Abstract—Evidence is accumulating that autophagy occurs in advanced atherosclerotic plaques. Although there is an almost relentless discovery of molecules that are involved in autophagy, studies of selective autophagy induction or inhibition using knockout mice are just now beginning to reveal its biological significance. Most likely, autophagy safeguards plaque cells against cellular distress, in particular oxidative injury, by degrading the damaged intracellular material. In this way, autophagy is protective and contributes to cellular recovery in an unfavorable environment. Pharmacological approaches have recently been developed to stabilize vulnerable, rupture-prone lesions through induction of autophagy. This approach has proven to be successful in short-term studies. However, how autophagy induction affects processes such as inflammation remains to be elucidated and is currently under investigation. This review highlights the possibilities for exploiting autophagy as a drug target for plaque stabilization. (Arterioscler Thromb Vasc Biol. 2011;31:2787-2791.)

Key Words: atherosclerosis • pharmacology • autophagy • cell death • plaque stabilization

Autophagy in Atherosclerosis

A utophagy, or “self eating,” refers to a conserved cellular process for the turnover of organelles and proteins that occurs in all eukaryotic cells.1 It is activated as an adaptive response to environmental stress (eg, nutrient deprivation, hypoxia, oxidative stress, exposure to xenobiotics) to promote cell survival through the recycling of precursors (amino acids, free fatty acids, nucleotides) derived from the degradation of endogenous cellular components. Typical of autophagy is the formation of double-membrane structures, called phagophores, that engulf intracellular material such as protein aggregates, lipid droplets, and complete organelles for degradation (Figure 1). The phagophore expands and, on completion, forms an autophagosome, which then fuses with lysosomes, thereby generating an autophagolysosome.2 Incorporation of the outer autophagosomal membrane in the lysosomal membrane allows the degradation of the remaining inner single membrane and the cytoplasmic content of the autophagosome by lysosomal hydrolases. The molecular machinery and the signaling cascades that regulate autophagy are very complex and beyond the scope of this review, but they are nicely reviewed elsewhere.3,4

Autophagy generally acts as a housekeeping mechanism, and it is crucially involved in the maintenance of normal cellular homeostasis. When stimulated by cellular stress conditions, autophagy functions as a self-cannibalization pathway that promotes cell survival in an unfavorable environment. Preclinical studies have demonstrated that autophagy is associated with cancer, neurodegenerative disorders (eg, Alzheimer, Parkinson, and Huntington diseases), embryogenesis, aging, and immunity, and also with cardiovascular disease, including ischemia-reperfusion injury of the heart, cardiomyopathy, and atherosclerosis.5–9 Despite tremendous recent advances in the field, the functional significance of autophagy in human disease remains incompletely understood and potentially involves both adaptive and maladaptive outcomes. Nonetheless, a growing body of evidence suggests that manipulation of the signaling pathways regulating autophagy provides novel therapeutic strategies in the prevention or treatment of human disease, as discussed for atherosclerosis in more detail below.

Autophagy in Atherosclerosis

Because of technical limitations, in particular the lack of adequate marker proteins, autophagy in atherosclerotic plaques has not yet been analyzed in full detail. As a consequence, the role of autophagy in atherosclerosis is unclear and currently under intense investigation. However, transmission electron microscopy of smooth muscle cells (SMCs) in the fibrous cap of advanced plaques revealed ultrastructural features of autophagy, such as vacuolization and formation of myelin figures.7 The latter structures, composed of phospholipids and membrane fragments, refer to autophagic degradation of membranous cellular components. Moreover, Western blot analysis of human carotid plaques showed processing of microtubule-associated protein 1 light chain 3 (LC3) into the autophagosome-specific isoform...
factor deprivation, a well-known condition leading to induc- larsification, that is associated with nutrient and growth human atherosclerotic plaques, caused by inadequate vascu- inclusions have been found in SMCs of human plaques. Ten myelin figures, and LC3 processing, cytoplasmic ubiquitin mentioned above, and interpreted these events as increased autophagosome formation or LC3 processing, as groups, including our own laboratory, have measured in- autophagy data has to be done with great caution. Many material in an adequate way. Consequently, interpretation of activated state, is no longer able to remove the damaged cytoplasm of cells seem to represent autophagy failure, rather than activation of the process, as genetic knockdown of essential autophagy genes in mice leads to similar effects. Possibly, cellular damage in atherosclerotic plaques is often so overwhelming that the autophagic machinery, even in an activated state, is no longer able to remove the damaged material in an adequate way. Consequently, interpretation of autophagy data has to be done with great caution. Many groups, including our own laboratory, have measured increased autophagosome formation or LC3 processing, as mentioned above, and interpreted these events as increased autophagic activity. However, these parameters can also reflect impaired autophagic degradation. Therefore, it is essential to measure autophagic flux, which reflects the dynamic process of autophagosome formation, lysosomal fusion, and degradation. In tissue, this can be very challenging. A very elegant method now widely accepted to measure flux is using a tandem fusion protein of LC3 with the red acid-insensitive mCherry (or red fluorescent protein) protein and the green acid–sensitive green fluorescent protein to measure formation of autolysosomes and their degrada- tion. Green fluorescent protein fluorescence is quenched in the acidic environment of the lysosome, whereas mCherry (or red fluorescent protein) fluorescence is stable at low pH. As a consequence, detection of yellow fluorescence (overlap of green fluorescent protein and mCherry) reflects impaired flux, and the presence of red fluorescence reflects quenching of green fluorescent protein and thus ongoing degradation in the lysosome. Besides LC3, levels of other autophagy substrates can be used for measuring autophagic flux, of which the best studied is p62, an adaptor protein that links ubiquitinated proteins to LC3. Accumulation of p62 reflects impaired degradation in the autophagolysosome, whereas low p62 levels indicate active degradation. Unfortunately, no data are available on autophagic flux during atherosclerotic plaque formation and destabilization.

Beneficial Role of Autophagy in Atherosclerosis
Basal autophagy can protect plaque cells against oxidative stress by degrading damaged intracellular material, in particular polarized mitochondria. In this way, successful autophagy of the damaged components promotes cell survival. The protective role of autophagy in atherosclerosis was illustrated by in vitro findings showing that SMC death induced by low concentrations of statins is attenuated by the autophagy inducer 7-ketocholesterol. Probably, the engulf- ment of defective mitochondria by autophagosomes limits the release of proapoptotic proteins, such as cytochrome c, into the cytosol. Also, excess free cholesterol or exposure of SMCs to lipid peroxidation products, such as 4-hydroxynonenal, activates autophagy, thereby prolonging SMC survival. Similar to SMCs, exposure of endothelial cells in culture to oxidized lipoproteins or advanced glycation end-products induces autophagy, which is protective against endothelial cell injury. Altogether, induction of autophagy represents a vital component of a general stress response in vascular cells and could therefore be an important determinant of the stability of atherosclerotic plaques (Figure 2).

Figure 1. Schematic depiction of the autophagy process. A phagophore is formed at the initiation of autophagy to sequester cytoplasmic components for degradation. On completion, the phagophore forms a double-membraned vesicle called an autophagosome. After fusion with a lysosome, the content is degraded by lysosomal hydrolases (LH). Following breakdown, the resulting macromolecules (eg, nucleic acids, amino acids, free fatty acids) are released back into the cytosol for reuse by the cell.

LC3-II, indicating activation of autophagy. Indeed, in vitro studies identified several potential triggers for autophagy that are present in atherosclerotic plaques, such as inflammation, reactive oxygen species production, accumulation of oxidized lipoproteins, and endoplasmic reticulum stress. Also, hypoxia is a common feature of advanced human atherosclerotic plaques, caused by inadequate vascu- larization, that is associated with nutrient and growth factor deprivation, a well-known condition leading to induction of autophagy. In addition to autophagic vesicles, myelin figures, and LC3 processing, cytoplasmic ubiquitin inclusions have been found in SMCs of human plaques. Ten years ago, detection of such inclusions by immunohistochem- istry was an attractive non-electron microscopy–based tech- nique to detect autophagy in heart failure. New insights, however, have shown that ubiquitinated inclusions in the cytoplasm of cells seem to represent autophagy failure, rather than activation of the process, as genetic knockdown of essential autophagy genes in mice leads to similar effects. Possibly, cellular damage in atherosclerotic plaques is often so overwhelming that the autophagic machinery, even in an activated state, is no longer able to remove the damaged material in an adequate way. Consequently, interpretation of autophagy data has to be done with great caution. Many groups, including our own laboratory, have measured increased autophagosome formation or LC3 processing, as mentioned above, and interpreted these events as increased autophagic activity. However, these parameters can also

Detrimental Consequences of Autophagy in Atherosclerosis
In contrast to basal autophagy, excessive stimulation of autophagy in SMCs or endothelial cells may cause auto- phagic death. SMC death in turn results in plaque destabi- lization because of the reduced synthesis of collagen and thinning of the fibrous cap. Also, endothelial cell death may be detrimental for the structure of the plaque, as endothelial injury or death represents a primary mechanism for acute clinical events by promoting lesional thrombosis. Conversely, autophagic death of macrophages is considered a promising approach to stabilize advanced plaques. Recent evidence,
neighboring phagocytes. Moreover, severe oxidative stress has the potential to inhibit or stimulate the autophagy machinery at a basal or moderate stimulatory level. Over the past decade, there has been a true explosion of in vitro and in vivo evidence that demonstrates the beneficial effects of autophagy induction in atherosclerosis. However, several studies have shed light on the potential detrimental consequences of autophagy inhibition with regard to plaque stability.

To target autophagy as a tool for plaque stabilization, one needs to consider the different outcomes of autophagic cell death. Autophagic cell death is most likely detrimental, because this will accelerate other forms of cell death (apoptosis and necrosis) and impair the phagocytic process. However, indicates that phagocytosis of cells dying through autophagy results in an inflammatory response through inflammasome activation, interleukin-1β release, and subsequent interleukin-6 and tumor necrosis factor-α induction in neighboring phagocytes. Moreover, severe oxidative stress combined with autophagy leads to the formation of ceroid, a complex of protein associated with oxidized lipids. Ceroid deposits cannot be degraded by lysosomal hydrolases and might lead to preferential allocation of lysosomal enzymes to ceroid-loaded lysosomes at the expense of active autolysosomes, which in turn would lead to progressive inhibition of autophagy and the induction of apoptosis. In view of plaque stability and regression, these observations might advise against excessive autophagy induction in plaques (Figure 2).

Drug Targeting of Autophagy for Plaque Stabilization: For Better or for Worse?

Over the past decade, there has been a true explosion of in vitro studies discovering new or existing drugs that have the potential to inhibit or stimulate the autophagy machinery at a certain level in the signaling pathway, mainly in the setting of cancer or neurodegenerative diseases. Pharmacological modulation of autophagy can be achieved by targeting key players in the autophagy machinery. The classical pathway that regulates autophagy acts through mammalian target of rapamycin, a protein kinase that plays a key role as an intracellular nutrient sensor and controls protein synthesis, cell growth and metabolism. For example, rapamycin or its derivatives (eg, everolimus) inhibit mammalian target of rapamycin, thereby activating autophagy. Another way to modulate autophagy is to target the mammalian target of rapamycin–independent route, mainly regulated by inositol-1,4,5-triphosphate levels. This can be achieved with drugs such as lithium, sodium valproate, and carbamazepine. It should be noted that altering autophagy using pharmacological agents may have some additional effects, as these agents can interfere with general processes such as glucose metabolism (eg, metformin, deoxyglucose) or mitochondrial respiration (eg, oligomycin). Moreover, broad-spectrum phosphatidylinositol 3-kinase inhibitors, such as wortmannin and 3-methyladenine, which are widely used in autophagy research to inhibit the process, also inhibit activation of Akt. Thus far, there has been no specific inhibitor for autophagy. Because inhibition of Atg4 activity severely blocks autophagy and Atg4-specific substrates have recently been developed, the design of Atg4-specific inhibitors may be a promising approach to abrogate the process of autophagy.

Induction of Autophagy in Atherosclerosis

The first line of evidence that demonstrates the beneficial effects of autophagy induction in atherosclerosis was obtained after stent-based delivery of the rapamycin derivative everolimus in plaques of cholesterol-fed rabbits. This treatment resulted in a marked reduction of macrophages via autophagic cell death without affecting the SMCs. However, recent in vitro work in our laboratory has demonstrated that pharmacological induction of autophagy in macrophages triggers secretion of proinflammatory cytokines, such as interleukin-6, monocyte chemoattractant protein-1, Rantes, and tumor necrosis factor-α (W. Martinet and I. De Meyer, unpublished data, 2011), suggesting that the autophagic process is not immunologically silent. This cocktail of cytokines has the potential to induce SMC death and exacerbate the inflammatory infiltration of leukocytes in the plaque. Combined treatment with antiinflammatory agents, such as glucocorticosteroids, may help to prevent the adverse effects of drug-induced autophagy induction, hopefully without affecting the ability to deplete macrophages in atherosclerotic plaques.

Excess free cholesterol induces the activation of autophagy in SMCs in vitro as a cellular defense mechanism, possibly through the degradation of dysfunctional organelles, such as mitochondria and endoplasmic reticulum. Further induction of autophagy in these free cholesterol-loaded SMCs by rapamycin inhibited apoptotic cell death. These findings provide a rationale for the use of rapamycin or analogs, such as everolimus, to stabilize advanced atherosclerotic plaques.

Inhibition of Autophagy in Atherosclerosis

At present, the list of drugs with proven autophagy inhibitory capacity is as yet very short and limited to compounds that affect the lysosomal compartment (eg, bafilomycin A, chloroquine). None of these compounds have been specifically tested in a setting of atherosclerosis. However, several studies have shed light on the potential detrimental consequences of autophagy inhibition with regard to plaque stability. First, autophagy is essential for efficient phagocytosis of dying cells. Apoptotic cells derived from cells lacking essential autophagy genes (Atg5 or beclin-1) fail to present the “eat-me” signal phosphatidylserine and secrete lower levels of the “come-and-get-me” signal lysophosphatidylcholine. This will...
result in a marked decrease in the engulfment of apoptotic corpses, enhanced plaque necrosis, and recruitment of inflammatory cells.\(^{39,40}\) Thus, inhibition of autophagy may further destabilize advanced plaques, where phagocytosis of apoptotic cells is already compromised (Figure 2).\(^ {41}\)

Second, when autophagy is blocked in vitro by depletion of essential autophagy genes, such as beclin-1, Atg5, or Atg10, cells will not reveal autophagic vacuoles but instead are sensitized to undergo apoptosis or necrosis, indicating that a strong interaction exists between autophagy and other forms of cell death.\(^ {42}\) For example, inhibition of autophagy using 3-methyladenine in free cholesterol–treated SMCs enhances apoptosis and necrosis.\(^ {29}\) Moreover, in vivo experiments confirmed that the inactivation of Atg genes can cause apoptotic cell death.\(^ {43}\) Autophagy proteins can also exert proapoptotic functions by themselves. For example, Beclin-1 (Atg6), a key protein involved in autophagy, can interact with the antiapoptotic proteins Bcl-2 and Bcl-xL, and this binding is apoptotic and antiautophagic, at least under nonautophagic stimuli. However, during autophagic conditions, Beclin-1 binding to Bcl-xL is antiapoptotic.\(^ {44,45}\) In addition, Atg5 (when cleaved by activated calpain) can bind to Bcl-xL and induce apoptosis.\(^ {46,47}\) These data demonstrate that the cross-talk between autophagy and apoptosis should not be neglected when designing pharmaceutical interventions aimed at stabilizing atherosclerotic plaques via autophagy.

**Conclusion and Future Perspectives**

Autophagy may be viewed as a “cry for survival,” and such survival is the result of an adaptive response to fight against cellular stress. If this stress—such as oxidative damage in atherosclerotic plaques—is mild, autophagy is activated to survive. In this way, damaged, detrimental, and unwanted components can be easily removed. On the other hand, if cellular stress is overwhelming or continuous, the adaptive response fails and cells undergo an autophagic type of death. Nonetheless, several questions remain unanswered. For example, how long can we activate autophagy without detrimental consequences for the cell? Does autophagy have a significant impact on other cell death pathways in the plaque? Crossbreeding of mouse models for atherosclerosis (eg, apolipoprotein E or low-density lipoprotein receptor knock-out animals) with autophagy-deficient mice (eg, conditional Atg5 or Atg7 knockout animals) will undoubtedly help to answer these questions and may shed more light on the potential role of autophagy in atherosclerosis. Based on the literature and promising experiments in our laboratory and those of others, it is definite that cells need autophagy to be able to survive under stressful circumstances. Therefore, controlled (moderate) induction of autophagy, but not excessive induction or inhibition of autophagy, seems to be a promising strategy for stabilization of atherosclerotic plaques. The challenge for the future in the stabilization of atherosclerotic plaques will be to turn on the protective prosurvival effects of autophagy in a selective manner, without activating unwanted death pathways or proinflammatory signaling cascades. With progress being made in tissue-specific drug targeting using nanoparticles,\(^ {48}\) one potential future approach to stabilize atherosclerotic plaques would be to develop macrophage-specific autophagy inducers combined with antiinflammatory drugs. However, stimulation of autophagy can only be beneficial if autophagic flux is not impaired, because this condition could lead to lysosomal leakage or ejection of autophagosomes, as well as the induction of cell death.\(^ {22}\)

Furthermore, evidence is emerging for a role of histone deacetylases in both autophagy and atherosclerosis.\(^ {49–51}\) For example, histone deacetylase-1 inhibition promotes autophagy, whereas class I histone deacetylase inhibition decreases neointima formation in a murine model of vascular injury.\(^ {52}\) Because of their broad spectrum of effects and limited side effects, histone deacetylases are promising therapeutic targets for the treatment of atherosclerosis,\(^ {53}\) possibly through modulation of autophagy.

**Sources of Funding**

This work was supported by the Fund for Scientific Research-Flanders and the University of Antwerp.

**Disclosures**

None.

**References**


Autophagy in Atherosclerosis: A Potential Drug Target for Plaque Stabilization
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Arterioscler Thromb Vasc Biol. 2011;31:2787-2791
doi: 10.1161/ATVBAHA.111.224899
Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 1079-5642. Online ISSN: 1524-4636

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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