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Contemporary approaches in anti-aging therapy

Ionela Daniela Ferțu [1,2], Claudia Simona Stefan [1,2*], Ancuta Dinu Iacob [1,2], Simona Steliana Tudor [1,2]

[1] Department of Pharmaceutical Sciences, Faculty of Medicine and Pharmacy, "Dunarea de Jos" University, Galati, ROMANIA
[2] Medical and Pharmaceutical Research Center, Faculty of Medicine and Pharmacy, "Dunarea de Jos" University, Galati, ROMANIA
***Corresponding Author:** claudia.stefan@ugal.ro

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ABSTRACT

Aging is a complex biological process influenced by genetic, epigenetic, and environmental factors. The development of anti-aging therapies has become a major area of interest in biomedical sciences, aiming to both extend life span and improve their quality. Identifying safe, accessible, and non-invasive interventions capable of moderating the pace of the aging process and promoting healthy senescence could have a substantial impact on both the quality of life and the sustainability of healthcare systems for the elderly population. Although numerous supplements and interventions available on the market claim the ability to slow down the aging process, the scientific validation of these claims remains, in most cases, insufficient or non-existent. This paper reviews current anti-aging therapies, including pharmacological interventions, gene therapies, and regenerative methods. Their efficacy, mechanisms of action, and challenges associated with clinical application are also discussed.

Keywords: anti-aging therapies, aging, pathologies, remedies, risk factors

INTRODUCTION

With economic and medical development, the lifespan of human beings continues to increase, and healthy aging is becoming an increasingly common desire throughout the world [1]. The field of study of the physiological aging process and age-related pathologies with major implications for longevity, decline in quality of life in old age, and the costs of healthcare in the later stages of life. The identification and implementation of interventions capable of moderating the pace of aging, delaying the manifestation of age-related conditions, and supporting the maintenance of physical functionality and vitality would represent a significant advance in optimizing geriatric health. However, the proliferation of anti-aging therapies has led to a market dominated by remedies lacking a scientific basis. Therefore, specialists in the field must provide solutions to these challenges through systematic investigation, based on rigorous and reproducible methodologies, to identify those strategies with a demonstrable impact on healthy aging. Cellular aging is determined by the progressive accumulation of damage at the molecular and cellular levels, being influenced by oxidative stress, inflammation, and mitochondrial dysfunction. Genomic instability, telomere attrition, epigenetic modifications, loss of proteostasis, deactivated macroautophagy, nutrient sensitivity dysregulation, mitochondrial dysfunction, cellular senescence, stem cell depletion, altered intercellular communication, and chronic inflammation are hallmarks of aging on which specialists have the role of acting through specific therapeutic interventions. In recent decades, advances in the biology of aging have led to the development of therapies aimed at slowing or reversing the effects of this process. Among the most studied methods are the use of senolytics, caloric restriction, gene therapy, and regenerative medicine. The purpose of this article is to analyze the most recent anti-aging therapeutic strategies and their impact on human longevity.

MATERIALS AND METHODS

This study was designed as a narrative review that aims to synthesize and critically discuss current knowledge about anti-aging therapies, their biological mechanisms, and their clinical relevance. The approach to this review was intentionally qualitative, focusing on conceptual integration and thematic interpretation rather than quantitative aggregation of evidence. The relevant scientific literature was explored using major international scientific databases, including PubMed, ScienceDirect, and Google Scholar, selected for their broad coverage of biomedical and life sciences research. Additional relevant sources were identified by manual screening of reference lists of key publications.

The selection of scientific literature was guided by relevance to the topic of this study, namely, aging and anti-aging interventions, scientific rigor, and contribution to the understanding of mechanisms, therapeutic potential, and limitations of current strategies. The focus was on peer-reviewed articles published predominantly within the last decade, without applying rigid temporal or numerical constraints, in order to capture both fundamental and complementary perspectives.

Key terms related to the biology of aging and therapeutic interventions (e.g., anti-aging therapies, aging mechanisms,

senescence, regenerative medicine, caloric restriction, and bioactive compounds) were used flexibly to identify relevant studies. The inclusion process was iterative, allowing for refinement of the thematic area as the analysis progressed.

Rather than applying a formal systematic selection protocol, studies were evaluated based on the clarity of their scientific rationale, methodological soundness, and relevance to the objectives of the review. Publications lacking sufficient scientific support, conceptual coherence, or direct relevance to anti-aging research were not considered in the final synthesis.

Practically, the selection of databases used in this study was based on the criterion of relevance and diversity of recent studies, taking into account their importance for understanding the phenomenon investigated in the current context.

The selected literature was analyzed comparatively to identify convergent findings, divergent viewpoints, and emerging trends across pharmacological, genetic, regenerative, nutritional, and lifestyle-based anti-aging approaches. This narrative synthesis enabled an integrated perspective on the multifactorial nature of aging and the current landscape of therapeutic strategies aimed at promoting healthy longevity.

Only scientific papers addressing the topic of anti-aging therapies, risk factors that favor aging, and their consequences were included in the analysis.

The study selection criteria targeted their relevance to the research subject, using keywords such as anti-aging therapies, aging, pathologies, remedies, risk factors, and strategies. Articles that did not provide relevant data or that did not meet the established methodological criteria were excluded from the analysis.

The study selection process was structured in several stages to ensure relevance and methodological rigor.

In the first stage, studies were pre-selected based on titles and abstracts, eliminating those irrelevant to the topic under investigation.

Subsequently, the studies identified as eligible were re-evaluated in detail, allowing for an in-depth analysis of them, with those that met the scientific validity criteria being included in the systematic review.

The selection was made based on clearly defined inclusion criteria. The data obtained were subsequently systematized and analyzed according to the field of applicability, the nature of the analysis (theoretical or practical), the specific objectives of the study, and the results obtained.

To identify the convergences and discrepancies between the different methodologies used in the selected scientific studies, as well as to assess their potential, a comparative approach was used.

To ensure an integrated perspective on the topic investigated, the analysis included all relevant sections of the articles and papers examined. The selection criteria concerned, among others, the clarity of the information presented and the objectivity of the approach to the subject.

The data collection method focused on the qualitative aspects of the subject, and additional analyses addressed topics such as defining the aging process, identifying risk factors, establishing types of anti-aging therapies, and the impact on quality of life.

The exclusion criteria for studies initially selected for this research were established based on the following fundamental aspects:

1. Lack of relevance to the investigated objective, leading to the exclusion of studies that do not present a clear and substantiated connection with the research topic.
2. Significant methodological deficiencies, which determine the elimination of studies characterized by low validity, reduced reliability, or an insufficiently scientifically substantiated approach.
3. Insufficiency of essential information for the development of the analysis, excluding studies that do not provide relevant or necessary data to achieve the research objectives.
4. Presentation of contradictory results or lacking empirical support, determining the exclusion of studies that are not supported by solid scientific evidence or that generate interpretative incoherence.
5. Redundancy of sources through the existence of duplicate studies, eliminating works that replicate the same results and methodologies without making significant additional contributions.
6. The absence of a coherent and rigorously substantiated theoretical framework leads to the exclusion of studies that do not integrate clear theoretical concepts or that do not provide an adequate justification of the investigative approach.
7. Studies not fitting into the established analysis time frame, leading to the exclusion of studies that do not meet the period defined for the selection of the specialized literature.

RESULTS AND DISCUSSION

The aging process and anti-aging have been an interesting topic since ancient times, to the point that immortality was considered a utopia in antiquity. Today, the search for the most effective anti-aging remedies is a serious concern among scientists, with notable results. Several anti-aging hypotheses have been put forward, such as the mitochondrial free radical theory [2], telomere theory [3], DNA damage theory and error theory [4]. Practically, the aging process, broadly speaking, has 2 causes: genetic, individual cause, and a cause generated by the individual's evolution following the accumulated pathologies and lifestyle. Systemic deterioration constitutes the main risk factor for a wide range of major pathologies, including cancer, diabetes, cardiovascular diseases, and neurodegenerative diseases, following the natural aging process of the body. In recent decades, the field of aging research has recorded remarkable progress, especially due to the elucidation of the mechanisms by which the pace of this process is regulated, at least in part, by genetic pathways and biochemical processes deeply conserved throughout evolution.

Today, aging is subject to scientific control based on the ever-expanding knowledge of the molecular and cellular bases of life and disease [5].

The definition of the hallmarks of aging and the elucidation of the causes of its occurrence can contribute to building a framework regarding the mechanisms of aging, as well as to

designing interventions to reduce it and improve the duration of human health [5]. However, there are numerous challenges in understanding this complex biological process [6]. It appears that molecular analysis of genome-environment interactions that modulate aging will help identify drug targets for promoting longevity [7]. Senescent cells are viable cells with a high degree of resilience, surviving despite active responses to DNA damage, increased metabolic flux, and increased local levels of inflammatory cytokines and other factors that are capable of inducing apoptosis. They are more able to withstand stress than non-senescent cells [8, 9]. Approaches to reduce the effects of aging are diverse and include several types of therapeutic approaches.

Pharmacological Interventions

Senolytics, such as dasatinib and quercetin, have demonstrated the ability to eliminate senescent cells by preferentially inducing apoptosis in these cells and improving tissue function [10]. Navitoclax demonstrated senolytic capabilities, but not in all senescent cell types [9], as well as piperlongumine. Fisetin, a natural flavone with low toxicity, is also senolytic, selectively inducing apoptosis in senescent but not proliferating human umbilical vein endothelial cells [11]. Metformin, a pharmacological agent commonly used for the management of type 2 diabetes, has been shown to exert pro-longevity effects in experimental models. Studies in laboratory mice show that in males, starting in middle age, at a moderate dose of 0.1% w/w in the diet, it extended lifespan and improved metabolic health, mimicking some of the benefits of caloric restriction, including increased insulin sensitivity and reduced oxidative stress. It has been shown to have cardiovascular protective effects, has anticancer effects, and supports cognitive function in elderly patients [12]. At the molecular level, this action is mediated by the activation of AMP-activated protein kinase and the enhancement of antioxidant mechanisms, suggesting a potential role for metformin in promoting healthy aging, consistent with existing epidemiological evidence [13]. Dasatinib and quercetin have shown particular promise in clearing senescent cells [9] dasatinib is a multiple tyrosine kinase inhibitor used to treat cancers [14]. The effect is that it induced cell death in senescent human preadipocytes [10]. Rapamycin, an inhibitor of mTOR, has been associated with lifespan extension in studies in invertebrates, including yeast, nematodes, and fruit flies; however, it is not known whether inhibiting mTOR signaling can extend lifespan in a mammalian species [15, 16].

Despite the growing interest in pharmacological anti-aging interventions, the strength of evidence varies substantially depending on the experimental model. Most senolytic compounds, including dasatinib, quercetin, fisetin, and navitoclax, have demonstrated efficacy primarily in in vitro systems and animal models, where selective elimination of senescent cells was associated with improved tissue function and delayed onset of age-related pathologies. However, robust clinical evidence remains limited, and human trials are still scarce or exploratory in nature. Metformin represents a notable exception, as epidemiological data and limited clinical observations suggest potential benefits on healthspan; nevertheless, its direct anti-aging effect in humans remains controversial. Major limitations include differences in senescent cell phenotypes across tissues, potential off-target effects, and the lack of long-term safety data. These gaps highlight the need for well-designed, large-scale clinical trials to validate translational relevance and establish standardized therapeutic protocols.

Gene and Epigenetic Therapy

Partial cellular reprogramming by Yamanaka factors is effective in cellular rejuvenation. In vitro studies have shown that cellular reprogramming to pluripotency reverses cellular age, but alteration of the aging process by reprogramming has not been directly demonstrated in vivo [17].

It is important for studying aging-related diseases and further elucidating the role of epigenetics in aging [17]. CRISPR-Cas9 and other gene-editing technologies offer promising prospects for correcting aging-associated mutations [18]. The acronym “CRISPR” stands for Clustered Regularly Interspaced Short Palindromic Repeats. CRISPR imaging is a powerful tool to monitor cellular senescence [19].

Gene- and epigenetic-based anti-aging strategies represent one of the most innovative, yet experimentally limited, areas of current research. Evidence supporting partial cellular reprogramming comes predominantly from in vitro studies and animal models, where markers of rejuvenation and reversal of age-associated molecular signatures have been observed. To date, clinical application remains largely theoretical due to concerns about genomic instability, tumorigenicity, and ethical considerations. Furthermore, the long-term consequences of epigenetic reprogramming are not fully understood, and reproducibility in biological systems remains inconsistent. The lack of clinical trials in this area reflects both technological and regulatory challenges, highlighting a significant knowledge gap between experimental promise and clinical feasibility.

Regenerative Medicine

The therapeutic potential of mesenchymal stem cells in regenerative medicine is due to their ability to modulate the immune response and promote tissue regeneration [20]. In the last decade of the current century, the high potential of mesenchymal stem cells to ameliorate a multitude of degenerative diseases has been indicated [21].

Stem cell-derived exosomes have been identified as essential mediators of regenerative effects, having a role in stimulating angiogenesis, reducing inflammation, and combating oxidative stress [22]. Research shows that mesenchymal stem cell-derived exosomes retain some of the characteristics of the parent stem cells, such as modulating the immune system, regulating neurite outgrowth, promoting angiogenesis, and having the ability to repair damaged tissue [23]. In the context of clinical application, recent research suggests that mesenchymal stem cell-derived exosomes may represent a promising alternative to conventional cell therapy, offering advantages such as high biocompatibility and reduced risk of immunological side effects [24]. Furthermore, the molecular mechanisms involved in the beneficial effects of exosomes include the transport of microRNAs and proteins involved in tissue regeneration and neuroprotection [25].

Preclinical studies have shown that the administration of exosomes derived from mesenchymal stem cells causes significant improvement of histological and functional parameters in experimental models of ischemic injury and chronic degenerative diseases. The direct effect of exosomes on axonal growth and the molecular mechanisms underlying exosome-enhanced neurite outgrowth are still unknown [26].

The therapeutic use of these extracellular vesicles can significantly reduce markers of inflammation and oxidative stress, offering a new therapeutic direction for conditions characterized by cellular dysfunction and programmed cell death [27].

Regenerative approaches, particularly those involving mesenchymal stem cells and stem cell-derived exosomes, have shown encouraging results in preclinical in vivo models, including improved tissue repair, reduced inflammation, and enhanced functional recovery. While early-phase clinical studies suggest acceptable safety profiles, clinical evidence supporting long-term anti-aging benefits remains insufficient. Variability in cell sources, isolation protocols, dosing strategies, and outcome measures represents a major limitation in translating experimental findings into standardized therapies. Additionally, the precise molecular mechanisms mediating exosome-driven rejuvenation are not fully elucidated. These uncertainties highlight the need for harmonized clinical protocols and mechanistic studies to bridge experimental and clinical research.

Caloric Restriction and Its Mimetics

Caloric restrictions and compounds that mimic its effects have been intensively studied in recent years, given their potential effects on extending lifespan and reducing the risks associated with degenerative diseases. When organisms' food intake is reduced by food restriction, they live longer than organisms fed a normal diet [28]. Food restriction and reduced activity of nutrient-sensing pathways may thus slow aging through similar mechanisms that have been conserved during evolution [29]. The use of this technique in combination with genetic models has led to the identification of key metabolic regulators of lifespan [30]. Several pharmacological agents that can replicate the beneficial effects of caloric restriction have been identified, termed caloric restriction mimetics [31]. Given that long-term caloric restriction can create severe challenges for human dietary compliance, the concept of caloric restriction mimetics has emerged as an active area of research in gerontology.

For example, resveratrol, a natural polyphenol present in grapes and other foods, has demonstrated the ability to activate sirtuins, proteins involved in the regulation of metabolism and cellular responses to stress [32]. This activation of sirtuins plays an essential role in promoting energy homeostasis and reducing inflammation, with the potential to delay aging processes and prevent the onset of age-related diseases [33].

Caloric restriction and its mimetics constitute one of the most extensively studied anti-aging strategies, supported by strong evidence from in vitro and animal models, where lifespan extension and metabolic improvements are consistently observed. However, human data are limited and often indirect, relying mainly on observational studies and short-term interventions. Long-term adherence, nutritional deficiencies, and interindividual variability represent significant challenges in clinical translation. While compounds such as resveratrol have demonstrated promising molecular effects, their bioavailability and clinical efficacy remain subjects of ongoing debate. Consequently, despite robust experimental support, the clinical applicability of caloric restriction mimetics requires further validation through controlled human studies.

Natural Compounds With Anti-Aging Effects

A substantial proportion of natural anti-aging compounds exert their biological effects through shared antioxidant and redox-modulating mechanisms, primarily involving the neutralization of reactive oxygen species and the regulation of oxidative stress-sensitive signaling pathways. Beyond direct radical scavenging, these compounds influence cellular homeostasis by modulating inflammatory responses, mitochondrial efficiency, and stress-adaptive transcription factors. To avoid redundancy, the following subsections emphasize compound-specific properties and translational relevance, rather than reiterating identical antioxidant mechanisms.

Given the large number of natural compounds investigated for anti-aging effects, individual subclasses often have overlapping biological mechanisms, particularly antioxidant and anti-inflammatory activity. For ease of navigation, we will focus on compound typologies and shared molecular processes. This method provides a clearer perspective on their clinical use while preserving the accuracy of mechanistic data.

Some bioactive compounds and their derivatives can delay aging and/or improve aging-related diseases, extending lifespan by regulating various physiological processes, including antioxidant reactions, anti-inflammatory response, immunity, telomere activation, mitochondrial repair, and anti-apoptosis, etc. [34-38].

Polyphenols, abundant in nature, are characterized by a wide spectrum of biological activities, including redox-modulating effects, neuroprotective properties, and the capacity to influence key pathways involved in cellular aging [39]. These compounds are generally considered safe and have been associated with a reduced risk of age-related disorders through their ability to modulate inflammation, cellular signaling, and metabolic homeostasis. Their pleiotropic biological actions support the development of novel therapeutic strategies based on dietary polyphenols, particularly in the context of integrative anti-aging approaches and functional nutritional supplements [40].

Recent studies have also highlighted the significant bioactive potential of certain polysaccharides, particularly those containing a β-(1, 3)-D-glucan structure, which exhibit a broad range of pharmacological activities, including antitumor, antidiabetic, immunomodulatory, and anti-aging effects, supporting their applicability in the development of innovative, low-toxicity therapeutic strategies [41]. Owing to their favorable safety profile and low cytotoxicity, these compounds are increasingly regarded as promising candidates for incorporation into anti-aging interventions [36]. Experimental evidence indicates that polysaccharides exert their anti-aging effects through multiple complementary mechanisms, such as regulation of age-associated genes and signaling pathways [42], mitigation of estrogen deficiency-induced cognitive impairment [43], protection against UVB-induced photodamage [44], modulation of apoptosis and cellular senescence [45], activation of autophagy via insulin- and mitochondria-related pathways [45], enhancement of immune function, and improvement of cellular defense systems through regulation of aging-related gene expression [46-49].

Accumulating evidence further demonstrates that anti-aging effects have been reported for polysaccharides derived from diverse biological sources, including plants [44, 50], fungi

[50], and marine algae [51, 52], underscoring the broad applicability of this class of bioactive compounds in aging-related research.

Tannins are natural and powerful antioxidants, which have the property of eliminating free radicals and delaying the aging process [53]. They have anti-inflammatory effects, prevent and treat hypertension and dyslipidemia [54] have antibacterial properties [55, 56] show antioxidant activity delaying aging and the onset of chronic diseases [57], show antiviral activity [58] have antidiabetic action [59, 60] have anticancer action by inducing apoptosis of cancer cells [61], promote osteogenesis and angiogenesis [62].

Carotenoids, due to their numerous properties, for example, antioxidants, antiangiogenic, antidiabetic, antiobesity, anti-inflammatory, antimalarial, provitamin A, and photoprotection [63, 64], are used in various fields, such as food additives and cosmetics, pigments, and pharmaceuticals [65, 66].

The most widely used key carotenoids on the global market are lycopene, lutein, astaxanthin, β-carotene, fucoxanthin, and canthaxanthin, which are chemically synthesized [67, 68].

Their properties make them more difficult to use because carotenoids have poor water solubility, high melting points, chemical instability, and low bioavailability [69].

Humans cannot synthesize carotenoids, so it is important to introduce them into the daily diet through food or supplements [70, 71].

Their most important properties are related to their antioxidant potential, but they also have antiangiogenic, antidiabetic, antiobesity, anti-inflammatory, antimalarial, and provitamin A effects [72, 73].

Lycopene has been the subject of numerous studies due to its potential in combating aging processes and related diseases. This bioactive compound exerts significant antioxidant and anti-inflammatory effects, contributing to the amelioration of oxidative stress and chronic inflammation, determining factors in the pathogenesis of age-related diseases. A study published in [74] highlights that lycopene can delay the aging process by reducing specific biomarkers and by mimicking the effects of caloric restriction, a mechanism known to prevent metabolic disorders and chronic diseases.

It has also been shown that tomato and lycopene supplementation improve the characteristics of skin affected by ultraviolet radiation, reducing erythema and pigmentation and increasing skin density and thickness. These results suggest a photoprotective role of lycopene, preventing skin photoaging.

Lycopene may have beneficial effects on the cardiovascular system, contributing to reducing the risk of myocardial infarction, lowering blood pressure, and preventing the oxidation of LDL cholesterol [75]. These effects are largely attributed to its potent antioxidant properties, being considered protective against several chronic diseases, such as cancer, diabetes, and cardiovascular and neurological diseases [76]. Thus, lycopene stands out as a promising therapeutic agent in the management of aging processes and associated diseases through complex mechanisms that include reducing oxidative stress, modulating the inflammatory response, and protecting against UV-induced damage [76].

Sterols, especially phytosterols, are a class of bioactive compounds found in various plant sources, including vegetable oils, whole grains, nuts, fruits, and vegetables. These compounds have attracted the attention of the scientific community due to their potential in promoting health and preventing aging processes. They are vital components of all eukaryotic cells, which can be classified as *zoosterols, phytosterols, and mycosterols*, depending on the source [77, 78].

A study published in [79] highlights that phytosterols can ameliorate premature skin aging through their antioxidant and anti-inflammatory properties. These compounds contribute to the neutralization of reactive oxygen species and the reduction of inflammatory mediators, factors involved in the degradation of collagen and elastin, and proteins essential for maintaining skin elasticity and firmness [80].

Phytosterols can positively influence markers associated with cellular aging by reducing levels of reactive oxygen species. Sterols also exhibit a wide range of pharmacological effects, including immunomodulatory, hepatoprotective, anti-cancer, antimicrobial, antifungal, anti-inflammatory, cardiotonic, and anti-aging activities [81, 82]. Phytosterols have been associated with cardiovascular benefits, such as reducing LDL cholesterol levels, which may indirectly contribute to the prevention of age-related cardiovascular disease.

Animal sterols include cholesterol, vitamin D, and steroid hormones. Cholesterol, the main animal sterol, acts as a precursor for the synthesis of steroid hormones, vitamin D, bile acids, and oxysterols [83].

Vitamins cannot be synthesized in the human body and must, therefore, be supplied through the diet.

Vitamin D3 is well known for its activities in maintaining and regulating calcium and phosphorus homeostasis and in modulating both male and female reproductive processes [84]. Studies have shown that vitamins have multiple biological effects, including antioxidants, anti-aging, anti-inflammatory, anti-nociceptive, and anti-cancer properties [85].

Riboflavin extends lifespan through its antioxidant properties [86], vitamin E exerts an obvious neuroprotective effect [87], and vitamin C has antioxidant effects [88]. Vitamin C can repair DNA, mitigate oxidative stress, and modulate telomere activity in the aging process, ultimately leading to longevity [89].

Vitamin E, or velvet antler polypeptide, can exert anti-aging activity by modulating the gut microbiota [90], can prevent age-related neuronal disorders by suppressing oxidative stress and increasing the activity of antioxidant enzymes [91], and protects the integrity of the skin barrier, thus having anti-aging activity of the skin [92, 93].

Retinol possesses the ability to reduce skin discoloration, stimulate collagen production, and reduce acne and uneven skin texture, thus exhibiting anti-aging activity of the skin [94].

Vitamin K is a vital cofactor in the activation of several proteins that act against age-related diseases [95]. Vitamin K treatment decreases the levels of reactive oxygen species and lipid peroxidation, increases the levels of glutathione and alkaline phosphatase activities, and promotes DNA proliferation [96]. An increase in dietary vitamin K intake was associated with better cognitive function scores in an older Mediterranean adult population at high cardiovascular risk and adults with chronic kidney disease [1].

Natural bioactive compounds, including polyphenols, polysaccharides, carotenoids, sterols, and vitamins, have been widely investigated for their anti-aging potential, with the majority of evidence originating from vitro assays and animal models. These studies consistently report antioxidant, anti-inflammatory, and cytoprotective effects. Nevertheless, clinical evidence remains fragmented, often limited to small-scale trials or surrogate biomarkers rather than definitive aging outcomes. Additional limitations include variability in compound composition, dosage, and bioavailability, as well as inconsistencies between experimental and human data. The lack of standardized clinical endpoints and long-term studies constitutes a major knowledge gap, emphasizing the need for rigorous clinical research to substantiate therapeutic claims.

Integrated Mechanisms and Translational Relevance of Anti-Aging Therapies

Despite the diversity of anti-aging interventions discussed, a convergence of underlying biological mechanisms emerges across pharmacological, genetic, regenerative, and nutritional approaches. Most strategies ultimately target a limited number of core pathways, including reduction of oxidative stress, modulation of chronic inflammation, improvement of mitochondrial function, regulation of nutrient-sensing pathways (mTOR, AMPK, and sirtuins), maintenance of genomic and epigenetic stability, and attenuation of cellular senescence. The convergence of these mechanisms indicates that senescence is not driven by discrete phenomena, but by the interdependence of molecular networks. Consequently, therapeutic strategies that influence multiple pathways simultaneously, either through pleiotropic drugs or combined interventions, may hold greater translational potential than highly specific, single-target approaches.

The transition from laboratory to clinical applications for anti-aging compounds requires a rigorous assessment of the quality and provenance of the evidence. Compounds such as metformin, rapamycin, and certain senolytics stand out due to their relatively advanced experimental validation and emerging clinical relevance. In contrast, many natural compounds, although biologically active in vitro and animal models, lack standardized formulations, optimal dosing regimens, and long-term clinical outcome data. Therefore, unlike natural bioactive agents, whose utility remains predominantly prophylactic, pharmacological compounds targeting multiple mechanisms and benefiting from partial clinical confirmations are considered more feasible candidates for short-term therapeutic use. This difference reminds us that promising results from experiments need to be validated by the real possibility of their application, based on solid evidence.

Clinical Relevance and Translational Limitations of Anti-Aging Therapies

Although the experimental landscape of anti-aging research has expanded considerably over the past decade, the clinical translation of these therapies remains limited and uneven, particularly when evaluated through the lens of routine medical practice. For most anti-aging interventions discussed in this review, evidence is derived predominantly from in vitro experiments and animal models, with only a small number of approaches supported by human data. This discrepancy represents a major challenge for clinicians, who require well-defined safety profiles, standardized dosing regimens, and clinically meaningful endpoints before considering implementation.

Pharmacological agents such as metformin and rapamycin currently represent the most clinically relevant candidates, given their established use in medical practice and partial evidence suggesting beneficial effects on healthspan-related outcomes. However, even for these compounds, direct evidence supporting their indication as anti-aging therapies in otherwise healthy individuals is insufficient, and off-label use raises ethical and regulatory concerns.

Senolytic therapies, while highly promising at the experimental level, remain largely confined to preclinical research, with significant uncertainties regarding long-term safety, tissue specificity, and potential adverse effects in humans.

Regenerative strategies, including stem cell-based interventions and exosome therapies, face additional translational barriers related to biological heterogeneity, manufacturing variability, regulatory constraints, and cost-effectiveness. Although early-phase clinical studies suggest acceptable short-term safety, robust evidence demonstrating sustained clinical benefit in aging populations is still lacking. Similarly, natural bioactive compounds and dietary supplements, despite widespread public use and favorable safety profiles, suffer from heterogeneity in formulation, bioavailability, and clinical study design, limiting the strength of conclusions that can be drawn regarding their efficacy in slowing physiological aging.

From a clinical perspective, the absence of validated biomarkers of aging, standardized outcome measures, and long-term randomized controlled trials significantly hampers the integration of anti-aging therapies into evidence-based medical practice. Moreover, aging itself is not currently classified as a disease entity, complicating regulatory approval and reimbursement pathways. Consequently, most anti-aging interventions should be regarded as adjunctive or preventive strategies, rather than established therapeutic options.

For clinicians, a cautious and critical approach is essential when interpreting anti-aging claims. Emphasis should be placed on interventions with demonstrated benefits for age-associated conditions, overall metabolic health, and quality of life, rather than unproven longevity enhancement. Future progress in this field will depend on the design of clinically oriented trials, the identification of reliable aging biomarkers, and the development of regulatory frameworks capable of bridging the gap between experimental innovation and safe medical application.

CONCLUSION

Anti-aging therapies are a rapidly expanding field with multiple applications in regenerative medicine and the prevention of age-related diseases.

Recent advances in anti-aging therapies reflect a multidisciplinary approach that combines insights from regenerative medicine, biotechnology, pharmacology, and nutrition. This integration enables the development of personalized strategies designed to delay the aging process and enhance quality of life.

Research demonstrates that the use of bioactive compounds, such as polyphenols, resveratrol, and coenzyme

Q10, can contribute to reducing oxidative stress and protecting cellular integrity. These substances play a key role in maintaining body homeostasis and preventing age-related diseases.

New directions in anti-aging medicine include gene and cell therapies, such as the use of stem cells and CRISPR technologies for tissue regeneration. These interventions offer promising solutions for extending lifespan and combating age-related degenerative diseases.

The development of pharmacological compounds with anti-aging effects, such as metformin, rapamycin, and senolytics, points to a promising direction in slowing physiological decline. Clinical studies highlight the potential of these substances to influence metabolic pathways and delay the onset of age-related pathologies. In addition to advanced therapies, adopting a balanced lifestyle, including a healthy diet, regular exercise, and stress management, remains essential for preventing premature aging. The synergy between innovative therapies and behavioral factors can help optimize longevity.

Future progress in anti-aging medicine will likely depend on the rational integration of therapies that target common molecular pathways, rather than the isolated application of single compounds. Emphasizing interventions supported by solid experimental and clinical evidence, while recognizing current limitations, helps move from experimental models to real-world applications.

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