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(REVIEW ARTICLE)

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Impact of stress on hair pigmentation: Neurobiological depletion of melanocyte stem cells

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Abstract

Hair pigmentation is a complex biological process regulated by the number and activity of melanocytes in the hair follicle. Although the classical understanding of hair graying is that the aging process is the primary factor, modern research increasingly suggests that psychological and physiological stress also significantly contribute to premature depigmentation.

Objective: This study aimed to analyze the biological mechanisms by which stress affects hair pigmentation, with a focus on the neural regulation of melanocyte stem cells.

Methods: A mechanistic research approach was applied using a systematic review of experimental and translational studies published between 2000 and 2025. The emphasis was on neurobiological, cellular, and molecular data describing stress-induced changes within the hair follicle.

Results: The study shows that stress activates the sympathetic nervous system, leading to excessive release of norepinephrine in hair follicles. This signal induces premature differentiation and depletion of melanocyte stem cells (McSCs), resulting in irreversible hair depigmentation. These results support the idea that stress-induced hair graying is a neurobiological process of aging and not a purely cosmetic or chronological phenomenon. A detailed overview of the processes may contribute to the development of future preventive or therapeutic strategies.

Keywords: Stress; Hair pigmentation; Melanocyte stem cells; Sympathetic nervous system; Hair graying; Neurocutaneous aging; Cortisol.

1. Introduction

Hair pigmentation results from the coordinated activity of melanocytes, which synthesize melanin and transfer it to keratinocytes in the hair shaft. These melanocytes originate from melanocyte stem cells (McSCs) located in the hair follicle [1]. The integrity of this cell lineage is critical for maintaining hair color throughout repeated growth cycles. Loss or dysfunction of McSCs leads to irreversible graying of hair.

Traditionally, the development of gray hair has been associated primarily with age-related factors, genetic predisposition, deficiencies, and the accumulation of oxidative damage [2,3]. In parallel with the study of the "classical" pattern of hair depigmentation, numerous clinical observations have been conducted indicating a link between intense stress and sudden or premature graying. However, until recently, this association was considered indirect and lacked a clear biological basis.

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Modern research in neurobiology and stem cells has identified direct mechanisms linking stress and hair pigment loss through activation of the sympathetic nervous system [4,5]. These findings significantly expand our understanding of the biology of hair aging and the role of neural regulation of skin structures.

2. Materials and Methods

This study was conducted as an original mechanistic research study, based on a systematic analysis of experimental and translational data on the effects of stress on hair pigmentation.

The analysis included publications published in PubMed, Nature Portfolio, NIH Research Matters, and ScienceDirect for the period 2000–2025. The work is based on studies on:

- Stress-induced activation of the sympathetic nervous system;
- The biology of melanocytes and mcscs;
- Neural interactions in the hair follicle.

All obtained data were carefully grouped according to parameters such as neural pathways of the stress response, the effect of norepinephrine on hair molecular structure, and the behavior of melanocyte stem cells. As a result, data were obtained confirming the irreversibility of pigment changes.

3. Results and Discussion

3.1. Activation of the Sympathetic Nervous System during Stress

A literature review has shown that both acute and chronic stress are accompanied by activation of the sympathetic nervous system and local release of norepinephrine in skin tissue and hair follicles [4,5]. Sympathetic nerve fibers directly innervate the bulge region where melanocytic stem cells (McSCs) are located, exerting a direct neural effect on their functional state.

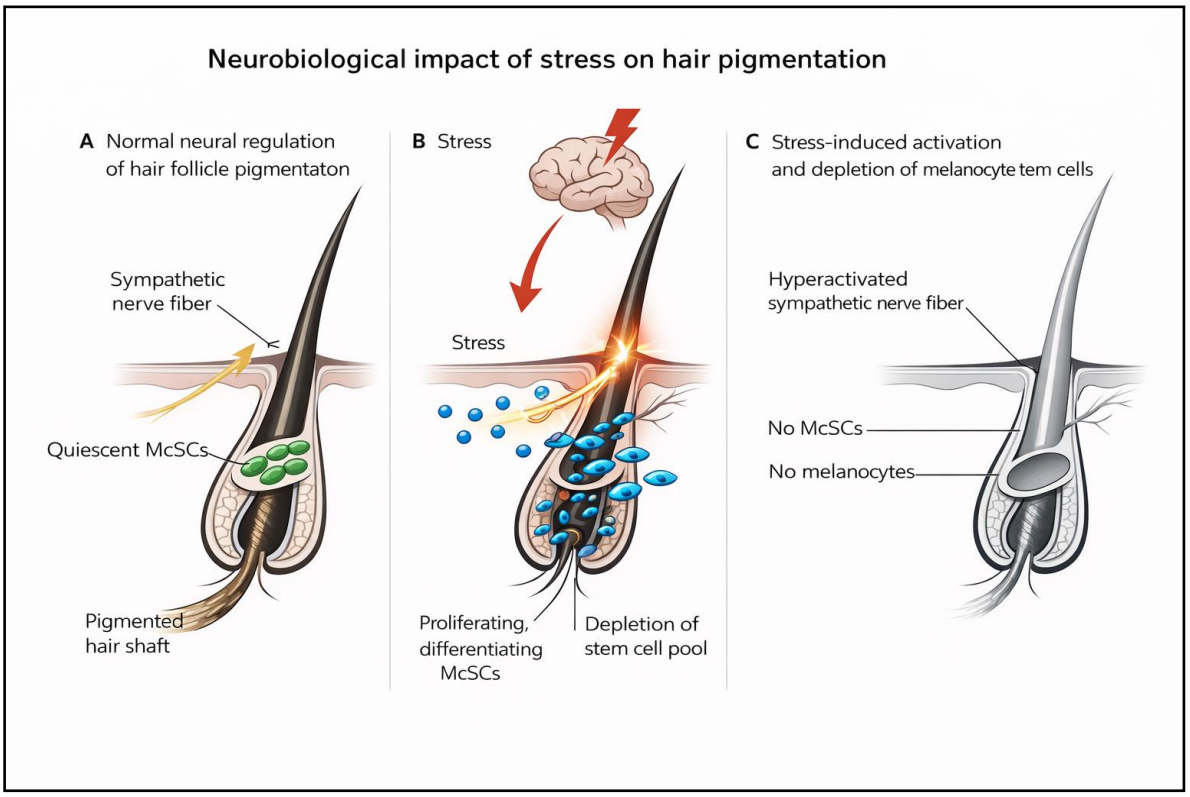

Figure 1 Stress-associated melanocyte stem cell depletion in the hair follicle

3.2. Depletion of Melanocytic Stem Cells

Experimental data indicate that elevated norepinephrine concentrations cause premature activation of McSCs, stimulating their accelerated proliferation and differentiation [4]. This process disrupts the physiological state of cellular quiescence and leads to rapid depletion of the stem cell population. Following the loss of McSCs, the hair follicle loses the ability to form new pigment-producing melanocytes, which clinically manifests as persistent hair graying [1,7].

3.3. Independence from Endocrine and Immune Pathways

Studies in models with adrenal insufficiency and immune cell deficiency have shown the persistence of stress-induced hair graying [4,5]. This confirms that stress hormones (cortisol) and immune mechanisms are not the leading factors in hair depigmentation under stress. A summary of stress-related neural and cellular pathways involved in hair depigmentation is provided in Table 1.

Table 1 Key stress-related pathways involved in hair follicle depigmentation

Stress mediator	Target cell	Molecular mechanism	Effect on pigmentation	Reference
Sympathetic nerve activation	Hair follicle stem cell niche	Stress-induced neural signaling disrupts McSCs quiescence	Progressive depletion of pigment-producing cells	[4,5]
Reactive oxygen species (ROS)	Melanocytes	Oxidative damage to melanosomes and melanogenic enzymes	Reduced melanin synthesis	[2,10]
Cortisol	Melanocytes	Modulation of melanogenesis-related gene expression	Minimal direct effect on pigmentation	[4,5]
Inflammatory cytokines (IL-6, TNF-α)	Melanocytes	Inhibition of tyrosinase activity and melanocyte survival	Hypopigmentation	[10,11]
DNA damage response signaling	McSCs	Stress-induced genotoxic stress	Permanent depigmentation	[1,7,8]
Aging-associated pathways	Hair follicle pigmentary unit	Reduced McSCs self-renewal capacity	Gradual hair graying	[3,7,8]

3.4. Irreversibility of Pigmentation Loss

Unlike pigmentation disorders associated with age-related, inflammatory, or metabolic processes, stress-induced depigmentation is characterized by irreversibility due to the structural destruction of some McSCs [7,8].

The accelerated depigmentation process associated with acute or chronic stress has been proven and studied by the author of this work not only based on scientific literature but also through many years of personal experience in the field of hair coloring and restoration.

4. Conclusion

Stress-induced hair graying is caused by activation of the sympathetic nervous system and subsequent depletion of melanocyte stem cells. This process is independent of hormonal and immune stress response pathways and leads to irreversible pigment loss. These findings advance our understanding of hair aging mechanisms and highlight the importance of neural regulation in maintaining skin homeostasis.

Understanding the specifics of stress-induced depigmentation will enable practicing hair restoration and color specialists to select the most appropriate formulations and care products for prematurely grayed hair.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The author declares that he has no conflict of interest.

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