Melanin and lipofuscin as hallmarks of skin aging

Anna Skoczyńska[1], Elżbieta Budzisz[1], Ewa Trznadel-Grodzka[2], Helena Rotsztejn[3]

[1]Department of Cosmetic Raw Materials Chemistry, Medical University of Lodz, Lodz, Poland
[2]Department of Dermatology and Pediatric Dermatology, Medical University of Lodz, Lodz, Poland
[3]Department of Cosmetology and Aesthetic Dermatology, Medical University of Lodz, Lodz, Poland

Abstract

Discoloration are symptoms of skin aging. They are connected with presence of melanin and lipofuscin, whose excess and abnormal distribution in the skin cause dark spots to appear. Melanin is formed under the influence of tyrosinase during melanogenesis. Its content changes with age, which may be a result of menopause. Lipofuscin is another example of the age pigment. It is composed of proteins, lipids and carbohydrates. It is described as an age pigment because its content increases with age. The formation and accumulation of lipofuscin is inevitable and leads to cell and homeostasis dysfunction because it reduces the proteasome activity.

Key words: melanin, lipofuscin, melanogenesis, lipofuscinogenesis, pigments, skin aging.

Melanin

The color of the skin, eyes and hair depends on melanin. Melanin is composed of polymorphous and multifunctional biopolymers, such as eumelanin (dominant in individuals with dark skin and hair), pheomelanin (dominant in individuals with red hair and skin phototypes I and II, in whom skin tumors are more common), neuromelanin (in human brain) and mixed melanin pigments [1] which are end products of a few-stage transformation of L-tyrosine. Human melanin can be found in the skin, iris, postmitotic cells such as neurons, cardiac myocytes, hepatocytes and glial cells. Melanin is a result of the activity of pigment cells – melanocytes and retinal pigment epithelial cells (RPE) [2], between melanosomes, which contain membrane proteins associated with lysosomes (LAMP) that protect the lysosomal membrane [1]. Melanosomes modify the cellular metabolism because they switch oxidative catabolism to anaerobic glycolysis [1, 3], alter NAD/NADH, NADP/NADPH ratios [1, 4] and stimulate the pentose phosphate pathway [1, 5]. Endosomes are precursors of melanosomes [6, 7]. Melanin pigments are different in terms of chemical composition, structural and physicochemical properties [1]. Eumelanins are polymorphous, nitrogenous biopolymers; the range of colors starts with black and finishes with brown and they are insoluble in most solvents [1]. They are covalently bonded to proteins. Eumelanins behave as polyanions and are capable to reversibly bind cations, anions, and polyamines [1]. An important feature of eumelanins is a stable paramagnetic state, which is a result of semiquinone units [1]. It also provides a redox activity, mostly towards oxygen species. Pheomelanin in turn is composed of benzothiazine units and its color is yellow to red. It is soluble in alkaline solvents and is a binding factor of proteins, drugs and chemicals [1, 8, 9]. Like eumelanin, it has paramagnetic properties due to additional semiquinone centers [1, 10, 11]. Neuromelanins are macropolymers composed of aminochromes and noradrenalinochromes and their color is brown and black. They are insoluble in organic solvents and demonstrate stable paramagnetic properties. They are able to chelate metals, interact with organic and inorganic compounds [1]. Melanin regulates the biosynthesis of vitamin D_3 and increases the skin resistance to sunburn and tumors. It is protective as an UV filter and affects thermoregulation, when absorption of solar radiation is changing. The skin contains estrogen, progesterone and androgen receptors. Estrogen receptors are located in keratinocytes, fibroblasts, sebaceous glands, sweat glands, hair follicles, and skin vessels. Progesterone receptors are found in melanocytes and play an important role in the formation of spots, whereas androgen receptors are located in keratinocyte nuclei, hair follicles, and sebaceous glands. These receptors are differently distributed in tissues and the expression of the genes encoding them changes in the course of life.

Table 1. Comparison of lipofuscin and melanin

| Criteria	Skin pigments	
	Lipofuscin	Melanin
Occurrence	Skin, neurons, cardiac myocytes, retinal epithelial pigment cells, hepatocytes	Skin, iris, neurons, cardiac myocytes, hepatocytes, glial cells
Structure	Proteins (30–70%) Lipids (20–50%) Carbohydrates (4–7%)	Eumelanin – copolymers of DHI and DHICA Pheomelanin – benzothiazine units Neuromelanin – aminochromes and noradrenalinochromes
Place of formation	Lysosomes	Melanocytes
Properties	Autofluorescence	Redox activity against free radicals due to the presence of semiquinone
Importance	Increased susceptibility to oxidative stress, which often leads to neurodegenerative diseases, telomere shortening (acceleration of aging fibroblasts), inhibition of proteasome activity	Protection from damaging effects of UV radiation, involvement in the immune response
Characteristics of pigmented skin spots	Brown spots; dark, smooth spots covered with the epidermis and filled with lipids	Melasma, freckles, post-inflammatory hyperpigmentation, senile lentigines, UV-induced pigmentation, pigmentation petaloides actinica

Hormonal disorders that occur during menopause significantly affect the overall condition and appearance of the skin and its appendages. They manifest themselves with hypo- and hyperpigmentation [3]. There are several types of skin spots being a result of increased melanin synthesis and different deposition (Table 1).

Melanogenesis

The skin is composed of epidermal units that are responsible for production and distribution of melanin. These units are composed of melanocytes, surrounded by keratinocytes and regulated by the paracrine system. In physiological conditions melanin synthesis occurs in melanocytes. Its enzymatic and structural elements are organized separately in a process resembling lysosome formation [1]. Melanocytes originate in neural crest melanoblasts that migrate to different destinations, such as the epidermis or hair follicles [1]. Tyrosinase presence causes oxidation of tyrosine or L-dihydroxyphenylalanine (L-DOPA) to dopaquinone, initiates eu- or pheomelanogenesis. Tyrosinase can be activated by UV radiation, inflammation, endocrine glands (the pituitary gland, gonads), vitamins A and PP, pantothenic and folic acid. A high concentration of metal ions (Mn^{2+} or Cu^{2+}) also leads to oxidation of L-DOPA to melanins [1, 12, 13]. Inhibition of tyrosinase can be modulated due to the action of vitamin C and endocrine gland activity (adrenal and pineal). Melanocytes are responsible for the production of proopiomelanocortin peptides (POMC), cytokines, nitric oxide (NO), prostaglandins, leukotrienes, which behave in a paracrine or autocrine way in keratinocytes. Furthermore, they are involved in the immune response. Keratinocytes produce several factors (such as POMC,

endothelin-1 (ET-1), steel/stem cell factor (SCF), neurotrophins, basic fibroblast growth factor (bFGF), NO) as a result of exposure to ultraviolet radiation, and that can stimulate or inhibit melanogenesis. Migration, proliferation and differentiation of melanocytes depend on mediators that are produced by cells of the dorsal neural tube, i.e. ectoderm, keratinocytes, such as WNT glycoprotein family, endothelin 3 (EDN3), stem cell factor (SCF) [1, 14, 15]. Melanogenesis is a process composed of several steps. Disruption of this process may lead to different types of pigment failures [1, 16, 17]. Understanding of the melanogenesis mechanism allows to explain its causes. In humans between 27 and 30 days of fetal development melanin granules are observed, while melanosomes before week 14 at all stages of maturation [18]. The melanogenesis process is stopped within several weeks, before full pigmentation of cells. Melanosomes mature during several stages [1, 19, 20]. At the beginning, protein matrix is formed in the smooth endoplasmic reticulum and released to cytosol. Then, tyrosinase (enzyme needed in the process of melanin formation) is transferred through vesicular transport from the Golgi apparatus to cytosol. Then, the process of melanin synthesis is activated [18, 20]. In the first step, melanosomes or premelanosomes assume the form of protein matrix, where melanin is deposited (mainly eumelanin). Deposition of melanin and maturation of granules last for another 2 years until melanosomes are fully pigmented [18]. Figure 1 shows a general scheme of melanin biosynthesis. Biosynthesis of melanin is initiated when L-phenylalanine is hydroxylated to L-tyrosine (in *in vivo* conditions) or directly from L-tyrosine, which is next transformed to L-DOPA. In the next stage L-DOPA is oxidized to dopaquinone. This stage occurs mainly in the course of biosynthesis of eumelanin
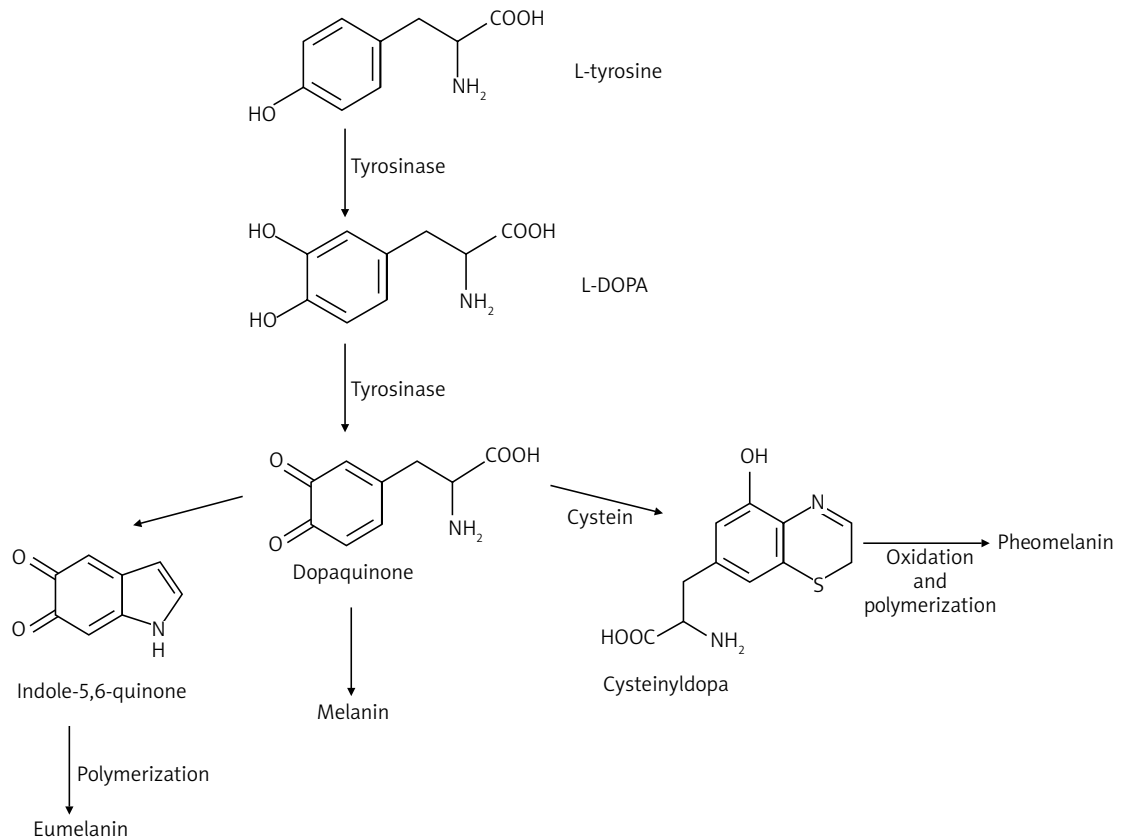
Figure 1. General scheme of melanin biosynthesis

and pheomelanin [1]. Melanosomes formation is a consequence of interactions between rough endoplasmic reticulum (RER) structures, vesicles and channels of the *trans*-Golgi Network (TGN). Hence, premelanosomes of the first stage are formed from an outpouching of a smooth membrane [1]. In the second stage of the eumelanogenic pathway, a fibrillar matrix is formed. The eumelanogenic pathway involves transformation of dopaquinone to leukodopachrome, which is preceded by oxidation and reduction reactions. That results in the production of intermediates such us dihydroxyindole (DHI), dihydroxyindole carboxylic acid (DHICA), which are polymerized to eumelanin [1]. There are two ways of maturation of eumelanosomes. Enzymes, which are significant for melanogenesis, are delivered through vesicles to melanosomes that originate from the endoplasmic reticulum and the Golgi apparatus [1]. In the second way tyrosinase and other proteins, involved in melanogenesis, are at first deposited in early developed endosomes through participation of the adaptor protein 3 and then in late developed endosomes. Later on, they connect with melanosomes from the first stage [1, 21]. Melanosomes at the first stage may contain proteins connected with melanogenesis (MRPs), but they are catalytically inactive, until they are released to melanosomes. This process

is accompanied by a change of shape of melanosomes and formation of eumelanosomes. Pheomelanogenesis starts with dopaquinone, which is conjugated to cysteine or glutathione. This results in the formation of cysteinyldopa and glutathionyldopa. These products are then converted to pheomelanin [1]. Vitamin E (α-tocopherol) is a potent inhibitor of melanogenesis because it inhibits tyrosinase activity during the post-translational processing. Retinoic acid stimulates maturation of melanocytes. In the basal layer of the epidermis it is able to induce tyrosinase only in white-skinned individuals.

Enzymes of melanogenesis

Tyrosinase is a glycoprotein that is situated in the melanosome membrane. Its domain is located in the internal membrane, transmembrane and in the cytoplasmic area. It is an enzyme dependent on copper ions and it catalyses transformation of L-tyrosine to L-DOPA. Mutations within a sequence of this enzyme may lead to different diseases connected with disorders of skin pigmentation. A cytoplasmic domain of tyrosinase participates in the transport of the enzyme from the cell nucleus to melanosomes. The internal domain contains a catalytic region (constitutes 90% of this protein), where

histidine is located in few residues and binds copper ions [2, 22]. Tyrosine hydroxylase isoform I is present in melanosomal membrane. It is adjacent to tyrosinase and catalyzes conversion of L-tyrosine to L-DOPA, by initiating tyrosinase activation. Phenylalanine hydroxylase (PAH), dependent on the cofactor 6BH4, catalyzes transformation of phenylalanine to L-tyrosine and also promotes activation of tyrosinase in cytosol [2, 22, 23]. Schallreuter *et al.* [23] emphasize that these three enzymes are required for melanogenesis [2, 22]. Proteins 1 and 2 are connected to tyrosinase (TRP-1, TRP-2) and are also located in the melanosomal membrane. Their role is not fully explained, but it is possible that TRP-1 plays a role in activation and stabilization of tyrosinase, melanosome synthesis, increases the eumelanin-pheomelanin ratio and also reduces oxidative stress [2, 23, 24]. TRP-2 is also known as dopachrome tautomerase and needs zinc ions for activation. The melanocortin receptor (MC1-R) belongs to the family of G-protein receptors. Its agonists include melanocyte stimulating hormone (α-MSH), adrenocorticotropic hormone (ACTH), which are cleavage products of proopiomelanocortin (POMC). Agonists of MC1-R activate adenylate cyclase enzyme, which leads to an increase in intracellular cAMP and activation of protein kinase A (PKA). cAMP response element (CREB) is phosphorylated by PKA and it is important for transcription in several genes. Apart from the POMC/MC1-R/cAMP pathway, there are other melanocyte receptors, which are associated with cAMP production and adenyl cyclase. These are muscarinic and α or β estrogen receptors. An increase in the estrogen level causes hyperpigmentation during pregnancy. ACTH 1-17/MC1-R and norepinephrine/α1-adrenergic receptor may cause activation of inositol trisphosphate/diacylglycerol pathway (IP3/DAG), which leads to release of calcium in cytoplasm of melanocytes. diacylglycerol (DAG) activates PKC-β and can be released from melanocytes through UVR action in the lipid membrane [2].

Lipofuscin

Lipofuscin is a waste material of intracellular structures that gets accumulated in lysosomes, between postmitotic cells. It is an undegradable material and cannot be removed dominantly from cells during exocytosis. Postmitotic cells such as neurons, cardiac myocytes, fibers, retinal pigment epithelial cells (RPECs) gradually become brown-yellow and show autofluorescence. Lipofuscin can be detected in neurons of 3- or 4-month old children and in cardiac myocytes of humans in their late childhood. For the first time Hannover [25, 26] described such pigment in neurons in 1842, and in 1886 Koneff [25, 27] pointed out its relationship with age. In 1912 Hueck [25, 28] introduced the term "lipofuscin", which derived from the Greek word *lipo,* which means "lipids" and from the Latin word *fuscus*, which means "dark". Later

on, a discovery of lysosomes and lysosomal enzymes made it possible to investigate a relationship between lipofuscin and these organelles [23]. An interference of lipofuscin with cellular recycling processes is supported by the fact that lipofuscin decreases proteasome activity in fibroblasts [23]. It was hypothesized that lipofuscin formation is a result of decreased activity of lysosomal enzymes, mainly cysteine proteases such as cathepsin B, H and L. An amount of lipofuscin rise with age in postmitotic cells and that is why it is called an age pigment or hallmark of aging [23].

Composition of lipofuscin

A chemical analysis of lipofuscin granules revealed the presence of protein and lipid compounds (20–50% and 30–70%, respectively). Protein content consists of different amino acids, while lipid includes triglycerides, free fatty acids, cholesterol, and phospholipids. Carbohydrates account for 4–7% of lipofuscin content. Metals are also abundant, and iron dominates. Lipofuscin can be detected with the use of histochemical techniques, such as staining for lipids and carbohydrates. Lipids can be stained with Sudan black, Nile blue, OsO_4 and carbohydrates with lectins. Lysosomal enzymes associated with lipofuscin granules can be revealed by light and electron immunocytochemistry. Autofluorescence of lipofuscin granules can be observed by fluorescence or electron scanning microscopy with the application of excitation lights of different wavelengths in combination with different barrier filters. Experiments revealed that a reaction between carbonyls and amino compounds produces Schiff bases, 1,4-dihydropyridines, 2-hydroxy-1,2-dihydropyrrol-3-ones, which have autofluorescent properties [25].

Lipofuscinogenesis

Research data imply there is a relationship between the mechanism of lipofuscin formation and Harman's free-radical theory [25, 29], when we bear in mind the role of oxidation reactions in aging. It was hypothesized that free-radical reactions cause damage and polymerization of lipids and proteins, which is an undegradable and fluorescent material. Proteins are the main target of free radicals (ROS) [30, 31]. This type of oxidation increases with age [32–34]. Oxidized proteins are not functional and they are repaired during digestion to peptides or free amino acids in the proteasome or are not removed in the process of exocytosis. With age, these mechanisms weaken. Hence, the oxidized proteins accumulate in cells and cause tissue damage and deposition of lipofuscin [32, 33]. Cysteine and methionine are most frequently oxidized amino acids. Intrachain aldehydes, ketones and crosslinked connection of cysteine are formed during the oxidation [35, 36]. Methionine reductases A and B (MSAR/A and MSAR/B, respectively) reduce oxidized me-

thionine. Other enzymes, such as thioredoxin (TXN) and glutathione reductase (GSR) reduces oxidized cysteine disulfide bridges involving NADPH and cooperate with the MSAR/B [37–40]. Aging and exposure to UV radiation causes dysfunctional recovery mechanisms, thus increasing the level of oxidized protein.

Connections of proteins and other biomolecules is one of results of a ROS attack and probably a reason why phagocytosed material is not degraded [25, 41]. Brunk *et al.* [25, 42] proposed a scheme of lipofuscin formation in conditions of oxidative stress. Reactive oxygen species, mainly H_2O_2, easily defund to lysosomes, which contain various phagocytosed macromolecules, as well as low molecular weight iron. Iron is released from metalloproteins during intracellular degradation. Interactions between H_2O_2 and iron lead to $HO^·$ formation, which facilitates a formation of cross-linking of surrounding macromolecules and finally lipofuscin. Lipofuscinogenesis gets more intense under the influence of lysosomal proteases which delay degradation of phagocytosed material and need more time for oxidation. Autophagocytosis of mitochondria is the main cause of lipofuscin formation [25] because mitochondria are one of places where ROS are generated so lipofuscin is the aim of their attack [25] and is separated from the cytoplasm by the lysosomal membrane and does not react directly with lysosomal components. An increase in iron between lipofuscin granules may lead to formation of ROS, which causes harmful oxygenation. Moreover, a large number of lysosomes containing lipofuscin may promote cell damage when lysosomal membranes are destabilized by pathogen factors. Fibroblasts containing lipofuscin are more susceptible to apoptosis induced by oxidative stress than cells with lower content of lipofuscin. Examinations of rat neurons revealed that an increase in lipofuscin content was induced by iron. Iron chelators such as desferrioxamine, antioxidants such as vitamin E, glutathione, selenium delay lipofuscin accumulation [25].

The content of melanin may increase or decrease with age. Reduction in melanin concentration in case of an old person can manifest itself mostly with gray hair and this symptom is typical for all people, regardless of gender or race. However, the reduction in melanin is not limited to hair follicles, but also affects the epidermis, the retinal pigment epithelium, certain areas of the central nervous system [43]. Cui *et al.* [44] demonstrated that activation of p53 occurs during hyperpigmentation, which occurred as a consequence of UV radiation in keratinocytes. The authors concluded that p53 is involved in signaling cytokine receptors paracrine pathway, which promotes the formation of senile lentigines. Their presence is associated with photo-aging and chronological aging. Administration of sex hormones during hormone replacement therapy (HRT) improves the quality and thickness of the skin and also stimulates the function of melanocytes. It leads to an increase in the synthesis of

the pigment and causes its uneven distribution. Senile lentigines appear, which may be caused by administration of estrogens and progestogens [3]. Lipofuscin, another marker of aging, is a brownish pigment produced during oxidation of lipoproteins in lysosomes. It has been found that the amount of lipofuscin increases in cells of old bodies [45]. Increased levels of lipofuscin can be assessed by histochemical staining. A higher level of lipofuscin increases susceptibility to oxidative stress, reduces lysosomal degradation, which promotes the development of various pathologies typical for old age. These changes occur in neurodegenerative diseases, such as Alzheimer's and Parkinson's diseases. Large quantities of lipofuscin and lysosomal enzymes are present in amyloid deposits in Alzheimer's patients. It is also believed that it delays the formation of lipofuscin [25]. The content of lipofuscin in postmitotic cells depends on oxidative stress, which causes oxidation of proteins and lipids, which are the structure of lipofuscin. Experiments were performed to determine the correlation between the accumulation of lipofuscin and oxidative stress in fibroblasts of the replication phase. Since studies have confirmed a correlation between telomere shortening and antioxidant efficiency in 22 strains of human fibroblasts, it can be concluded that telomere shortening is an indicator of oxidative stress [46]. Further explanations allow us to conclude that a significant increase in the formation of lipofuscin occurs when the culture almost achieves the replicative senescence. In senescence fibroblasts increase oxidative stress, reduce proteolysis or both of the symptoms appear [46]. The presence of lipofuscin inhibits the activity of the proteasome [46]. The formation of lipofuscin is not a sufficient factor explaining the aging process. It requires interactions with factors that significantly reduce cell growth. The process of shortening of telomeres clearly dominates among the above factors [46]. The presence of lipofuscin in the skin is associated with the appearance of pigmentation generally known as

Figure 2. Lipofuscin spots on the dorsal side of hands

liver spots on the dorsal side of hands (Figure 2), but also face (mainly the cheeks and chest).

These changes may be improved by an application of topical agents for skin lightening. It was also observed that application of high oral doses of vitamin E may reduce the level of lipofuscin in skin biopsies as well as lighten the skin [45].

Acknowledgments

Conflict of interest

The authors declare no conflict of interest.

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