Premature senescence of endothelial cells: Methusaleh’s dilemma

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Chen, Jun, and Michael S. Goligorsky. Premature senescence of endothelial cells: Methusaleh’s dilemma. Am J Physiol Heart Circ Physiol 290: H1729–H1739, 2006; doi:10.1152/ajpheart.01103.2005.—Senescence has been considered a programmed cellular response, parallel to apoptosis, that is turned on when a cell reaches Hayflick’s limit. Once cells enter the senescence program, they cease to proliferate and undergo a series of morphological and functional changes. Studies support a central role for Rb protein in controlling this process after it receives senescent signals from the p53 and p16 pathways. Cellular senescence is considered an essential contributor to the aging process and has been shown to be an important tumor suppression mechanism. In addition, emerging evidence suggests that senescence may also be involved in the pathogenesis of stem cell dysfunction and chronic human diseases. Under these circumstances cells undergo stress-induced premature senescence, which has several specific features. Focusing on endothelial cells, we discuss recent advances in our understanding of the stresses and their pathways that prompt the premature senescence response, evaluate their correlation with the apoptotic response, and examine their links to the development of chronic diseases and the impaired function of endothelial progenitor cells, with the emphasis on vasculopathy. Emerging novel therapeutic interventions based on recent experimental findings are also reviewed.

stress-induced premature senescence; endothelial progenitor cell; vasculopathy; metabolic syndrome; nephropathy

HISTORY OF SENESCENCE RESEARCH

Cessation of cell division after extended propagation in culture was first observed by Hayflick and Moorhead (61) in normal human fibroblasts in 1961, igniting research on cell senescence. This type of senescence, which usually requires weeks or months of culture, appeared to be related to the limited number of divisions that any particular cell type could undergo (thus determining its lifespan) and is termed replicative senescence. The bulk of evidence has linked senescence to the attrition of telomeres (60), which leads to chromosomal instability. In addition to telomere attrition, some stressors elicit a similar growth arrest within just a few days, referred to as stress-induced premature senescence (SIPS). The stressors that have been identified include activated oncogenes (17, 46, 117), DNA damage (50, 82, 96), oxidative stress (31, 119), suboptimal cell culture conditions (7, 8), and others (115, 143, 149). In either type of senescence, cells flatten and enlarge, acquiring a “fried egg” appearance. Initially thought to be a cell culture phenomenon, cell senescence has been more recently observed in vivo (30, 41, 44, 147). In addition to the above morphological changes, the recognized biomarkers of senescent cells include staining for β-galactosidase at pH of 6.0 [known as senescence-associated β-galactosidase (SA-β-gal) as opposed to the endogenous lysosomal enzyme detected at pH of 4.0 in normal cells]; decreased replicative capacity; increased expression of p53, p21, and/or p16 (vide infra) or other cyclin-dependent kinase inhibitors (e.g. p27 and p15); and accumulation of transcriptionally inactive heterochromatic structure [senescence-associated heterochromatic foci (SAHF)] (113). It is worth noting that many of the concepts related to senescence are developed from studies of human fibroblasts and from some immortalized cell lines; therefore, those concepts may be not fully relevant to primary endothelial cells.

REGULATION OF SENESCENCE

The above changes in cells undergoing replicative or SIPS have been mechanistically linked to the stabilization of p53 and hypophosphorylation of pRb. There is evidence supporting a linear p53-p21-pRb pathway (17, 32, 93) (Fig. 1). Overexpression of the tumor suppressor p53 results in transcriptional activation of many proteins, including p21, an inhibitor of the cyclin E/Cdk2 complex (87). Inhibition of this complex enables the maintenance of the hypophosphorylated (active) state of the Rb protein, which has been shown to interact with the transcription factor E2F family members and silence their transcriptional targets by invoking SAHF formation through the recruitment of heterochromatin proteins to E2F-responsive promoters (113). On the other hand, the activation of p16, an inhibitor of the cyclin D/Cdk4 and D/Cdk6 complex, provides an additional stimulatory pathway that maintains the Rb in its active state and hence leads to the induction of senescence (12, 84). Studies in mouse embryo fibroblasts have provided evidence that two other members of the Rb family, p107 and p130, may also be important factors for the senescent program because their inactivation was found to be necessary and sufficient to prevent senescence in Rb-mutated cells (39, 128). The contribution of these two proteins to the senescent programs in other cell types is currently under investigation.

Telomere shortening has been considered a hallmark of replicative senescence. It appears that the unprotected telomere structure can initiate DNA damage response and induce cell
senescence by activating the ATM-p53-p21-pRb pathway (64),
and that p16 has an important, but nonessential, role in this
senescence process in the human fibroblast (20, 78). However,
it may still possess a significant role in cells such as human
prostate epithelial cells (79). Recent evidence suggests that
telomere shortening may not be an indispensable element for
SIPS, which can usually be induced in days, and is unaltered by
experimental telomere extension through exogenous over
expression of human telomerase (hTERT) (53, 110). Oxidative
stress and the oncogenic ras expression appear to activate the
senescence program mainly by involving the p16-pRb pathway
through the mediation of the p38/MAPK signaling cascade
(21, 40, 89, 152). Although these processes have been studied
separately in vitro to permit dissection of the pathway in-
volved, this does not preclude the possibility that both the
telomere shortening-initiated and stress-induced senescent
types may jointly contribute to the pathogenic process of
chronic diseases in vivo.

It is worth noting that the signal cascades before the activa-
tion of p53 and p16 pathways remain poorly understood, and
the signal pathway downstream of Rb/E2F that results in the
various morphological and functional changes of senescence
remains largely unexplored. There is also an ongoing debate as
to the necessity and sufficiency of each of these tumor sup-
pressor pathways in cell entry to senescence. In mouse embryo
fibroblasts, these pathways may function independently,
whereas both pathways may be involved in human fibroblasts
(42, 76). It has been proposed that “distinct senescence pro-
grams can progress in parallel, resulting in mosaic cultures,”
here some cells overexpress p21 or p16 or both (12).

Little is known about senescence and SIPS of endothelial
cells. In aging vasculature, senescence has been found in
association with the accumulation of mitochondria peroxyni-
trite in endothelial cells (147). Proatherogenic and proinflam-
matory factors like oxidized LDL, TNF-α, or hydrogen pero-
oxide have been implicated in SIPS and shown to result in the
inhibition of phosphoinositols 3-kinase/Akt and suppression of
telomerase activity without discernible attrition of telomeres
(16). Chronic exposure of human umbilical vein endothelial
cells (HUVEC) to the nontoxic doses of tert-butyl-hydro-
peroxide or to an inhibitor of glutathione synthesis buthi-
one sulfoxamine resulted in the accelerated development of
senescence after 30 versus 46 population doublings (88). This
was accomplished by faster shortening of telomeres, their
increased heterogeneity, and decreased telomerase activity,
suggesting a key role for antioxidant cellular defense, specif-
ically glutathione, in the maintenance of telomerase activity
and telomere integrity. We found that culturing HUVEC on the
surface of nonenzymatically glycated collagen I leads to in-
creased proportion of SA-β-gal-positive endothelial cells in
a much shorter period of time. Whereas changes of telomeres or
in telomerase activity were undetectable compared with cells
cultured on native collagen, oxidative stress was markedly
increased (30).

Senescent endothelial cells are characterized by decreased
production of nitric oxide (NO), changes in expression or
phosphorylation of endothelial NO synthase (eNOS),
decreased synthesis of prostacyclin, increased expression of plas-
mogen activator inhibitor-1, and enhanced adhesiveness for
monocytes (37, 67, 97, 101, 111, 129). When human endothe-
lial cells enter SIPS under the oxidative stress induced by
glycated collagen (GC), we have found that despite an approxi-
ately twofold increase in the expression of immunodetectable
eNOS, calcium ionophore-stimulated NO release was
reduced (<50% of control), and 3-nitrotyrosine (3NT)-modi-
fied proteins, the footprint of peroxynitrite production, accu-
mulated. NO production and escape from senescence could be
achieved by use of a NO donor (hydroxy-L-arginine), super-
oxide dismutase mimetic manganese (III) meso-tetrakis (4-
benzoic acid) porphyrin, (MnTBAP), or peroxynitrite scavenger-
antioxidant (ebselen), arguing in favor of oxidonitrosative
stress as a proximal cause of SIPS in this model.

RELATION BETWEEN SENESCENCE AND APOPTOSIS

Many of the stressors described above can induce apoptosis
as well as initiate the senescent program, and both of these
responses have been shown to share some common elements in
the stress-activated signal pathways. How the cell chooses
between these two responses remains obscure. Several studies
have attempted to elucidate the mechanism by which a specific
outcome results from a certain type of stress. It has been
demonstrated that cells in the S-phase commit to apoptosis
when subjected to sublethal concentrations of H2O2; in con-
trast, cells in the G1 and G2/M phases commit to growth arrest
(33). In addition, the degree of the stress seems to play an
important role. Whereas a low dose of the oxidative stressor
H2O2 can induce senescence in the diploid human fibroblast,
apoptosis is the predominant outcome when cells are chal-
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point(s). Whereas cells are induced to apoptosis under stress, they will switch to senescence once their apoptosis pathway has been blocked either by exogenous overexpression of the bcl-2 gene (124) or by applying caspase inhibitors (122). On the other hand, it has been shown that aging enhances the sensitivity of endothelial cells toward apoptotic stimuli (67), and in some cases, the apoptosis program may spontaneously occur in senescent human and bovine endothelial cells (30, 144, 151, 161). In contrast to endothelial cells, human fibroblasts enter a stable growth arrest phenotype at the end of their lifespan and are resistant to various apoptotic stimuli (58). Interestingly, instead of undergoing p53-dependent apoptosis under conditions of DNA damage induced by a variety of genotoxic stressors, senescent fibroblasts underwent necrosis instead, which may result from their failure to stabilize p53 (135). These results again exemplify the varied senescent programs seen in different cell types.

LYSOSOMAL-MITOCHONDRIAL INTERACTION IN SIPS:
A HYPOTHESIS

Detection of senescent cells is based on the SA-β-gal assay, the molecular basis of which is still obscure (41). β-Gal is a lysosomal hydrolase cleaving β-linked terminal galactosyl residues from gangliosides, glycoproteins, and glycosaminoglycans. Its pH optimum is acidic (4–4.5), thus the appearance of the enzyme in the cytosol, as it occurs in cell senescence, could signify the loss of enzymatic activity. Why does the enzyme shift from the lysosomes to the cytosol? It has recently been demonstrated that p53 destabilizes and permeabilizes lysosomes (159), and this occurs before the effects of p53 induction on the mitochondrial permeability transition responsible for triggering apoptosis. Therefore, a plausible mechanism for the appearance of SA-β-gal cytoplasmatic staining with the build-up of undegraded gangliosides is emerging. The role of p16, another marker of cell senescence, remains obscure. We hypothesize that as long as cellular gangliosides are below a certain threshold, the predominant effect of stress-induced p53 would be cell cycle arrest and senescence-like phenotype. Upon reaching a threshold level, gangliosides exert their effect on the mitochondrion leading, in tandem with the effect of p53, to the permeability transition, escape of cytochrome c, ATP, caspases and protease activating factor-1 (APAF-1), formation of apoptosomal complex (700 kDa), which cleaves downstream caspasas, and heralds cell’s commitment to apoptosis. Numbers along the pathways denote the sequence of events.

Fig. 2. Hypothetical involvement of dysfunctional lysosome in premature senescence. It has recently been demonstrated that p53 destabilizes and permeabilizes lysosomes, and this occurs before p53 effects on mitochondrial permeability transition and commitment to apoptosis. Appearance of β-Gal, a lysosomal hydrolase, in the cytosol, as it occurs in cell senescence, could signify the loss of its enzymatic activity and the subsequent build-up of undegraded gangliosides. We hypothesize that as long as cellular gangliosides are below a certain threshold, the predominant effect of stress-induced p53 would be cell cycle arrest and senescence-like phenotype. Upon reaching a threshold level, gangliosides exert their effect on the mitochondrion leading, in tandem with the effect of p53, to the permeability transition, escape of cytochrome c, ATP, caspases and protease activating factor-1 (APAF-1), formation of apoptosomal complex (700 kDa), which cleaves downstream caspasas and heralds cell’s commitment to apoptosis. Numbers along the pathways denote the sequence of events.

Gangliosides synthesis did not appreciably affect cell senescence, it clearly prevented development of apoptosis (data not shown). These findings further support the proposed model where accumulation of gangliosides acts as a switch from senescence to apoptosis.

SENESCENCE AND DISEASES

In the field of cancer biology, suppression of senescence invariably predisposes animals to tumorigenesis, giving rise to the belief that cell senescence may have a protective role in vivo (3, 24, 100, 133, 137). Under certain irreparable stresses, normal cells will commit to a senescence program in which the senescent cells retain a relatively intact structure. One can speculate that this may help to maintain tissue structure in the event of sudden and diffuse cell death. However, senescence results in many deleterious structural changes, such as increased adhesion to extracellular matrix while losing cell-cell contacts and dramatic changes in chromatin structure and gene expression (113, 136, 138). In addition, senescence impairs normal cell function (25). In HIV-infected subjects, CD8+ T lymphocytes that displayed short telomeres could no longer proliferate and lost their cytotoxic efficiency to combat the virus (38, 43). Our in vitro studies indicate that prematurely senescent endothelial cells showed evidence of an impaired arginine-eNOS-NO functional system, changes similar to the aged endothelium of macrovasculature (147).

Evidence points to an important contribution of senescence to certain age-related diseases as has been suggested by our
recent studies and the studies from other research groups. Accumulation of senescent myocytes with significant telomeric shortening has been detected in aged hearts with dilated cardiomyopathy (34). Cellular senescence also has a proposed role in the deterioration of renal graft function, which has been associated with telomere shortening and subsequent activation of p21 and p16 (81, 104). In human atherosclerotic lesions, overexpression of p53 and p21 has been found in nonproliferating endothelial and smooth muscle cells (71), and SA-β-gal-positive cells have been detected in human atherosclerotic plaques in the coronary artery and in injured rabbit carotid arteries (45, 107, 108). In Zucker diabetic fatty rats, we observed an increase in the number of SA-β-gal-positive cells in the aortic endothelium and at ostia of intercostal arteries accompanied by upregulated p53, p21, and p16 expression as well as elevated oxidative stress (18, 30). The development of diabetic microvasculopathy may also be related to the endothelial senescence as discussed in more detail later in this review.

Interestingly, it has been noticed that, even though mitotically inactive, senescent cells are far from being physiologically inert. Many genes in senescent cells display higher expression levels that do not merely correlate with cell cycle arrest (160). Senescent cells can secrete proteins, including degradative enzymes, inflammatory cytokines, and growth factors that may stimulate tissue aging and tumorigenesis and hence possess a more complex role in promoting chronic diseases (25, 26, 156). For instance, an immortal, but nontumorigenic, mouse mammary epithelial cell line will acquire tumorigenic capability and form malignant tumors when injected into mice with irradiation-induced senescent human fibroblasts (118). This was at least partly mediated by matrix metalloproteinase-3, an enzyme secreted by the senescent cells.

Recently, endothelial progenitor cells (EPCs) have been shown to have an important role in maintaining endothelium integrity and repairing its damage (145). Increasing evidence suggests that EPC may originate from several bone marrow cell populations. According to the initial description, EPCs are defined as cells expressing both hematopoietic stem cell markers, such as CD34 and CD133, and endothelial markers such as vascular endothelial growth factor receptor-2 and Tie-2 (4, 49, 59). Other reports suggest that myelo/monocytic cells can give rise to endothelial cells as well, especially the CD14+/CD133+ myeloid cell population (131, 146). In addition, a subset of mesenchymal stem cells (termed multipotent adult progenitor cells) has the ability to differentiate into multiple cells types, including mature, functional endothelial cells (80, 123). They may represent a unique subset of EPCs. The above bone marrow-derived EPC can home to sites of ischemia and to damaged vessels. Infusion of EPCs was shown to augment capillary density and neovascularization of ischemic tissues, including infarcted myocardium (4, 85, 116), ischemic limbs (4, 5), or brain (162). Emerging evidence indicates that EPCs may play a critical role in the maintenance of intact vascular endothelium and in the repair of endothelial injury through the process of reendothelization as exemplified by atherosclerotic lesions (107, 121), direct mechanical injury to the endothelium (77), as well as inflammatory damage (158).

The balance between injury and repair is a life-long, carefully guarded process. The activation of local resident stem cells or the recruitment of circulating stem and progenitor cells may be a very important event during this process. A recent report indicated that early display of age-related endothelial dysfunction may be more strongly correlated to impaired EPC activity rather than decreased number when healthy young and old individuals were compared (63). Nonetheless, a study in the healthy individuals who bear cardiovascular risk factors has revealed a strong correlation between the number of circulation EPCs and the subjects’ combined Framingham risk factor score and the endothelial function (66). EPC level is suggested to be a surrogate biological marker for vascular function and cumulative cardiovascular risk.

Like any other cell type, EPCs are subjected to various stressors that could impair their function and proliferative capability. Circulating EPCs in healthy smokers exhibit impaired functional activities (66, 105). Hyperglycemia has been reported to reduce survival and impair function of EPCs (86). There is growing evidence that senescence may serve as an important mechanism mediating EPC dysfunction. Decreased numbers and an increased proportion of senescent EPC has been reported in patients with preeclampsia (141). Accelerated EPC senescence has also been noted in both experimental hypertensive rats and patients with essential hypertension (66, 75). Angiotensin II can induce EPC senescence through the induction of oxidative stress and influence telomerase activity (72). Oxidized low-density lipoprotein induces EPC senescence and leads to cellular dysfunction (74). EPCs from Type II diabetics exhibit impaired proliferation, adhesion, and engraftment in vascular structures (142). Except all of the pathological conditions mentioned above, EPC dysfunction has also been documented in Type I diabetes (95, 142), coronary artery disease (148, 155), atherosclerosis (107, 121), rheumatoid arthritis (54, 65), vasculitis with kidney involvement (69), and end-stage renal disease (27, 36).

**DIABETIC VASCULOPATHY AND SENESCENCE**

Even though the role of cell senescence in vascular biology remains underdeveloped, the adverse effects of endothelial SIPS appear to be obvious: the rapid development of macro- and microangiopathy as has been suggested by our recent studies and discussed briefly below.

Diabetic microvascular and macrovascular injury is central to the development of renal, retinal, neurological, and cardiovascular complications (22). In the early pathogenesis of diabetes, hyperglycemia perturbs several key vascular endothelial functions, leading to endothelial cell dysfunction, which is intimately linked to the impaired balance of the L-arginine-eNOS-NO system (52). These vascular alterations are thought to be of relevance to the onset and progression of diabetic complications (68, 114, 125).

Among the several proposed underlying mechanisms for hyperglycemia-induced vascular damage, evidence indicates a major role for increased advanced glycation end-products (AGEs). formation (29, 90, 132, 153). AGE precursors arise from the nonenzymatic reactions between glucose/glucose-derived dicarboxyls and cellular proteins, known collectively as Maillard reactions, which represent a series of reactions of rearrangement, dehydration, oxidation, and fragmentation of glucose or its adducts to protein (9). As a result of its chemical and structural alteration (62), AGEs cause excessive cytotoxic stress to the vascular system. In endothelial cells exposed to
high glucose, intracellular AGE formation can occur within a week. In long-living tissue proteins, like collagen, AGE will accumulate over time at a rate that correlates with the protein half-life. During diabetes, AGEs are formed at an accelerating rate (157) resulting in very high tissue levels (23, 70).

We have examined the contribution of endothelial cell senescence to the pathogenesis of diabetic vasculopathy by using a glycated collagen I (GC)/endothelial cell culture system (30). We found that the senescent phenotype can be induced in early-passage HUVEC when cultured on a glycated matrix protein collagen I. An increased frequency of prematurely senescent cells, as judged by the presence of SA-β gal and overexpression of p53, p21, and p16, was similarly observed in the endothelium of aortas from 22-wk-old Zucker diabetic fat (ZDF) rats compared to Zucker lean (ZL) controls (Fig. 3, A and B).

![Image](http://ajpheart.physiology.org/DownloadedFrom)

**Fig. 3.** Vignettes illustrating the extent and mechanisms of vasculopathy in Zucker diabetic fatty rats and the results of treatment with ebselen (Ebs, E). A: en face view of SA-β-galactosidase expression by the aortic endothelium in 22-wk-old Zucker diabetic fatty rats and prevention of endothelial cell senescence with chronic ebselen treatment. B: thoracic aortic cross-sections and the expression of p53, p16, and p21 by endothelial cells. Representative images obtained from 22-wk-old ZL, ZDF, and ZDF + ebselen rat aortas. C: functional characteristics of prematurely senescent vasculature (a, diminished NO production; b, impaired vasorelaxation; c, maintenance of total pterin levels and reduction of tetrahydrobiopterin level). For NO production and aorta relaxation levels (Ca and Cb): *P < 0.05 vs. ZL 22w, ZL 22w +E, and ZDF 22w + E; #P < 0.05 vs. ZDF 22w. For BH4 levels (Cc): *P < 0.05 vs. 8-wk-old ZL rats; **P < 0.01 vs. 22-wk-old ZL rats; ***P < 0.01 vs. 22-wk-old ZDF rats. For BH4 levels (Cc): #P < 0.05 vs. 22-wk-old ZL rats; ##P < 0.05 vs. 22-wk-old ZDF rats. Compiled and modified from Brodsky et al. (18) and Chander et al. (28).
Separate experiments were performed to quantify the number of senescent endothelial cells in the aorta and correlate it with parameters characteristic of endothelial dysfunction, including the measurement of NO production, the vascular reactivity to acetylcholine, abundance of endothelial microparticles in the circulation, and the angiogenic competence of various vascular beds (18, 28, 48). Our results indicate that accumulation of senescent endothelial cells in the aorta of 16- to 22-wk-old ZDF rats is accompanied by reduced NO production and severely impaired acetylcholine-induced vasorelaxation (Fig. 3C, left and middle). The ability to form collateral blood vessels after femoral artery ligation is also noticeably reduced as assessed by laser Doppler flowmetry/imaging and histochernical detection of the capillary density in the affected striated muscle (18). Similar results were obtained by an ex vivo angiogenesis assay (19).

The development of microvasculopathy was also evaluated in the kidney of ZDF rats. At 22 wk of age, these animals developed proteinuria and a reduced creatinine clearance. Histological assessment showed that both the glomerulosclerosis and tubulointerstitial scarring index increased and focal segmental glomerulosclerosis was observed in 9.5 ± 1.8% glomeruli. Oil-Red-O staining revealed widespread lipid deposits (28, 47). Immunodetectable 3NT, a footprint of peroxynitrite formation and oxidative stress (28, 30), as well as immunodetectable lipid peroxides, were both significantly elevated in tissues of 22-wk-old ZDF rats compared to age-matched ZL rats. The levels of glutathione and tetrahydrobiopterin in the renal tissue were markedly reduced in 22-wk-old ZDF (Fig. 3C, right). Collectively, these findings are indicative of oxidative and nitrosative stress in ZDF rats, operant at 22 wk, in the tubules, glomeruli, and throughout the vascular tree, particularly the endothelium.

**THERAPEUTIC HORIZONS**

The so-called anti-aging therapy would be, at least conceptually, aimed at “reversing age-related changes...and decelerating or preventing aging changes” (57). In practice, the approaches that are being proposed to modulate aging in a wide variety of organisms commonly bear the ultimate aim of improving the quality of human life in old age. The approaches that have been tested include gene therapy, stem cell transfusion, hormonal supplementation, nutritional modulation, and intervention by antioxidants and other molecules (55, 98, 120).

On the basis of studies of aging, cellular senescence, and calorie restriction (the only experimental manipulation that is known to extend the lifespan of a number of organisms), several genes have been tested for gene therapy. These genes include, but are not limited to, the following: the DNA-associated proteins, such as Rad51 and Rad54, which may provide more efficient gene repair in human cells (94); the p66shc gene, which controls the production of reactive oxygen species (ROS) (106); the reverse transcriptase protein component of telomerase (hTERT), which has served as a target gene for transducing targeted cells, or a targeted antigen itself for cancer immunotherapy (102, 127, 134, 150); the Sirt1 gene, a mammalian homology of SIR2 that encodes an NAD-dependent deacetylase in yeast and may mediate the effects of calorie restriction (15, 56).

Given the unique abilities of stem cells to self-renew, differentiate, and proliferate, they are critically important to an organism not only during development but also for homeostasis. The anticipated therapeutic potential of utilizing stem cells for the treatment of many chronic human diseases has created much attention. The feasibility of the strategy of stem cell transfusion has been tested with many promising results reported (11, 13, 109, 126, 130). Some investigators have been trying to preserve the endothelial progenitor cell population from early onset of senescence by using, for instance, 3-hydroxy-3-methylglutaryl coenzyme A reductase inhibition (statins) or estrogen (6, 73, 140). Detailed analysis of these strategies is beyond the scope of this review, and interested readers are referred to the excellent reviews mentioned above. In the following, we focus our discussion on antioxidant therapy and summarize some of our in vitro and in vivo study results related to this strategy.

Whereas in short-lived species, antioxidant treatment has been successful in prolonging lifespan (83), this has not been the case in mammals. The lifespan was unchanged in middle-age mice receiving lipoic acid or coenzyme Q10 antioxidant supplements but increased by 13% in mice receiving caloric restriction (91). Antioxidant therapy was reported to be ineffective in prolonging the lifespan in mammalian model systems, but there is evidence that antioxidant treatment protects against age-related dysfunction, including cognitive decline, as discussed in a recent review (51). On the other hand, targeted mutation of mouse p66shc gene, which controls the production of ROS, induces resistance to stress and a 30% increase in lifespan. Improvement of vascular function in p66shc ablated aging mice has been observed, and the p53/p21 stress response pathway is impaired in p66shc−/− cells (106). The deletion of p66shc was shown to reduce systemic and tissue oxidative stress, vascular cell apoptosis, and early atherogenesis in mice fed a high-fat diet (112). In this regard, it is intriguing to note that calorie restriction can also increase the resistance to oxidative stress (139), which is believed to contribute to the beneficial outcomes of calorie restriction.

Senescence has been classically viewed as a state of permanent growth arrest, and hence cells are rendered unable to re-enter the cell cycle. Though this concept is still widely accepted, recent studies have provided evidence indicating that under certain conditions senescence is reversible, at least in the early stages. Stable suppression of p53 expression in senescent mouse embryo fibroblasts through RNA interference leads to rapid cell cycle re-entry and to immortalization, indicating that both initiation and maintenance of senescence is p53 dependent (6). In a separate experiment, senescent human fibroblasts and mammalian epithelial cells with low levels of p16 resumed robust growth after inactivation of p53, whereas those with high levels of p16 remained senescent. Exogenous expression of oncogenic ras can also induce limited growth in the same low p16 level senescent cell population (10), Caveolin-1 reduction, using an antisense and small interfering RNA strategy, can also induce senescent human fibroblasts to re-enter cell cycle upon epidermal growth factor stimulation (35).

We have tested the hypothesis that premature endothelial cell senescence is not only preventable but also reversible. Based on the finding of enhanced peroxynitrite formation in aging and stressed vasculature (30, 147), we performed a series of in vitro and in vivo experiments addressing the effect of a...
bona fide peroxynitrite scavenger and antioxidant ebselen. This seleno-organic compound scavenging peroxynitrite (99) was able to prevent and reverse senescence of early-passage HUVECs and preserve functional activity of eNOS in vitro by scavenging peroxynitrite (18, 30). The ability to prevent and reverse vascular dysfunction was tested in vivo by treating ZDF rats with ebselen between the ages of 8 to 22 wk (treatment initiated when the hyperglycemia has just developed), 13 to 22 wk, or 16 to 22 wk (treatment initiated when vasculopathy was already present) (18, 28, 47). Our results indicate that ebselen cannot only prevent macro- and microvasculopathy in Zucker diabetic fatty rats when administered from weeks 8 to 22 but partially reverses vasculopathy when administered from weeks 13 to 22 (i.e., starting shortly after the early onset of vasculopathy). This was accompanied by the prevention and reversal of endothelial cell senescence in the aorta. The above effects either diminish or disappear when administration of ebselen starts at week 16 and lasts until 22 wk of age in Zucker diabetic fatty rats.

Macro- and microvascular complications of metabolic syndrome and diabetes are among leading causes of morbidity and mortality. Tight glucose control alone is insufficient to prevent macrovasculopathy, but there are indications that the soluble extracellular portion of the AGE receptor or AGE “breakers” are capable of preventing these complications (154). Notably, both agents are acting on the upstream, prereceptor mechanisms of endothelial dysfunction. Ebselen therapy, on the other hand, targets downstream, postreceptor cellular consequences of endothelial oxidative stress. One of the possible attractive features of selenorganic compounds is their combined peroxynitrite scavenging and antioxidant effect (99), thus, potentially not only preventing further oxidant stress, but also accelerating the clearance of preformed 3-NT-modified proteins. Indeed, the fact that ebselen not only prevents, but also reverses, the preexisting vasculopathy makes it a promising therapeutic agent.

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