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Hair Graying: Mechanisms, Prevention, and Innovative Treatment Strategies – literature review

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Abstract

Hair graying, or canities, is a complex biological process characterized by the progressive loss of hair pigment, often leading to aesthetic and psychological concerns. This review delves into the multifactorial nature of hair graying, examining the underlying biochemical and physiological mechanisms. Key contributors include oxidative stress, genetic and environmental factors, and disturbances in melanogenesis and signaling pathways such as Notch and Kit. Our extensive literature review from PubMed, involving 33 scientifically rigorous papers, explores the efficiency of various strategies aimed at delaying or preventing hair graying. We highlight the roles of antioxidants, lifestyle modifications, and advanced therapeutic approaches like genetic therapy and liposome delivery systems. Additionally, we explore the impact of diet and UV protection, among other factors, on maintaining hair pigmentation. This review underscores the intricate interplay of biochemical processes in hair graying and sheds light on promising interventions for managing this natural yet often unwelcome sign of aging.

Keywords: Hair, melanogenesis, oxidative stress

Introduction

Canities (hair graying) is a multifaceted process that involves the gradual growth of hair with less and less pigment, causing aesthetic concerns and in many cases psychological challenges, when the natural hair color changes to gray or white. It is caused by a gradual decrease in the production of melanin formed in cytoplasmic organelles called melanosomes which are found in specific cells termed melanocytes. The entire biochemical process of

melanin production is referred to as melanogenesis and is regulated by genetic pathways. A signaling pathway is a series of biochemical processes called signals that originate from outside or inside the cell. The signaling cascade occurs through biochemical substances coming from outside the cell, such as neurotransmitters, cytokines, and hormones, which bind to receptors contained in the cell membrane or inside it, leading to the initiation of a number of reactions inside the cell and ultimately leads to changes in the cell's life cycle. There are many signaling pathways that play an important role in regulating processes such as embryogenesis, differentiation, survival and cell proliferation. Physiologically, canities is associated with the ageing process, while premature graying of the hair often signifies pathological causes. Known causes include disturbances in the process of melanogenesis, oxidative stress, genetic and environmental factors such as radiation, diet, family history of atopic dermatitis, hormonal disorders or inflammation. In the desire to extend youthfulness many people dye their hair, which involves regular expenses, changes in the natural appearance and destruction of the hair structure. In this comprehensive review, we explore the causes, contributing factors and mechanisms of hair graying, which allows us to develop effective strategies for the treatment of canities.

Methodology

To explore effective strategies for delaying or preventing hair graying, we conducted an exhaustive literature review using PubMed as our primary resource. Our search utilized specific key terms including "hair graying," "prevention," "delaying graying," "anti-graying," "antioxidants," "lifestyle changes," "genetic therapy," "UV protection," "environmental factors," and "stress." This initial search identified 55 papers. After a detailed evaluation, 33 of these papers were selected for their scientific relevance and rigor. These selected studies encompassed a range of research types, from empirical studies to review articles, and were systematically analyzed to assess the efficiency and underlying mechanisms of various anti-graying strategies. This analysis aimed to provide a comprehensive understanding of the current approaches and future directions in the prevention and delay of hair graying.

Main factors affecting graying

Oxidative Stress

Oxidative stress is a primary driver of hair graying. It arises from an imbalance between free radicals and antioxidants in the body, leading to cellular damage. Several studies highlight the importance of oxidative stress in the ageing process, particularly in relation to hair pigmentation. Research indicates that hair ageing is heavily influenced by oxidative stress, which disrupts follicle homeostasis. Factors such as hormonal disorders, inflammation, DNA damage, and repair defects are exacerbated by oxidative stress, accelerating the graying process. This disruption leads to the degeneration of melanocytes, the pigment-producing cells in hair follicles[1]. Another study underscores oxidative stress as a significant factor in hair graying. The accumulation of oxidative damage in hair follicle melanocytes leads to their dysfunction and eventual depletion, resulting in gray hair. This connection suggests that managing oxidative stress through antioxidants and lifestyle changes could delay hair graying[2]. Further research supports the role of oxidative stress in the overall ageing process, affecting various tissues and organs, including hair follicles. Reducing oxidative stress may slow down ageing and maintain hair pigmentation for a longer period. This insight emphasizes the importance of a holistic approach to combating oxidative stress[3]. Disruptions in specific cellular pathways, such as Notch signaling, also contribute to oxidative stress and hair graying. Notch signaling is crucial for maintaining melanocyte stem cells' function. When this pathway is disrupted, it leads to increased oxidative stress and subsequent hair graying. Understanding these mechanisms opens new avenues for potential interventions to prevent canities[3]. Environmental factors like radiation and genetic mutations further induce hair graying. Radiation increases the production of reactive oxygen species (ROS), causing oxidative stress and DNA damage in hair follicles. Genetic mutations affecting pathways like Kit signaling exacerbate this process, highlighting the intricate relationship between environmental and genetic factors in hair graying[4].

Lifestyle Factors

Lifestyle choices significantly impact hair health and pigmentation. Stress, diet, and genetic predispositions are key lifestyle factors that contribute to canities. Acute stress accelerates hair graying by depleting melanocyte stem cells. These cells are vital for maintaining hair pigmentation. Stress triggers physiological responses that rapidly deplete these stem cells, leading to gray hair. Managing stress through relaxation techniques, mindfulness, and other methods can help mitigate this effect[5]. Diet, atopy history, and family history of

premature hair graying (PHG) are related to canities. A balanced diet rich in antioxidants, vitamins, and minerals supports overall hair health and can delay the graying process. Nutritional deficiencies and poor dietary choices, on the other hand, exacerbate oxidative stress and accelerate hair graying[6]. One specific biochemical pathway affected by lifestyle is the repair of methionine sulfoxide in proteins. H2O2-mediated oxidative stress inhibits this repair mechanism, leading to the accumulation of damaged proteins in hair follicles. This damage impairs melanocytes' ability to produce pigment, contributing to hair graying. Minimizing oxidative stress through antioxidants and protective measures helps maintain these repair mechanisms and to preserve hair color[7]. Research indicates also that Kit signaling can prevent radiation-induced hair graying. Kit signaling plays a protective role in melanocyte function, and its activation can counteract the damaging effects of radiation on hair pigmentation. This finding suggests that targeting specific genetic pathways can offer new strategies for preventing hair graying[8].

Melanogenesis

Many substances that stimulate the melanogenesis process have been tested. Natural products and synthetic compounds are easily available, low cost, act on many biochemical pathways and have few side effects.

Gynostemma pentaphyllum Makino leaf extract (Gp)

One of the substances tested is Gynostemma pentaphyllum Makino leaf extract (Gp) as a potential active ingredient to protect melanocytes from norepinephrine stress, which is a factor contributing to the graying of hair.

The protective potential of Gp was investigated by measuring melanocyte viability, melanin content, intracellular TYR (tyrosinase) activity, which is a key enzyme necessary in melanogenesis, mRNA expression of TYR, TRP-1 (tyrosine-related protein-1), TRP-2 (tyrosine-related protein-2), and MITF (microphthalmia-associated transcription factor) in mice B16 melanocytes cells[9]. Gp has been shown to increase TYR activity and melanin production in B16 cells exposed to norepinephrine stress. Gp was researched to induce melanogenesis and activate the cAMP/PKA and Wnt signalling pathways in mice B16 melanocytes. Moreover, the hair loss-related gene TGF-β1 was downregulated, whereas β-catenin, an indispensable gene in the Wnt signaling cascade, was upregulated as well as Wnt 5a, which activates the Wnt signaling transduction[9]. Histological differences revealed that entry into the catagen phase was

delayed after Gp treatment, which suggests extending the hair cycle and slowing down the hair graying process.

All those discoveries mentioned above contribute to the development of new therapeutic options for canities, which deserves further clinical trials involving humans.

Fuzhuan brick tea (FBT)

Reactive oxygen species (ROS) are molecules that are produced physiologically during many processes e.g. melanogenesis. Large amounts of ROS are released during tyrosine hydroxylation and L-3,4-dihydroxyphenylalanine (DOPA) to melanin oxidation. The concentration of ROS is tightly regulated in the cell by antioxidants. Disturbance of this regulation leads to a condition called oxidative stress which can result in cell apoptosis. An imbalance between prooxidants and antioxidants often indicates a pathological condition such as the premature graying of hair[10]. Fuzhuan brick tea (FBT) is made in a microbiological process, during which, in addition to its unique taste, catechin derivatives, flavonoids and their glycosides, phenolic acids, alkaloids, and terpenoids are produced. The compounds improve the metabolism of sugars and lipids, regulate intestinal microflora, but above all they are natural antioxidants. By examining the effect of hexane extract of FBT (FBTH) on Melan-A cells and C57BL/6 mice, it turned out that FBTH increases the expression of antioxidant enzymes such as SOD, catalase, GPx-1, and HO-1, reducing the harmful effect of ROS and increasing the expression of tyrosinase, TRP-1, TRP-2 and MITF via MAPK signaling activation, stimulating melanogenesis[10]. These valuable discoveries related to hexane extract of fuzhuan brick tea may have a significant impact on the prevention and therapy of graying hair.

Yerba Santa (Eriodictyon angustifolium and Eriodictyon californicum)

The influence of Yerba Santa (Eriodictyon angustifolium and Eriodictyon californicum) on hair pigmentation was examined. After being exposed to X-ray radiation, yerba santa extracts were evaluated for their cytological effects before being put to the test directly to see if they could stop human hair from graying. The distinct components of the extract were identified using ultra-performance liquid chromatography (UPLC). Eriodictyon angustifolium extract activated the WNT/MITF/tyrosinase-signaling pathway, which led to a substantial increase in melanin formation in the melanoma cell line. On the other hand, E. californicum had no impact on the synthesis of melanin. In human keratinocytes, E. angustifolium extract also showed a protective effect against X-ray-induced damage. Subjects with gray beards who applied the extracts showed a decrease in the amount of gray beard hair per year, especially

with the E. angustifolium extract. E. angustifolium extract treatment was also associated with a notable reduction in gray hair. Following the application of E. angustifolium extract, there was a documented upregulation of gene expression linked to the synthesis of melanin and WNT signaling. The most prevalent flavonoid in the E. angustifolium extract that was found by UPLC was sterubin. Furthermore, the greatest amount of difference between both extracts was seen in sterubin[11]. Those new findings open new avenues for potential interventions to prevent hair graying.

Spermidine

Spermidine is an organic chemical compound which activates MITF transcription factors, which in turn affects the expression of TRP-2 and c-kit. Furthermore, considering spermidine's overall effects on lowering H2O2 buildup and the expression of associated proteins including MITF, catalase, MSRA, and MSRB3, it leads to the conclusion that spermidine has the potential to be employed as both a promotor and an inhibitor of melanin formation, and thus constitutes the basis for developing a treatment for hair graying[12].

Pueraria thunbergiana (PT) extract and its active ingredient, puerarin (7,40-dihydroxyisoflavone-8b-glucopyranoside)

Pueraria thunbergiana (PT) extract and its active ingredient, puerarin (7,40-dihydroxyisoflavone-8b-glucopyranoside) were studied for their ability to prevent follicular depigmentation in a hair cycle-accelerated hair graying mouse model and for their ability to stimulate melanogenesis in vitro via the cAMP/MITF-M signaling pathway. Both upregulate the synthesis of melanin and the transcription of MITF by raising intracellular cAMP levels. While the expression of the CREB protein overall remained unchanged, the elevated cAMP caused by the puerarin and PT extract caused the phosphorylation of CREB to reach its maximum after two hours of treatment in cultured melanocytes[13]. Moreover, puerarin and the PT extract elevated the expression of the proteins tyrosinase, TRP-2, and Bcl-2, which enhanced the creation of melanin and the ability of melanocytes to survive. Through the cAMP/MITF-M signaling pathway, the PT extract and puerarin promoted melanogenesis in vitro, inhibited vitiligo and follicular depigmentation by promoting melanin production[13]. These findings in mice deserve further research in humans to create new therapeutic options for hair graying.

3-O-methylquercetin (3MQ) and 3,4',7-O-trimethylquercetin (34'7TMQ)

34′7TMQ stimulates the p38 pathway and the expression of MITF, a tyrosinase transcription factor, to enhance tyrosinase expression in B16 melanoma cells. Compared to its

impact on B16 melanoma cells, 3MQ and 34′7TMQ showed no influence on melanogenesis in Caucasian melanocytes. In the 3D skin model, which contained melanocytes from an Asian donor 3MQ and 34′7TMQ elongated and expanded the melanocytes. They also shown a potential to induce melanogenesis. According to these findings, 3MQ and 34′7TMQ may find use in skin care products and anti-graying hair agents[14].

Thyrotropin-releasing hormone (TRH)

The thyrotropin-releasing hormone (TRH) stimulates melanin formation in appendages of normal adult human skin and stimulate human hair follicles (HF) but not human epidermal melanocytes. It was discovered that TRH can upregulate the MITF which is involved in lineage-specific pathway regulation of many types of cells including melanocytes[15].Since TRH is a very stable tripeptide, it is possible that topical administration of HF-targeting liposomes, for example, could result in large intrafollicular TRH dosages[16,17]. This may assist in preventing an unfavorable increase in systemic TRH levels that could result in an overabundance of thyroid hormone secretion.

Follicular Liposomal delivery system

This connection suggests that TRH, especially using liposome as a carrier, can be used in developing the new strategy for preventing hair graying. In addition to substances, extracts, synthetic molecules and hormones that can influence melanogenesis, techniques for manipulating melanocytes have been investigated such as the suppression of melanocyte proliferation[5]. There are two types of cell populations in the bulge and hair germ region of the follicle. The first of them are hair follicle stem cells (HFSCs), the activation of which leads to the production of new hair follicles. The second one is melanocyte stem cells (MeSCs), which, when activated in their niche, produce differentiated melanocytes. The growth cycle of human hair consists of: anagen (growth, synthesis and the secretion of melanin), catagen (degeneration), and telogen (rest). These cells are activated during anagen to regenerate pigmented hair follicles, while remaining inactive during the rest of the cycle. During catagen, mature melanocytes undergo apoptosis, while MeSCs remain in the niche to participate in melanogenesis in the next cycle. It has been proven that acute stress and hyperactivation of neuronal activities cause rapid depletion of MeSCs in mice. Therefore, the effect of transient suppression of the proliferation of MeSCs was examined, during which it was proven that this suppression protects MeSCs against rapid proliferation, differentiation, migration and

permanent depletion from the niche, which prevents stress-induced hair graying[18]. Moreover, it was observed that after radiation therapy for cancer and after scalp inflammatory events, some gray hair was repigmented. This gave rise to the idea of inducing melanocytes to differentiate and proliferate in vitro to repigment gray hair follicles.

Oxidative Stress

Oxidative Stress Mitigation

Mitigating oxidative stress is a crucial strategy in preventing hair graying. Oxidative stress, caused by an imbalance between free radicals and antioxidants in the body, can damage hair follicles and impair melanin production. Several protective molecules and pathways have been identified that can help counteract this process.

Protective Molecules and Pathways

One significant molecule in protecting against oxidative stress is ATM. ATM plays a pivotal role in the cellular response to oxidative stress, helping to preserve the integrity of hair follicle melanocytes. By enhancing the function of ATM, it is possible to protect against oxidative damage and maintain hair pigmentation[19]. Another critical pathway involves the activation of NRF2, a transcription factor that regulates the expression of antioxidant proteins. NRF2 activation has been shown to benefit redox-associated disorders by boosting the body's natural antioxidant defenses, thereby reducing oxidative stress and its harmful effects on hair follicles[20]. Natural compounds also offer promising protective effects against oxidative stress. Rhynchophylline, for example, is an alkaloid that has demonstrated potential in mitigating oxidative damage. By targeting specific pathways, rhynchophylline helps to neutralize free radicals and protect melanocytes, contributing to the prevention of hair graying[21]. Polygonum Multiflorum Radix extract is another natural substance known for its antioxidant properties. This extract has been shown to effectively protect hair follicles from oxidative stress, thereby supporting the maintenance of natural hair color[22]. Gambogic amide, a selective TrkA agonist, is another compound that offers protection against oxidative stress. By activating the TrkA pathway, Gambogic amide helps to enhance the survival and function of melanocytes under oxidative conditions, thus preventing the loss of hair pigmentation[23]. Superoxide dismutase - SOD is an enzyme that catalyzes the conversion of superoxide radicals into oxygen and hydrogen peroxide, significantly reducing oxidative stress within cells. SOD has been found to protect against oxidative damage and photosensitization reactions in hair follicles, making it a

vital component in the defense against hair graying[24]. Together, these protective molecules and pathways offer a robust defense against oxidative stress, providing promising avenues for preventing and potentially reversing hair graying. By enhancing the body's natural antioxidant defenses and targeting specific oxidative pathways, these strategies can help maintain healthy hair pigmentation and slow down the hair ageing process.

Other Treatment Approaches

While avoiding factors that contribute to hair graying and mitigating oxidative stress are crucial strategies, there are also several innovative treatment approaches that have shown promise in preventing or reversing hair graying. These approaches leverage advanced technologies and therapeutic methods to target the underlying mechanisms of hair pigmentation directly.

Liposome Delivery Systems

One such innovative approach involves the use of liposome delivery systems. Liposomes are spherical vesicles that can encapsulate various substances including drugs, genes and proteins, then deliver them directly to targeted cells. Liposome delivery systems offer several advantages. They can enhance the stability and bioavailability of the encapsulated substances, ensure targeted delivery to hair follicle cells, and minimize systemic side effects. By using liposomes to deliver melanin directly to hair follicles, it is possible to restore pigmentation to gray hair. Moreover, liposomes can be engineered to deliver genes that regulate melanin production, providing a genetic approach to maintaining hair color. Additionally, proteins that support melanocyte function and survival can be delivered to hair follicles, enhancing their ability to produce pigment. Research has shown that liposome delivery systems are effective in targeting hair follicles and delivering their payloads with precision. This targeted delivery system ensures that the therapeutic substances reach the melanocytes in the hair follicles, where they are needed most. This approach represents a significant advancement in hair graying treatment, offering a method to directly address the cellular and molecular mechanisms involved in hair pigmentation[25].

Phototherapy

Phototherapy, particularly UVB phototherapy, is another promising treatment approach for hair graying. UVB phototherapy involves exposing the scalp to ultraviolet B light, which

has been shown to stimulate melanocyte stem cells in the hair follicles[26]. These stem cells are responsible for producing melanocytes, the cells that generate hair pigment. UVB phototherapy works by inducing the proliferation and differentiation of melanocyte stem cells, leading to the repopulation of melanocytes in the hair follicles. This process can rejuvenate hair pigmentation by restoring the population of pigment-producing cells. This therapy has been particularly effective in conditions such as vitiligo, where repigmentation of the skin and hair is desired. Studies have demonstrated that UVB phototherapy can result in significant repigmentation of gray hair. This stimulates the migration of melanocytes to the hair follicles, where they can produce melanin and restore hair color. This effect is achieved through the activation of various signaling pathways that promote melanocyte proliferation and differentiation. The benefits of UVB phototherapy extend beyond just repigmentation. The treatment is non-invasive, relatively safe, and can be administered in a controlled manner. It offers a practical approach to addressing hair graying, especially in cases where traditional topical or systemic treatments may not be effective. In summary, UVB phototherapy represents a promising approach to the treatment of hair graying by harnessing the regenerative potential of melanocyte stem cells.[27]

Nutritional and Dietary Influences

Hair graying, a natural part of the ageing process, can be influenced by various factors, including diet. Research has shown that nutritional intake plays a crucial role in maintaining hair health and delaying the onset of gray hair. Two key articles discuss the impact of diet on hair graying, highlighting the relationship between dietary habits, specific nutrients, and the overall health of hair follicles. Many vitamins and minerals have been identified as particularly beneficial in preventing or slowing down hair graying. Vitamin B12 is essential for healthy hair growth and pigmentation, a deficiency in this vitamin is often linked to premature hair graying[28]. Foods rich in B12, such as meat, dairy products, and fortified cereals, are crucial for maintaining hair color. Folic acid (Vitamin B9) plays a vital role in the production of red blood cells and the repair of DNA, both of which are important for hair health. Leafy greens, legumes, and fortified grains are excellent sources of folic acid. Biotin (Vitamin B7) is known for its role in strengthening hair and nails. A deficiency in biotin can lead to hair loss and graying hair[29]. Biotin-rich foods include eggs, nuts, and whole grains. Vitamin D supports hair follicle cycling and hair growth. Adequate levels can be maintained through sun exposure and foods such as fatty fish, egg yolks, and fortified products. Iron deficiency is linked to hair loss and hair graying, eating iron-rich foods like red meat, lentils, and spinach essential for maintaining healthy hair pigmentation[30]. Copper is involved in the production of melanin, the pigment

responsible for hair color. Foods such as shellfish, seeds, nuts, and whole grains provide a rich source of copper. By incorporating these vitamins and minerals into the diet, individuals can support hair health and potentially delay the onset of hair graying. A balanced diet that includes a variety of nutrient-rich foods can help mitigate the effects of oxidative stress, hormonal imbalances, and other factors that disrupt follicle homeostasis. A vegetarian diet, while generally healthy, may lack certain nutrients critical for hair health, if not properly balanced with essential vitamins and minerals. This highlights the importance of ensuring a diverse and nutrient-rich diet to support hair pigmentation and prevent premature hair graying. One study revealed that individuals with a vegetarian diet, a history of atopy, and a family history of premature hair graying were more likely to experience early onset of graying hair. This suggests that dietary habits and genetic predispositions play a combined role in influencing hair pigmentation[6].

Another study delves into the broader aspects of hair ageing, emphasizing that disruption in follicle homeostasis is influenced by factors such as oxidative stress, hormonal disorders, inflammation, and DNA damage. These disruptions can accelerate the ageing process of hair, leading to graying. Nutritional deficiencies can exacerbate these issues by failing to provide the necessary support for maintaining healthy hair follicles[1].

Pharmacological Approaches

Hair graying is a natural symptom of ageing, so there is no medicine that will alleviate this aesthetic problem. However, premature ageing may result from disturbances in the body's homeostasis and may indicate disease. Understanding the process and causes of hair graying allows for basic prevention and development of effective therapy, including pharmacotherapy. Current research on gray hair repigmentation medications focuses on melanogenesis stimulation as well as inflammation inhibition.

In our article, we described the role of liposomes in delivering specific substances, molecules, genes and proteins involved in melanogenesis as well as hormones (such as TRH) directly to the hair follicle.

Moreover, the substances specified in the article that influence melanogenesis and reduce oxidative stress deserve further research for use in humans as supplements.

Rarely, drugs that encourage melanogenesis (like latanoprost or imatinib) or target inflammatory cytokines (like psoralen and cyclosporin) have been shown to cause gray hair repigmentation[31]. The limited success of these medications in treating gray hair, despite the low

quality of the evidence supporting them and the difficulty of studying them adequately, provides insight into potential processes to target for the development of future hair repigmentation medications.

Lifestyle Factors

Activation of the sympathetic nervous system during stressful situations is essential for body mobilization and survival. However, it has been demonstrated that in mice, acute stress and hyperactivation of neural activity rapidly depletes MeSCs, resulting in stress-induced graying of the hair. Therefore, it is important not to expose yourself to long-term acute stress and to maintain homeostasis between the sympathetic and parasympathetic systems[5].
UV radiation and pollution leads to oxidative stress, which results from an imbalance between prooxidants and antioxidants, which leads to cell destruction and therefore faster hair graying[25,32].

Limitations

The literature review was confined to PubMed, potentially overlooking significant studies available in other databases or journals not indexed by PubMed. The use of English-only sources may have introduced a language bias, excluding relevant research published in other languages. Variability in study designs among the selected articles makes it challenging to uniformly assess the efficiency of different anti-hair graying strategies.

Conclusion

In our article, we discussed many new discoveries regarding hair graying and the processes that influence hair graying, and we also distinguished tested substances that influence biochemical pathways and thus ensure balance in oxidative stress and influence the melanogenesis process, to develop the best possible therapy for graying hair.

Particularly noteworthy discoveries regarding liposomes, which enable the delivery of specific substrates to the hair follicle, as well as UVB therapy, which has shown promising results in stimulating melanocyte stem cells, potentially reversing hair graying. These methods offer targeted, innovative approaches that address the underlying mechanisms of pigment loss directly at the cellular level, enhancing treatment efficiency and precision. The potential of

these technologies to restore natural hair color represents a significant advancement in the cosmetic and therapeutic management of hair graying.

We have studied the factors influencing hair graying, which allowed us to thoroughly understand this process from scratch and shows that avoiding these factors prevents hair graying.

Understanding the process of melanogenesis has allowed the development of methods influencing this process, such as suppression of melanocyte proliferation, which prevents MeSCs from permanently leaving their niche and enables the participation of these melanocyte-producing cells in the next hair cycle.

Our analysis underscores the importance of a holistic approach to understanding and managing hair graying, suggesting that a combination of genetic, lifestyle, and therapeutic strategies could be the key to developing effective treatments for this common sign of ageing.

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