been well-characterized in yeast (6) and are conserved in mammals; the specific details of autophagosome formation have been reviewed extensively elsewhere (2, 8). Briefly, the Atg12-Atg5-Atg16 complex, in conjunction with Atg9, mediates the induction of autophagosome formation. During this process, LC3 (Atg8) is conjugated to phoshatidylethanolamine with the assistance of the Atg4, Atg7, and Atg3 molecules and incorporated into the autophagosomal membrane. This membrane next expands and engulfa anticls, including entire organelles. Upon formation of the autophagosome, the Aut12-Atg5-Atg16 complex dissociates from this structure while LC3 (Atg8)-phoshatidylethanolamine remains in the autophagic lumen as an autophagosomal marker. The outer membrane of the autophagosome fuses with the lysosomal membrane, forming an autolysosome within which the single membrane structure, or autophagic body, is degraded by lysosomal esterases, lipases, and proteases.

During periods of prolonged cellular stress, bulk autophagy declines, and the process of CMA is up-regulated. In CMA, specific cytosolic proteins displaying homologous pentapeptide

³ Abbreviations used in this paper: CMA, chaperone-mediated autophagy; ALIS, aggresome-mediated induced structures; Aut, autophagy-related gene; cTEC, cortical thymic epithelial cell; DC, dendritic cell; ERNA, EBV nuclear Ag; ER, endoplasmic reticulum; GAD, glutamic acid decarboxylase; hsc70, heat shock cognate 70-kDa protein; II, invariant chain; LAMP, lysosome-associated membrane protein; 3-MA, 3-methyladenine; MP1, influenza matrix protein 1; mTOR, mammalian target of rapamycin; siRNA, small interfering RNA.

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motifs bind to a molecular chaperone complex composed of multiple heat shock proteins including the heat shock cognate 70-kDa protein (hsc70) (reviewed in Ref. 9). This molecular chaperone complex transports the substrate protein to the lysosomal membrane, where it associates with an isoform of the lysosome-associated membrane protein (LAMP) 2A, which functions as part of the lysosomal receptor for CMA. The cytoplasmic domain of LAMP-2A serves as a potential docking site for the molecular chaperone-substrate complex, and chaperone-mediated substrate unfolding likely enables proteins to bind and translocate across the lysosomal membrane. Lysosomal hsc70 assists with the transport of substrate proteins into the organelle lumen, where these molecules are degraded by mature acidic proteases.

**Autophagy and MHC class I Ag presentation**

In the conventional paradigm, MHC class I molecules are restricted to surveying the cytosol for endogenous Ag from viruses, tumors, or self-proteins for presentation to CD8+ T cells (reviewed in Ref. 10). These endogenous Ag are degraded into peptide fragments by cytosolic proteases such as the proteasome and transported via a heterodimeric complex composed of TAP1 and TAP2 into the endoplasmic reticulum (ER). Once in the ER, peptides of the appropriate length (8–10 aa) bind nascent MHC class I H chains and β2-microglobulin and then transit through the secretory pathway to the cell surface for recognition by CD8+ T cells. A direct role for autophagy in the conventional pathway for MHC class I presentation has not been firmly established, yet recent studies discussed below demonstrate potential roles for autophagy in regulating class I-mediated cross-presentation of exogenous Ag.

During the process of cross-presentation, bone marrow-derived APC such as dendritic cells (DC) internalize and degrade Ag from the extracellular environment and display the resulting peptides in association with MHC class I molecules on their cell surfaces (11). The stimulation of naive CD8+ T cells by these peptide-MHC class I complexes is known as cross-priming. The class I-restricted cross-presentation pathway plays an important role in the immune surveillance of infected cells as well as tumors and the subsequent development of an appropriate cytotoxic T cell response to these pathogens or malignancies. Precisely how peptides from exogenous Ag access the MHC class I presentation pathway is still under investigation, although several routes have recently been proposed. These pathways have been described extensively elsewhere (11–13); thus, only a brief summary of the current models of class I-mediated cross-presentation is offered here.

Studies have suggested that MHC class I molecules may acquire peptides derived from exogenous Ag in phagosomes in a TAP-dependent or TAP-independent manner. In the TAP-dependent phagosome-to-cytosol-to-phagosome pathway, Ag is transported to the cytosol by a yet unknown mechanism, possibly Sec61, and degraded by the proteasome. Peptides are then reimported into the phagosome, which has acquired TAP as well as other ER proteins such as MHC class I. The phagosome-to-cytosol pathway calls for peptides generated in the cytosol by the proteasome to be directly transported to MHC class I molecules in the ER via TAP. Another possible mechanism of class I-restricted cross-presentation may involve the ER-associated degradation pathway. Here, exogenous Ag internalized in endosomes is transported into the ER, translocated for degradation in the cytosol by the proteasome, and finally transported back into the ER by TAP. It has also been reported that DC may acquire exogenous peptides from other cells via gap junctions to cross-prime naïve CD8+ T cells. Lastly, in the vacuolar pathway, MHC class I molecules may acquire peptides that are generated in phagosomes by cysteine proteases such as cathepsin S in a TAP-independent manner. The mechanisms that potentiate MHC class I peptide loading in phagosomes via this latter pathway have not yet been determined.

Autophagy has recently been proposed as another possible mechanism for the MHC class I-mediated cross-presentation of exogenous Ag with results pertinent to tumor Ag (14). In this study, the authors induced macroautophagy in HEK 293T cells expressing a model Ag OVA by starvation or treatment with the compound rapamycin, which inhibits the mTOR molecule (15). Following these treatments in vitro, enhanced cross-presentation of OVA to epitope-specific CD8+ T cells was observed. Conversely, the treatment of the OVA-expressing HEK 293T cells with 3-methyladenine (3-MA), an inhibitor of PI3K and macroautophagy (16), significantly reduced OVA cross-presentation in vitro. These authors also used rapamycin, 3-MA, and another PI3K inhibitor, wortmannin (17), to modulate macroautophagy in melanoma cells and then measured the MHC class I-restricted cross-presentation of the tumor Ag gp100 in vivo. Similar to the results with the OVA-expressing HEK 293T cells, induction of macroautophagy enhanced the cross-presentation of gp100 whereas inhibition of macroautophagy reduced the cross-presentation of this Ag to epitope-specific CD8+ T cells. Macroautophagy was also specifically inhibited through the use of small interfering RNA (siRNA) against the autophagy gene Atg6/beclin-1 in melanoma cells, and a significant reduction in the in vivo MHC class I-mediated cross-presentation of gp100 was again observed.

These results support a potential role for macroautophagy in the MHC class I-restricted cross-presentation of tumor Ag; yet further mechanistic studies to define the role of autophagy pathways in class I-mediated Ag presentation are needed. The induction of macroautophagy by rapamycin in the OVA-expressing HEK 293T cells as well as the melanoma cells leads to the conversion of LC3-I to its LC3-II form, suggesting that the MHC class I-restricted cross-presentation of OVA and gp100...
FIGURE 2. Autophagy as a potential mechanism for MHC class I-mediated presentation of tumor Ag. Macroautophagy can be induced in tumor cells undergoing cellular stress as a result of nutrient depletion or chemotherapy. Autophagosomes containing tumor Ag may be released into the extracellular environment where they are internalized by DC. How and where tumor Ag in autophagosomes intersect with MHC class I molecules in DC is unknown. DC present tumor peptides in the context of class I for the activation of CD8+ T cells. MHC class II complexes consist of α and β subunits, which are first assembled in the ER with the chaperone molecule invariant chain (II) (28, 29). The cytoplasmic tail of II contains a motif that targets the II-MHC class II complexes to endosomal/lysosomal compartments where acidic proteases degrade II to a small fragment known as the class II-associated invariant chain peptide or CLIP, which remains associated with the MHC class II peptide binding groove (30, 31). Ag delivered into the endosomal/lysosomal network via receptor-mediated or fluid phase endocytosis are also exposed to proteases and denaturing reactions, yielding peptide ligands for class II molecules (32). CLIP removal and the capture of antigenic peptides by MHC class II proteins is catalyzed by the MHC-encoded molecule HLA-DM (33–35) and occurs in a highly specialized organelle resembling a late endosome/lysosome known as the MIIC (36). The resultant peptide-MHC class II complexes are ultimately trafficked to the cell surface for immune surveillance by CD4+ T cells.

In addition to its role in tumor immunity, autophagy may also contribute to the CD8+ T cell response to intracellular pathogens such as bacteria, parasites, and viruses. For example, autophagy is required for the clearance of several pathogens (reviewed in Refs. 18–20), including the parasite *Toxoplasma gondii*, which is localized in autophagosomes in infected macrophages (21, 22). Because CD8+ T cells are essential for protective immunity from *T. gondii* (23), it is possible that peptides derived from *T. gondii* access MHC class I molecules through autophagy. Several pathogens have been localized in autophagosomes that contain ER proteins (24), and perhaps components of the MHC class I presentation pathway such as class I molecules or TAP may also be found in autophagosomes. Furthermore, during periods of cellular stress, aggresome-like induced structures (ALIS) containing polyubiquitylated proteins are formed and serve as substrates for autophagy (25). ALIS can form in DC (designated DALIS) experiencing cellular stress, perhaps as a result of an infection by a pathogen, and the clearance of these DALIS by autophagy has been proposed as a source of peptides for MHC class I molecules (26).

**Autophagy and MHC class II Ag presentation**

Traditionally, MHC class II molecules present antigenic peptides derived from exogenous proteins to CD4+ T cells (27). MHC class II proteins are constitutively expressed on the surface of a number of professional APC such as DC, B cells, and macrophages, as well as both cortical and medullary thymic epithelial cells (cTEC and mTEC, respectively). Treatment with an inflammatory signal such as IFN-γ can induce MHC class II expression on the surfaces of nonprofessional APC such as endothelial cells, fibroblasts, epithelial cells, and many tumors.
Autophagy and the regulation of immune responses

Autophagy pathways may be induced or altered during infection and immunity as cellular stress responses are initiated. In vitro studies have demonstrated recognition of viral, self Ag, and tumor Ag dependent upon autophagy in the context of MHC class II Ag presentation. A role for autophagy in the cross-presentation of tumor Ag via MHC class I molecules has also been reported both in vitro and in vivo (14). Less is known about whether autophagy influences either CD4+ or CD8+ T cell responses to bacterial pathogens. A recent report on autophagy in the thymus provides a clue as to the importance of this process in the presentation of self Ag and its impact on the induction and maintenance of CD4+ T cell tolerance (55). The potential role of autophagy in regulating immune responses to pathogens, tumors, and self Ag has been reviewed extensively elsewhere (18, 41, 56, 57), with highlights of recent studies discussed here.

Intracellular pathogens

Studies have begun to examine the role of autophagy in a host cell’s defense against intracellular pathogens such as viruses and bacteria, although the precise molecular steps involving autophagy or autophagy-linked gene products are still poorly understood (reviewed in Refs. 41 and 58). Autophagy limits the virus-induced encephalitis observed during Sindbis virus infection through the interaction of the Atg6 gene Beclin 1 with Bcl-2 (59). Additionally, during the process of xenophagy, autophagosomes engulf and destroy viruses (7). For example, HSV-1 is degraded within autophagosomes in a dsRNA-activated protein kinase-dependent manner (60). Autophagy has recently been shown to play a role in the innate immune response to vesicular stomatitis virus (61). In plasmacytoid DC, autophagy facilitates the transport of vesicular stomatitis virus replication intermediates from the cytosol to lysosomes potentially to promote TLR7 engagement. Activation of TLR7 in DC results in the induction of important mediators of antiviral immunity such as IFN-α and IL-12. Plasmacytoid DC also recognize viruses.
through TLR9 localized in endosomes, and signaling through TLR9 recruits and activates the transcription factor IFN response factor 7, which is essential for the production of type I IFNs (62). Using rapamycin and siRNA against mTOR, Cao et al. recently demonstrated that virus-induced TLR9-dependent signaling through the mTOR pathway is also critical for the production of type I IFNs in plasmacytoid DC as well as bone marrow derived DC and macrophages (63). Whether signaling through mTOR following virus-induced activation of TLR9 affects the autophagy pathway during an innate antiviral immune response has yet to be investigated. Lastly, as discussed above, the MHC class II-mediated presentation of the EBV Ag EBNA1 by autophagy suggests that this pathway may also play a role in the adaptive immune response to viruses (48). The demonstration that targeting influenza MP1 to autophagosomes enhanced MHC class II presentation of the MP1 epitope (38) may suggest that in virally infected cells, fusion of autophagosomes containing viral particles with lysosomes could promote viral Ag association with class II for presentation to CD4+ T cells.

Host cells also use autophagy pathways in their defense against bacteria and parasites. Autophagy limits bacterial replication by enveloping free bacteria such as group A Streptococcus in autophagosomes for delivery to lysosomes (64) or by targeting phagosomes containing bacteria such as Mycobacterium tuberculosis for fusion with lysosomes (65, 66). The innate immune response initiated as a result of pathogenic infections also influences autophagy pathways. For example, signaling through TLR7 during infection of macrophages with Mycobacterium bovis bacilli Calmette-Guerin induces macroautophagy, resulting in the elimination of the intracellular bacteria (67). Furthermore, cytokine expression may modulate macroautophagy to limit pathogen replication. Type II IFN enhances the degradation of M. tuberculosis and Rickettsia conorii in infected cells (65, 66), and the TNF family member CD40 ligand induces macroautophagy to facilitate the fusion of phagosomes containing T. gondii with lysosomes during parasite infection (21). Finally, although the role of autophagy in the adaptive immune response to bacteria and parasites has not yet been carefully examined, it is possible that in infected cells the fusion of autophagosomes containing intracellular pathogens with lysosomes could be a mechanism by which bacterial or parasitic Ag associate with MHC class II molecules for presentation to CD4+ T cells.

Cancer

Similar to its role in infectious disease, autophagy is believed to contribute to both cancer development and tumor suppression (57). Autophagy may be induced during the later stages of oncogenesis as the rapid proliferation of the tumor depletes critical nutrients, thus suppressing further tumor growth. Additionally, following chemotherapy, tumor cells may initiate autophagy as a protective measure to recycle nutrients or remove damaged cellular components. For example, the induction of macroautophagy increases the survival of breast cancer cells undergoing treatment with 4-hydroxytamoxifen (68). Yet, how the modulation of autophagy pathways in tumor cells influences immune recognition and clearance has not yet been thoroughly investigated. As discussed above, one recent report suggests autophagy as a potential mechanism for the cross-presentation of tumor Ag onto MHC class I molecules. It is also possible that during the induction of autophagy within a tumor cell, the formation of autophagosomes might provide a source of tumor Ag that could intersect with MHC class II molecules upon fusion of the autophagosomes with lysosomes.

Autoimmunity and tolerance

Autophagy appears to also play a role in the breakdown of tolerance and the development of autoimmunity (reviewed in Refs. 41 and 69). During autophagy, contents of the cytosol and nucleus, including potential self-Ag, are degraded in lysosomal compartments where MHC class II molecules reside. Thus, alterations in autophagy pathways may lead to a breakdown in tolerance or to insufficient tolerance induction and the development of autoimmunity. A recent report by Nedjic et al. demonstrated that autophagy plays a key role in the generation and maintenance of tolerance in the thymus (55). In this study, autophagosomes were not readily detected in murine peripheral APC, yet cTEC, which express MHC class II molecules, were found to display high levels of constitutive macroautophagy. The authors postulated that macroautophagy within cTEC may favor the presentation of a broader spectrum of self Ag via class II on these cells. Using thymi from Atg5−/− mice, the authors evaluated the positive and negative selection of several MHC class II-restricted transgenic TCRs and found that the loss of Atg5 altered the selection of some, but not all, TCRs. These results suggested that in the absence of autophagy, the composition of peptide-MHC class II complexes on the surface of cTEC was altered, thus skewing the T cell repertoire that was positively selected. Additionally, the lack of autophagy may also prevent MHC class II presentation of certain tissue-specific Ag in medullary thymic epithelial cells, thus impairing negative selection and allowing autoreactive T cells to exit into the periphery. In support of this, the authors observed severe colitis and inflammation of multiple organs in athymic mice that received thymi from Atg5−/− mice. Studies of T cells deficient in Atg5 revealed defects in cellular proliferation and survival (70), suggesting further analysis of the role of this gene product in regulating T cell responses as well as the thymic microenvironment is needed.

In humans, recent studies have identified ATG16L1 (autophagy-related 16-like 1), which is involved in autophagosome formation, and IRGM GTPase, which stimulates autophagy, as susceptibility loci for Crohn’s disease (71–74). It has been proposed that mutations in these genes may lead to defective macroautophagy, thus impairing the innate immune response to bacterial infection and increasing the bacterial load in the gut, resulting in enhanced mucosal inflammation and the development of disease. A recent study using ATG16L1-deficient mice demonstrated an increase in the production of the inflammatory cytokines IL-1β and IL-18 and in the susceptibility to colitis (75). Alternatively, as the data from the Atg5−/− mice would suggest, inhibition of autophagy pathways might also lead to the failure to induce tolerance to mucosal self Ag. Lastly, the tissue damage associated with certain autoimmune diseases such as systemic lupus erythematosus has been attributed to the defective clearance of apoptotic cells. Macroautophagy plays a role in the removal of these apoptotic cell corpses, and the impairment of this process may result in the buildup of necrotic material in tissues and, thus, inflammation.
Conclusions
Multiple mechanisms, including CMA and macroautophagy, have been implicated in the delivery of several endogenous Ag to lysosomes for their eventual presentation by MHC class II molecules. Although substantial research has been conducted into the role of autophagy in MHC class II presentation of endogenous Ag, far less is known about autophagy in MHC class I presentation and cross-presentation pathways. Further studies are also needed to more clearly define the relationship between the various autophagy pathways and MHC class I and class II Ag presentation during the immune response to intracellular pathogens, tumors, and self Ag. Inhibition or enhancement of autophagy may alter the MHC class I and class II presentation of Ag to CD8+ or CD4+ T cells, respectively, thus providing novel therapeutic strategies for the treatment of infectious diseases, cancer, and autoimmunity.

Disclosures
The authors have no financial conflict of interest.

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