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Proteomic and Bioinformatic Characterization of the Biogenesis and Function of Melanosomes

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Melanin, which is responsible for virtually all visible skin, hair, and eye pigmentation in humans, is synthesized, deposited, and distributed in subcellular organelles termed melanosomes. A comprehensive determination of the protein composition of this organelle has been obstructed by the melanin present. Here, we report a novel method of removing melanin that includes in-solution digestion and immobilized metal affinity chromatography (IMAC). Together with in-gel digestion, this method has allowed us to characterize melanosome proteomes at various developmental stages by tandem mass spectrometry. Comparative profiling and functional characterization of the melanosome proteomes identified ~1500 proteins in melanosomes of all stages, with ~600 in any given stage. These proteins include 16 homologous to mouse coat color genes and many associated with human pigmentary diseases. Approximately 100 proteins shared by melanosomes from pigmented and nonpigmented melanocytes define the essential melanosome proteome. Proteins validated by confirming their intracellular localization include PEDF (pigment-epithelium derived factor) and SLC24A5 (sodium/potassium/calcium exchanger 5, NCKX5). The sharing of proteins between melanosomes and other lysosome-related organelles suggests a common evolutionary origin. This work represents a model for the study of the biogenesis of lysosome-related organelles.

Keywords: proteomics • organelles • lysosome related • biogenesis

Introduction

Melanosomes are membrane-bound organelles, specialized in the production and distribution of melanin pigment, that are conserved in structure from primitive organisms to mammals. In lower species, melanin pigmentation plays important roles in thermoregulation, camouflage, and sexual attraction. In humans, melanin in the skin, hair, and eyes protects the body against environmental challenges such as solar UV exposure, toxic free radicals, and heavy metals. Variations in chemical composition, melanosome structure, and distribution result in distinct skin, hair, and eye color differences in human populations. Dysfunctions in pigmentation and melanosome biogenesis are associated with a wide variety of inherited genetic disorders and pigmentary diseases, including oculocutaneous albinism and Hermansky–Pudlak syndrome. Melanosome-specific proteins also provide important markers for malignant melanoma.

To date, about 125 genes affecting mammalian pigmentation have been identified,[1] about half of which have been cloned. Six of these genes encode proteins that are specifically localized in melanosomes including enzymatic and structural compo-

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nents required for melanin biosynthesis.[2] The specific roles of more than 80 proteins previously identified in melanosomes[3] have yet to be defined. In mammals, melanosomes mature from undifferentiated vesicles (stage I) to elongate and form internal fibrils (stage II).[2,4,5] In the presence of tyrosinase and other enzymes, melanin is synthesized and deposited on the internal fibrils (stage III) and can become uniformly dense (stage IV) in heavily pigmented melanocytes. As melanosomes mature, they are gradually transported to the peripheries of the melanocytes in which they form and, in human skin, are transferred to neighboring keratinocytes.

A detailed understanding of how melanosomes mature and move within and between cells requires a comprehensive knowledge of proteins comprising them. Although methods for isolating melanosomes at various developmental stages have been established,[2,3,6] obtaining them in sufficient quantities and removing endogenous melanins remains challenging. Melanins are highly heterogeneous polymers of various quinones, indoles, indole-quinones, and sulfhydryl derivatives[7,8] that can covalently bind to proteins, causing difficulties in solubilization. Even small amounts of melanin result in motility shifts that adversely affect electrophoretic resolution of proteins, block antibody epitopes needed for Western blotting, and bind to chromatographic columns, degrading liquid chromatography/mass spectrometry (LC/MS) performance. Pursuit of a proteomic analysis of melanosomes, thus, required an effective approach for purifying and solubilizing them, and removing the melanin.

Global melanosome proteome characterization was made possible by using LC/MS to analyze both in-solution digests after removal of melanin by immobilized metal affinity chromatography (IMAC)[9] and in-gel digests. Proteins identified in various maturation stages by LC/MS were organized into families or subgroups based on functional classifications such as gene ontology (GO).[10] A combination of immunoblotting, immunofluorescence microscopy, and bioinformatics analysis was used to characterize the protein profiles of melanosomes at various developmental stages. The stage-related proteins provide direct evidence of protein sorting and trafficking to this organelle and information about their biogenesis as lysosome-related organelles. Further, 17 of the 63 human homologues of mouse pigment gene products were identified in various melanosome stages.

Materials and Methods

Cell Cultures and Biochemical Procedures. Pigmented (MNT-1) and nonpigmented (SK-MEL-28) human melanoma cells were cultured, and various stages of melanosomes were isolated by sucrose density gradients, as described previously.[2,3,6]

In-Gel Trypsin Digestion. Early stage melanosomes (150 μg) were solubilized directly in sample loading buffer and were separated on 10% SDS-PAGE gels, according to the manufacturer's instructions (Bio-Rad Laboratories, Inc., Hercules, CA). Gels were stained with colloidal Coomassie blue for 1 h and were then destained in water (Bio-Rad). Lanes containing samples were cut into 15 slices from the top to the bottom of the gel. In-gel trypsin (Promega Corp., Madison, WI) digestion was performed as previously described.[11] Peptides from bands of similar staining intensity were pooled together, while peptides from dark bands were analyzed individually.

In-Solution Digestion. Late stage protein pellets (150 μg) were frozen and thawed three times before being solubilized in a mixture of 8 M urea and 10% acetonitrile in 100 mM ammonium bicarbonate (Sigma-Aldrich, St. Louis, MO). Each sample was sonicated briefly and mixed using a vortexer. Samples were then reduced with 10 mM dithiothreitol (Sigma-Aldrich) at 51 °C for 1 h and carboxyamidomethylated with 20 mM iodoacetamide (Sigma-Aldrich) in the dark at room temperature for 45 min. Endo-Protease Lys-C (Roche Diagnostics, Indianapolis, IN) was then added to each sample (1:20 enzyme/protein ratio) after diluting the urea to 4 M with 100 mM ammonium bicarbonate (pH 8.5). After digestion for 6 h at room temperature, samples were further diluted with 100 mM ammonium bicarbonate until the final urea concentration reached 1 M. Trypsin (1:20 enzyme/protein ratio) was added at room temperature for 10 h at pH 8.5.

IMAC Melanin Removal. IMAC columns were constructed as previously described[12] with some modifications. Briefly, a 360 μm o.d. × 200 μm i.d. (Polymicro Technologies, Inc., Phoenix, AZ) fused-silica column was packed with 8 cm Poros 20MC resin (PerSeptive Biosystem, Framingham, MA). The IMAC column was washed for 5 min with 50 mM EDTA (Sigma-Aldrich), pH 9, followed by a 5 min wash with NANOPure (Barnstead, Dubuque, IA) water to bring the pH back to neutral. The columns were then activated with 100 mM $FeCl_3$ (Sigma-Aldrich) at a flow rate of 2 μL/min for 10 min. Excess $FeCl_3$ was removed with 5−10 column volumes of 0.01% acetic acid (Sigma-Aldrich). A fused-silica precolumn (360 μm o.d. × 75 μm i.d.) packed with irregular C18 beads (5 μm, ODS-AQ, YMC, Waters, Milford, MA) was then end-connected to the IMAC column using a Teflon sleeve (0.012 in. o.d. × 0.060 in. i.d., Zeus, Orangerburg, SC). An aliquot of the in-solution digest sample was directly loaded onto the IMAC/C18 reverse-phase precolumn assembly. The precolumn alone was then washed with 0.1% acetic acid to remove contaminating salts.

In-Gel Tryptic Digest Analyzed with 3D Ion Trap Mass Spectrometer. An aliquot of the in-gel tryptic digest was loaded onto a C18 reverse-phase precolumn (360 μm o.d. × 75 μm i.d.). For sample analysis by mass spectrometry, the precolumn was Teflon-sleeve-connected to an analytical reverse-phase HPLC column (360 μm o.d. × 50 μm i.d.) packed with 5 cm regular C8 beads (5 μm, ODS-AQ, YMC). Each sample was then analyzed by on-line nanoflow RP-HPLC (Agilent 1100, Palo Alto, CA) interfaced to a microelectrospray ionization source of a LCQ^{DecaXP} mass spectrometer (Thermo Electron, San Jose, CA) that was operated in the data-dependent MS/MS mode on the 5 most abundant ions detected in precursor MS scans, as previously described.[13] The HPLC gradient (buffer A = 100 mM acetic acid in water, buffer B = 70% acetonitrile/100 mM acetic acid in water) was 0−5% B in 5 min, 5−40% B in 180 min, 40−60% B in 30 min, 60−100% B in 10 min, 100% B in 2 min, and 100−0% B in 5 min. Full scan mass spectra were acquired over an m/z = 300−2000 range.

In-Solution Tryptic Digest Analyzed with Hybrid Linear Ion Trap-Fourier Transform Mass Spectrometer. The precolumn loaded with the melanin-depleted sample was Teflon-sleeve-connected to an analytical reverse-phase HPLC column (360 μm o.d. × 50 μm i.d.) with an integrated electrospray emitter tip as previously described.[13] Samples were analyzed by nanoflow RP-HPLC micro-ESI coupled to an LTQ-FT hybrid linear ion trap-Fourier transform mass spectrometer (Thermo Electron). The instrument was cycled through a single (FT) MS experiment followed by 10 data-dependent (LTQ) MS/MS experiments. Gas-phase fractionation in the mass-to-charge (m/z) dimension[14] was employed such that the following

segmented m/z ranges were selected in series for MS precursor ion selection: m/z 300−500, 500−700, 700−900, 900−1200, and 1200−2000. For m/z 500−700 and 700−900, the HPLC gradient used was 0−5% B in 5 min, 5−40% B in 180 min, 40−60% B in 30 min, 60−100% B in 10 min, 100% B in 2 min, and 100−0% B in 5 min; for the other m/z ranges, a shorter HPLC gradient (0−5% B in 5 min, 5−60% B in 60 min, 60−100% B in 10 min, 100% B in 2 min, and 100−0% B in 5 min) was used.

Data Analysis. Acquired data were searched against the human database [National Center for Biotechnology Information (NCBI)] with SEQUEST.[9] All SEQUEST search parameters were conducted with "no enzyme" specificity and a static modification of 57 Da on cysteine, representing alkylation with iodoacetamide, and a differential modification of 16 Da on methionine, representing the possibility of oxidation. For data acquired from in-gel digests on the LCQ^{DecaXP}, the precursor mass window was set to ±3 Da (amu), and fragment ion mass tolerance was set to 0.35 Da (amu). For data acquired from in-solution digests on the LTQ-FT, the precursor mass window was set to ±0.05 Da (amu), and the fragment ion mass tolerance was set to 0.35 Da (amu). SEQUEST search results were evaluated by the following parameters prior to manual validation: DelMass < 1.0, Xcorr > 2.4, DelCn > 0.1, Sp > 500, RSp < 10, Ion Ratio > 0.6.

Bioinformatics Analysis. Systematic bioinformatics analysis of the melanosome proteomes was conducted using the PIR *i*ProXpress system,[15] which provides functionalities for peptide and protein mapping and functional annotation and profiling. Protein lists and peptide sequences generated from proteomic experiments were mapped to UniProt Knowledgebase (UniProtKB)[16] entries based on ID and peptide mappings. The ID mapping, through the UniProt/PIR ID mapping service,[16] maps protein/gene IDs from about 30 data sources (including NCBI identifiers such as gi number, Entrez Gene and RefSeq ID) to UniProtKB. For many-to-one mapping, where multiple IDs map to the same UniProtKB protein, as is often the case for gi numbers, the mapping effectively removes redundancy. For proteins not mapped through ID mapping, their peptide sequences are searched against the UniProtKB for sequence mapping to assign the protein ID. In the case of one-to-many mapping, if all the matched entries are in the same UniRef90 cluster, in which members share at least 90% sequence identity, one representative sequence is chosen. If the proteins belong to different UniRef90 clusters, assignment is made with retroinspection and manual validation of the original MS/MS protein identification results. When both ID and peptide mappings were combined, a total of 1438 UniProtKB entries were mapped from proteomic data in this study. Following the protein mapping, a protein information matrix was generated to describe all melanosome proteins based on sequence analysis and extensive annotations extracted from the *i*ProClass[14] database. *i*ProClass integrates annotations from over 90 biological databases for all UniProtKB proteins, including protein name, family classification, isoform, sequence features (domain, motif, and functional site), GO (molecular function, biological process, and cellular component), function and functional category, structure and fold classification, pathway and pathway category, protein−protein interaction and complex, and post-translational modification. The profiling analysis involved functional categorization of proteins and cross-comparison of coexpressed or differentially expressed proteins from multiple datasets to discover plausible functions and pathways. The melanosome proteome datasets in this study were organized into 12 subsets according to stage and cell type (Supplementary Table 1, Supporting Information). Iterative categorization and sorting of protein attributes, especially of GO classes and pathways (KEGG and BioCarta), revealed major functional categories in the proteome. Interesting unique or common proteins at different stages of melanosome biogenesis were identified by manual examination and comparison of these functional profiles from the melanosome data subsets. Organelle proteomes reported for lysosomes, endoplasmic reticulum, synaptosomes, neuromelanin granules, exosomes, and platelet were also incorporated into the matrix for comparison with the melanosome proteome.

Immunochemical Techniques. For dual immunofluorescence, cells were seeded in 2-well chamber slides (Nalgene, Naperville, IL), fixed, and stained as described previously.[17] SLC24A5 polyclonal antibodies were generated in rabbits and chickens against synthetic peptides corresponding to sequences at the carboxy terminal region of human SLC24A5 and were affinity-purified prior to use. Other antibodies used are noted in the legend to Figure 2 and were obtained from sources as cited in the text. Images were obtained using an LSM 510 confocal microscope (Zeiss, Jena, Germany). Analysis and quantification of the colocalization signal was evaluated under equal microscope parameters using Zeiss colocalization software. For Western blotting, extracts of cells and of melanosomes were separated by SDS-PAGE and were subjected to Western blotting as reported previously.[17]

Results

Comparative Profiling of Melanosome Proteomes. Characterizing the melanosomal proteome is especially challenging due to the inefficient solubilization of highly hydrophobic membrane proteins[18−20] and contamination with endogenous melanin. After screening a number of solvent conditions to solubilize melanosomes, we found that a combination of urea and 10% acetonitrile was highly effective. Black melanosome pellets were gradually solubilized on a shaker for ~10 h, and the sample became light brown after 12 h of subsequent digestion with trypsin. We then took advantage of the heavy metal ion[21,22] sequestering property of melanin by loading the resulting peptides onto an IMAC column activated with an excess volume of $FeCl_3$, assembled back-to-back with an RP precolumn. The melanin was retained on the IMAC column due to the high affinity of Fe(III) for the *o*-diOH groups of melanin,[23] while the peptides passed through and were subsequently caught on the C18 reverse-phase precolumn. This assembly allows the efficient and concurrent removal of melanin and the loading of the sample onto the column in a single step prior to the LC/MS analysis.

Proteomic analysis was applied to stages I and II melanosomes purified from pigmented (MNT1) or from unpigmented (SK-MEL-28) human melanoma cells, and to stage IV melanosomes from MNT1 cells. About 600 (range 551−652) distinct proteins were detected in each preparation. Proteins identified were grouped into 12 subsets according to stage and cell type (Supplementary Table 1, Supporting Information). Proteins unique to unpigmented SK-MEL-28 melanosomes "Unique SK-MEL-28" or to pigmented MNT1 melanosomes "Unique MNT1" are likely involved in the regulation of pigmentation, whereas proteins in the MNT1 stage IV ("Unique late stage") group may be related to melanosome maturation.

About 100 proteins were common among all stages of melanosomes isolated from MNT1 and from SK-MEL-28 cells ("Common all stages") (Supplementary Table 2, Supporting Information). Unlike-stage-related or cell type-specific melanosome proteins, these common proteins are considered constituent proteins or resident proteins of melanosomes. Interestingly, these proteins are associated with several other cellular compartments that collectively may represent the basic components necessary to define melanosomes. About 25% of these proteins are potential transmembrane proteins with various functions, including ion/solute transporters, receptors, and membrane trafficking proteins. Over 33% are enzymes with heterogeneous and broad catalytic activities (oxidoreductases, transferases, hydrolases, lyases, and isomerases). Other proteins include molecular motor and cytoskeleton proteins, and potential signaling molecules. There are also proteins known to be associated with the plasma membrane (e.g., Na,K-ATPase subunits) and other organelles, such as the endoplasmic reticulum (e.g., ribophorin I, GRP 78/BiP, and calnexin) and lysosomes (e.g., cathepsin D, B, and γ-Glu-X carboxypeptidase). The presence of vacuolar proton ATPases (e.g., vATPases A, B, H, and the clathrin coated vesicle/synaptic vesicle proton pump) in both early and late melanosomes is consistent with the critical importance of pH in regulating the physiological functions of melanosomes.[24,25] In addition, the presence of sulfhydryl enzymes (e.g., glutathione *S*-transferase pi, protein disulfide isomerases, and quinone reductase) indicates their likely importance in regulating melanin synthesis, since pheomelanins, a major subclass of melanins, contain sulfur.

Proteins participating in membrane dynamics also represent a major component of the melanosome proteome.The identification of regulatory molecules involved in cellular protein sorting and trafficking, vesicle formation, docking, and fusion emphasizes the critical nature of melanosome interactions with other subcellular components. These include trafficking proteins (e.g., SEC22b), synaptic vesicle-associated proteins (e.g., VAT-1), lipid raft-associated proteins (e.g., stomatin and flotillin-1), secretory vesicle-associated proteins (e.g., calumenin), and Ca^{2+}-dependent annexin proteins (organizers of membrane domains and membrane-recruitment platforms). In addition, elements of the cytosolic fusion machinery important for organelle biogenesis, for example, SNARE proteins and small GTPase family members and related proteins (RABs) (e.g., Rab7, Rab27a, Rab5c, and P21-rac1), were also identified. As shown in Supplementary Table 3 (Supporting Information), a total of 18 RABs was identified in early melanosomes from MNT1 and SK-MEL-28 cells, some of which were detected only in stage I or only in stage II melanosomes.

Of special note are proteins known to be present both in endocytic and in secretory pathways. For example, Pmel17, one of the six known melanosomal-specific proteins, reaches the cell surface and is internalized by receptor-mediated endocytosis;[26,27] it has been widely studied as an immunotherapy target for melanoma.[28]

Identification and Validation of Stage-Related Melanosomal Proteins. Proteins present in individual stages of melanosomes can potentially play important roles in melanosome morphogenesis. Table 1 shows a list of putative stage-related proteins of special interest from the MNT1 melanosome proteome. There are over twice as many unique proteins in stage IV than there are in early stages of the melanosome, which may reflect the complex functions of mature melanosomes. We selected several interesting targets for validation by immunoblotting and immunofluorescence analysis, including proteins more abundant in some stages and those distributed similarly among the stages (Figure 1).

Pigment-epithelium derived factor (PEDF) is a potent inhibitor of angiogenesis and is a potent inductor of Fas-ligand-dependent apoptosis.[29] Dual immunofluorescence revealed that PEDF has a granular distribution in the cytoplasm of MNT-1 cells and does not colocalize with the stage II melanosome marker HMB-45 (Figure 1B) or the lysosomal marker LAMP1 (not shown). The pattern is similar to that of Pmel17 stained by αPEP13h (a stage I melanosome marker). Two PEDF bands were recognized by immunoblotting: a major band at 50 kDa, which corresponds to full-length PEDF (418 aa) and is most abundant in stage I melanosomes; and a minor band at 37 kDa (possibly a truncated form), which was distributed throughout the melanosome fractions.

We validated the presence of integrin β1 (Iβ1), a cell surface protein involved in melanoma cell migration[30] that sorts through the secretory pathway.[31] Iβ1 was highly enriched in stage I melanosomes (as well as late melanosomes) and showed partial colocalization with Pmel17 in granular structures near the perinuclear area. Since the early endosome marker (EEA1) is present in stage I melanosomes, we next validated the presence of Rab5, which directs the fusion of early endosomes, is recruited to endocytic vesicles, and is present in sorting endosomes.[32] Rab5 was highly enriched in stage I melanosomes, but was also detected in other stages. Dual immunofluorescence shows limited colocalization of Rab5 and Pmel17 in granular structures. These results are consistent with reports that early endosome markers can be found, in lesser amounts, in stage II melanosomes.[33]

In late-stage melanosomes, we confirmed the presence of the G2 subunit of vATPase which supports the important role of this pump in regulating pH, melanin production, and organelle stabilization. SLC24A5, a cation exchanger that transports Ca^{2+} and K^+ in exchange for Na^+, is also present in greater abundance in late melanosomes. As recently reported, SLC24A5 is involved specifically in melanogenesis and in the formation of pigmented granules.[34]

Melanosome Proteins Mapped to Known Mouse Coat Color Genes. Currently, 63 cloned mouse coat color genes have human homologues, and many are associated with inherited human pigmentary diseases [http://ifpcs.med.umn.edu/micemut.htm]. Among these human homologues, 16 proteins were identified in this proteomics analysis (Table 2), including 6 previously validated melanosome proteins and 10 new ones. Four of those had been identified and validated as specific melanosomal proteins (Tyr, Tyrp1, si/Pmel17, and OA1).[3,5,35,36] Two others (Rab27a and Rab38) had also been identified as melanosomal proteins,[37,38] although not specific to those organelles. In this study, we identified 10 novel proteins that map to coat color genes as melanosomal components. Although further analyses will be required to confirm their specificity for melanosomes and their possible functions there, several have known activities plausibly related to melanosome function. For example, Atp7a is a copper transport protein, and copper is a critical metal ligand required for tyrosinase function.[39] Golden has recently been shown to be important to determining constitutive levels of human skin pigmentation,[34] perhaps functioning as an ion transporter regulating intramelanosomal pH, which tightly regulates pigment production.[25,40] Lyst is involved in regulating organelle biogenesis and size and is mutated in Chediak−Higashi syndrome, where giant melano-

Table 1. Putative Stage-Related MNT1 Melanosomal Proteins of Special Interest[a]

UniProtKB accession no.	gene name	protein name	functional description
		Stage I (of 86)	
O14880	MGST3	Microsomal glutathione *S*-transferase 3	Glutathione *S*-transferase and glutathione peroxidase activities
O15533	TAPBP	Tapasin precursor (TPSN)	Involved in association of MHC-I with TAP and MHC peptide loading
P36955*	SERPINF1, PEDF	Pigment epithelium-derived factor precursor (PEDF)	Neurotrophic, induces neuronal differentiation; inhibitor of angiogenesis
Q14254	FLOT2	Flotillin-2 (Epidermal surface antigen)	Scaffolding protein, participating in formation of caveolae-like vesicles
Q16864	ATP6V1F	Vacuolar ATP synthase subunit F	Subunit of vacuolar ATPase essential for assembly or catalytic function, V-ATPase is responsible for acidic intracellular compartment
Q9HAQ7	PRP	ATP-binding cassette half-transporter	ABC transporter activity
		Stage II (of 131)	
P14415	ATP1B2	Sodium/potassium-transporting ATPase $\beta-2$ chain	Noncatalytic component of the active enzyme, which catalyzes the hydrolysis of ATP coupled with the Na^+ and K^+ ions exchange
P46459	NSF	Vesicle-fusing ATPase (*N*-ethylmaleimide sensitive fusion protein)	Required for vesicle-mediated transport, and transport from ER to Golgi; catalyzes fusion of transport vesicles within the Golgi cisternae
P53992	SEC24C	Protein transport protein Sec24C	Component of the COPII coat, that covers ER-derived vesicles involved in transport from the ER to the Golgi apparatus
Q04656	ATP7A	Copper-transporting ATPase 1	Supply copper to copper-requiring proteins within the secretory pathway, when localized in the trans-Golgi network
Q13277	STX3A	Syntaxin-3	Potentially involved in docking of synaptic vesicles
Q15036	SNX17	Sorting nexin-17	May be involved in several stages of intracellular trafficking
Q96A65	EXOC4	Exocyst complex component Sec8	Component of exocyst complex involved in docking of exocystic vesicles
Q9P0L0	VAPA	VAP-A, vesicle-associated membrane protein-associated protein A	Associate with SNARE and cytoskeleton proteins, may play a role in vesicle trafficking
		Stage IV (of 287)	
O00159	MYO1C	Myosin Ic	Myosins are actin-based motor molecules with ATPase activity and serving in intracellular movements
O94832	MYO1D	Myosin Id	
Q86T83	DKFZp451j0218	Hypothetical protein DKFZp451J0218	Nonmuscle myosin heavy chain, may have motor activity
Q16643	DBN1	Drebrin	May play some role in cell migration, extension of neuronal processes, and plasticity of dendrites, respectively. Binds F-actin
Q14847	LASP1	LIM and SH3 domain protein 1	Regulate dynamic actin-based, cytoskeletal activities. Agonist-dependent phosphorylation may regulate actin-associated ion transport
Q9H193	KIN13A	Kinesin-13A2	Microtubule-dependent motor protein involved in mannnose-6-phosphate receptor transport to the plasma membrane
P59998	ARPC4	Actin-related protein 2/3 complex subunit 4, ARPC4	Part of a complex implicated in the control of actin polymerization
P18206	VCL	Vinculin (Metavinculin)	Involved in cell adhesion. May be involved in the attachment of the actin-based microfilaments to the plasma membrane
Q13561	DCTN2	Dynactin subunit 2 (Dynactin complex 50 kDa subunit)	Modulates cytoplasmic dynein binding to an organelle, and plays a role in chromosome alignment and spindle organization during mitosis. May play a role in synapse formation during brain development
Q05682	CALD1	Caldesmon (CDM)	Actin- and myosin-binding protein implicated in the regulation of actomyosin interactions in smooth muscle and nonmuscle cells
P37802	TAGLN2	Transgelin-2 (SM22-α homologue)	Calponin-like, actin-, tropomyosin-, and calmodulin-binding protein believed to be involved in regulation or modulation of contraction
Q9H444	CHMP4B	VPS32	Component of ESCRT-III complex required for multivesicular bodies (MVBs) formation and sorting of endosomal cargo proteins into MVBs
*Q71RS6	SLC24A5	Sodium/potassium/calcium exchanger 5 precursor	Cation exchanger involved in pigmentation, probably transports 1 Ca^{2+} and 1 K^+ in exchange for 4 Na^+
P51810	GPR143	G-protein coupled receptor 143	Integrated membrane receptor, binds heterotrimeric G proteins
P45974	USP5	Ubiquitin thiolesterase 5	Cleaves linear and branched multiubiquitin polymers with a marked preference for branched polymers
Q96FW1	OTUB1	Ubiquitin thiolesterase protein OTUB1	Remove conjugated ubiquitin from proteins in vitro, may play regulatory role in preventing degradation. Regulator of T-cell anergy
P61088	UBE2N	Ubiquitin ligase	Catalyzes synthesis of noncanonical poly-ubiquitin chains. Mediates transcriptional activation and plays roles in cell cycle and DNA repair
Q8NE71	ABCF1	ATP-binding cassette sub-family F member 1	ATPase activity, may function in drug resistance

[a] Genes are listed that were found in only one stage of melanosome, as indicated. * = validated in this study.

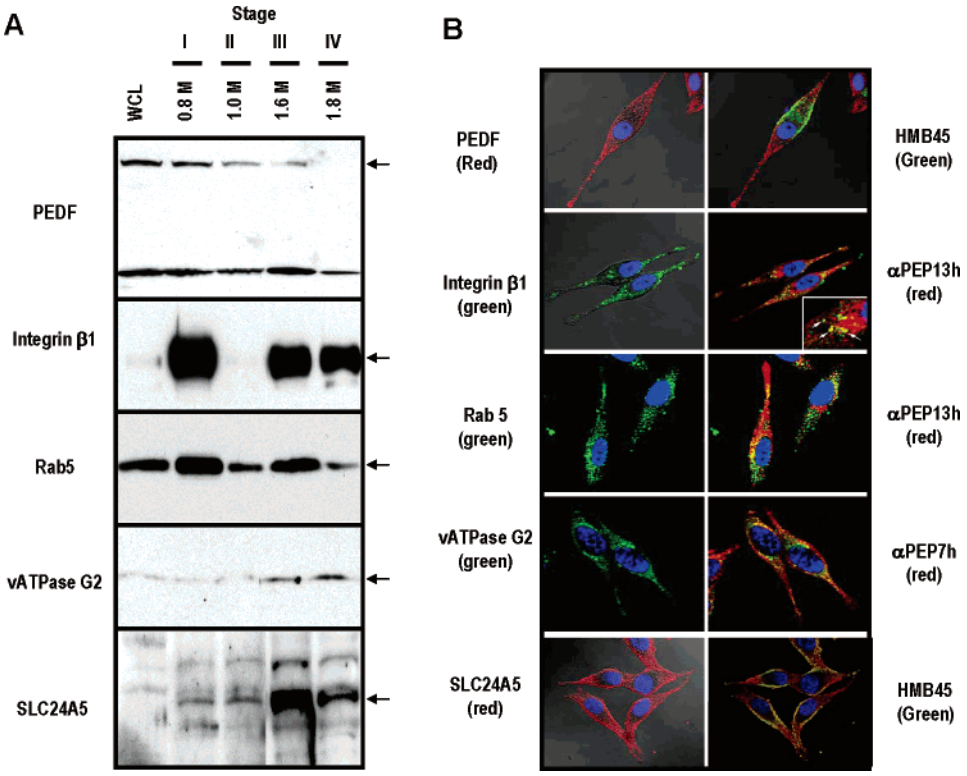

Figure 1. Validation of protein localization in melanosomes. (A) Confirmation of melanosome-identified proteins through antibody-specific detection in whole cell lysates (WCL) and melanosome fractions from MNT-1 melanoma cells using immunoblotting. (B) Dual immunofluorescence confocal microscopy confirmed the localization of proteins in melanosomes through comparison of the immunoreactivity patterns of polyclonal antibodies against PEDF,[29] SLC24A5, tyrosinase,[2] and Pmel17[17] (all in red) with reactivity patterns of monoclonal antibodies against integrin β1, RAB-5, vATPase, and HMB-45 (all in green). Differential interference contrast (DIC) images and nuclear counterstain with DAPI (blue) are included for visualization purposes.

somes, lysosomes, and platelet dense bodies are formed.[41] Matp is another transporter that regulates tyrosinase trafficking to melanosomes,[42] and mutations in that gene lead to a form of oculocutaneous albinism (type 4). Myo5a is part of the motor regulating melanosome transport to the periphery of melanocytes, a process essential to the distribution of melanosomes in the skin; mutations in Myo5a result in Griscelli syndrome.[43]

Mapping of Melanosome Proteins to Melanosomal Biogenic Pathways. To facilitate understanding of the dynamic process of melanosome biogenesis, the contribution of elements and complex membrane protein traffic input from several other organelles (e.g., the endoplasmic reticulum, early and late endosomes, and lysosomes) is illustrated, and the newly identified as well as known melanosome proteins are mapped to the melanosome biogenic pathways (Figure 2). The following five groups of proteins are depicted: (1) newly identified and validated in this study (e.g., PEDF and SLC24A5); (2) human homologues of mouse color genes identified in this study (e.g., Atp7a and MyoVa); (3) proposed stage-related proteins newly identified (e.g., Sec24 and vinculin); (4) proteins known as melanosome proteins from previous studies (e.g., Pmel17 and TYR); and (5) proteins common to other organelles (e.g., LAMP1). Many proteins detected in stage IV melanosomes are molecular motor- and cytoskeleton-related proteins, which may be necessary for directing fully pigmented melanosomes toward the cell periphery and their eventual transfer to keratinocytes. While it is obvious that multiple sources of cellular components contribute to the biogenesis of melanosomes, proteins more abundant in specific stages may define unique functions in that stage (e.g., the ion transporters VATPase and SLC24A5).

Discussion

Since the initial description of melanosome biogenesis by Seiji in 1963,[4] many research groups have attempted to further elucidate the synthesis and maturation of this organelle. The melanosome is an ideal model to study organelle biogenesis due to its characteristic maturation process and the fact that several specific markers are available.[5] Nevertheless, elucidating melanosome biogenesis has represented a formidable challenge due to the difficulty in isolating relatively short-lived early undifferentiated stage I melanosomes and in removing the melanin present in stage IV melanosomes. In this study, we took advantage of the fact that unpigmented SK-MEL-28 cells produce only stage I and II melanosomes and are thus a rich source of material. In addition, the enhanced combinations of sucrose density gradient purifications and an improved solubilization method, which allowed complete mass spectrometric analysis, provided information about melanosomal proteins at all stages of maturation. Many known integral membrane proteins were detected in late-stage melanosomes, such as those listed in Supplementary Table 2 (Supporting Information). However, full solubilization of hydrophobic membrane proteins in the presence of melanins is still difficult. The fact that some proteins were detected by LC/MS in early melanosomes but not in late melanosomes (or vice versa) may reflect

Table 2. Melanosomal Proteins Mapped to Mouse Coat Color[a]

gene symbol	murine locus	function in pigmentation	human melanosome protein (UniProtKB)	human disease (OMIM)
		Melanosome-Specific (Previously Identified)		
*DCT**	*slaty* (*slt*)	Tyrosinase-related protein 2 (TRP2)	**P40126:** L-dopachrome tautomerase precursor (EC 5.3.3.12)(DT)(DCT)	unknown
Gpr143	*Oa1* (*oa1*)	Melanosome biogenesis signal transduction	**P51810**: G-protein coupled receptor143	Albinism, ocular, type I [300500]; Albinism, ocular, with late-onset sensorineural deafness (OASD) [300650]
si	*silver* (*si*)	melanosomal matrix protein	**P40967**: Melanocyte protein Pmel 17 precursor	Some oculocutaneous albinism? [155550]
Tyr	*albino, color* (*c*)	melanogenic enzyme	**P14679**: Tyrosinase precursor	OCA1 [203100]; OCA1B [606952]; WS2-OA [103470]
Tyrp1	*brown* (*b*)	melanosomal enzyme/stabilizing factor	**P17643**: 5,6-dihydroxyindole-2-carboxylic acid oxidase precursor.	Rufous albinism, ROCA [115501]; OCA3 [203290]; Precocious graying of hair [278400]
		Melanosome-Related (Previously Identified)		
Rab27a	*ashen* (*ash*)	melanosome transport	**P51159**: Ras-related protein Rab-27A	Griscelli syndrome, type 2 [607624]
Rab38	*chocolate* (*cht*)	Targeting of Tyrp1 protein to the melanosome	**P57729**: Ras-related protein Rab-38	unknown [606281]
		Melanosome-Newly Identified		
Atp7a	*mottled* (*mo*)	copper transport	**Q04656**: Copper-transporting ATPase 1	Menkes disease [309400]; Cutis laxa, X-linked [304150]
Ednrb	*piebald spotting* (*s*)	melanoblast differentiation	**P24530**: ET-B	Waardenburg-shah syndrome [277580]; Hirschsprung disease 2 (HSCR2) [600155]; Hirschsprung disease [142623]; ABCD syndrome [600501]
golden	*golden* (*gdn*)	Causes delayed and reduced development of melanin pigmentation	**Q71RS6:** Ion transporter JSX	Regulator of constitutive pigmentation
Gpnmb	i*ris pigment dispersion* (*ipd*)	Apparent melanosomal component	**Q14956**: Transmembrane glycoprotein NMB precursor (Transmembrane glycoprotein HGFIN)	Glaucoma-related pigment dispersion syndrome-1 [604368]
Krt2−17	*dark skin 2* (*Dsk2*)	Keratin	**P35908**: Keratin, type II cytoskeletal 2 epidermal	Ichthyosis, bullous type [146800]
Lyst	*beige* (*bg*)	Organelle biogenesis and size	**Q99698**: Lysosomal trafficking regulator	Chediak-Higashi syndrome; CHS [214500]
Matp	*underwhite* (*uw*)	transporter	**Q9UMX9**: Membrane-associated transporter protein, (SLC45A2)	OCA4 [606574]
Myo5a	*dilute* (*d*)	melanosome transport	**Q9Y4I1**:Myosin-5A	Griscelli syndrome, type 1; GS1214450; Elejalde syndrome 256710 Griscelli syndrome, type 3; GS3609227;
Ostm1	*grey-lethal* (*Gl*)	Pheomelanin and osteoclast function	**Q86WC4**: Osteopetrosis associated transmembrane protein 1 precursor	Osteopetrosis, autosomal recessive [259700]
Sfxn1	f*lexed tail*	Tricarboxylate carrier	**Q9H9B4**: Sideroflexin-1	unknown

[a] The mouse coat color gene source: http://ifpcs.med.umn.edu/micemut.htm. *DCT was previously identified and validated as melanosome-specific proteins,[9] but is not present in current proteomic data sets.

limits to detection efficiency resulting from the relative amounts of proteins/peptides and the recovery from the digested sample.

Critical questions to address include which components are specific to melanosomes, and which may be critical to their maturation, transport, and/or transfer. Thus, unpigmented SK-MEL-28 cells express enzymes essential to melanogenesis, and comparisons of melanosomes from those cells with pigmented melanosomes from MNT1 cells identify a group of proteins involved in the regulation of melanin production. Another group of proteins identified in various melanosome stages may be involved in melanosome biogenesis, structure, and/or function. The presence of PEDF in early melanosomes had not been previously suspected. PEDF is a secreted factor important in melanoma tumor growth. Its presence in stage I melanosomes may be related to the common origin of this organelle with early endosomes, which transport this factor to the plasma membrane for secretion alone or encapsulated in exosomes.

In mammalian skin, melanosomes are transported toward the surface of melanocytes via microtubules. After their release from microtubules, melanosomes bind neighboring actin filaments at the cell periphery, where they are ultimately transferred to adjacent keratinocytes. Analysis of late-stage melanosomes reveals the presence of several molecular motors important for melanosome transport, such as kinesin, myosin Va, and dynein/dynactin, which are actively involved in mel-

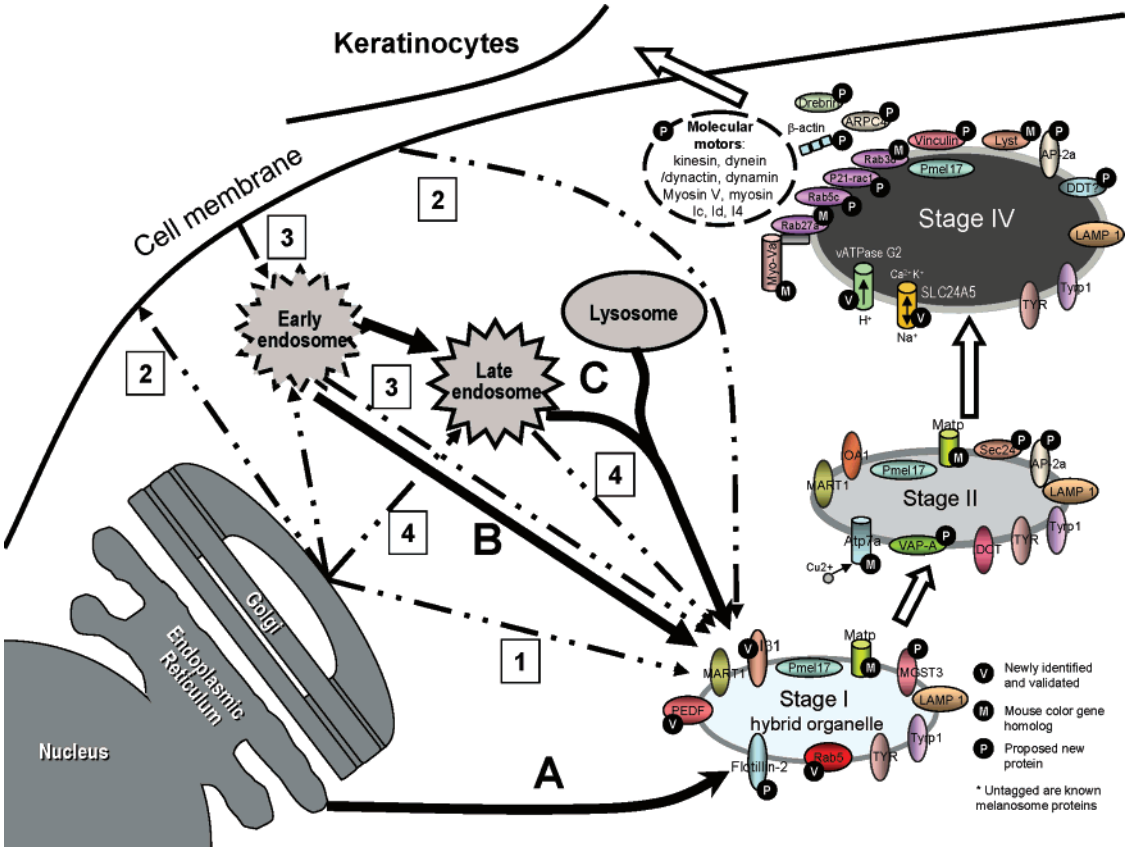

Figure 2. Overview of melanogenesis and protein sorting pathways as a dynamic source of proteins mapped in melanosomes (based on refs 17, 49, and 50). The melanosome proteome confirms the common origin of this organelle with other subcellular components, receiving elements (solid lines) from the endoplasmic reticulum (A), early endosomes (B), and from late endosomes or lysosomes (C). The dynamic nature of melanosomes is reflected in their complex membrane protein traffic (dashed lines) from Golgi (1), cell membrane (2), early endosomes (3), or late endosomes (4). Mature melanosomes are secreted to surrounding keratinocytes. Proteins of special interest related to each stage are depicted using oval (usually membrane-associated or cytosolic proteins) or cylinder shapes (usually known transmembrane proteins such as receptors or transporters). Proteins are tagged as V, newly identified and validated in this study; M, human homologous melanosome proteins of known mouse color genes, some known before and some newly identified in this study; and P, proposed stage-related proteins newly identified in this study. Known melanosomal and lysosomal proteins are not tagged (with V, M, or P).

anosome transport from melanocytes to keratinocytes. While they are not integral melanosomal proteins, they have important functions, such as melanophilin/Slac2-a, a binding protein involved in the transport of melanosomes via myosin Va.[44−46] In addition, several other organelle transport proteins were also detected in this study, such as dynamin, myosin Ic, myosin Id, and myosin I4. The roles of those proteins need to be examined in the future.

A number of proteins were exclusively detected in all stages of MNT1 melanosomes (which become pigmented) but were not present in SK-MEL-28 melanosomes (which remain amelanotic), indicating their potential importance in pigmentation. Melanosome-specific proteins directly involved in melanin synthesis, TYR and TYRP1, are primary examples, since they are expressed in nonpigmented cells but are not delivered to melanosomes, with the end result of disrupted pigmentation. Thus, the absence of TYR and TYRP1 in melanosomes from SK-MEL-28 cells (although they are expressed in those cells) is consistent with expectations.

Except for known melanosome proteins that give the organelle its unique structure and functions, a majority of proteins detected in the melanosome proteome are not organelle-specific. Some, such as ribosomal protein complexes, are obvious minor contaminants that were co-purified during sucrose gradient fractionation. Even though extra precaution was taken, sensitive mass spectrometers can always detect trace amounts of peptides that originate either from resident low-abundance proteins or from low-level contaminants. By searching our data against known human mitochondrial proteins annotated in UniProtKB, we estimate that the melanosome fractions at various stages are contaminated with mitochondrial proteins by <6% at early stage, and by <1−2% at late stage, indicating that our melanosome fractions are of high purity. On the other hand, many proteins identified in this study demonstrate that melanosomes are highly dynamic. They may be viewed as a microcosm of organelles, representing a dynamic balance of proteins as well as small molecules being transported in and out. Many of the "nonspecific" proteins might be associated with melanosomes only for a short period of time, or they may be proteins that reside in other subcellular compartments. In that sense, true permanent "resident" molecules for organelles may not exist.[47,48] Because of the uniqueness of melanosomes, a conventional negative control is not available for the analysis. Some of the most well-known endoplasmic reticulum, late endosomal, and lysosomal resident proteins have already proven to co-localize with melanosomes

and cannot be considered as contamination, although some proteins included in these datasets still need to be carefully evaluated and validated.

To explore the commonality between melanosomes and other organelles, we compared the melanosome proteome to partial proteomes of six other organelles currently available in the literature, including human neuromelanin granules, human platelets, human exosomes, rat synaptosomes, rat lysosomes, and mouse endoplasmic reticulum (human proteomes of the latter three organelles are not yet available). Interestingly, among all those six organelles, neuromelanin granules and exosomes have the highest percentage of proteins (60−75%) also found in melanosomes, while the other four have less than 50% of proteins common to melanosomes (data not shown). This comparison is consistent with the notion that neuromelanin granules are highly homologous to melanosomes. Melanocytes and neurons both derive from the neural crest, and the pigments in both types of organelles are derived similarly in the melanogenic and catecholamine pathways. This comparison also suggests a close relationship between the biogenesis of exosomes and melanosomes. This seems quite reasonable, given that both types of organelles are normally secreted from the host cells.

In summary, this multifaceted approach to understanding the makeup and biogenesis of melanosomes has not only revealed a large complement of constituent proteins, but has allowed many of them to be validated as components of melanosomes. Future work will examine the functions of those proteins in melanosomes and determine whether they play roles in regulating mammalian pigmentation, as well as further understand the biogenesis of lysosome-related organelles.

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Supporting Information Available: Tables showing the melanosome proteins grouped into 12 subsets according to stage and cell type (Supplementary Table 1), common proteins identified in all stages of melanosomes (Supplementary Table 2), and Rab family members identified in stage I and stage II melanosomes (Supplementary Table 3). This material is available free of charge via the Internet at http://pubs.acs.org.

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