

Proteomic Study and Marker Protein Identification of *Caenorhabditis elegans* Lipid Droplets*[§]

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Lipid droplets (LDs) are a neutral lipid storage organelle that is conserved across almost all species. Many metabolic syndromes are directly linked to the over-storage of neutral lipids in LDs. The study of LDs in *Caenorhabditis elegans* (*C. elegans*) has been difficult because of the lack of specific LD marker proteins. Here we report the purification and proteomic analysis of *C. elegans* lipid droplets for the first time. We identified 306 proteins, 63% of these proteins were previously known to be LD-proteins, suggesting a similarity between mammalian and *C. elegans* LDs. Using morphological and biochemical analyses, we show that short-chain dehydrogenase, DHS-3 is almost exclusively localized on *C. elegans* LDs, indicating that it can be used as a LD marker protein in *C. elegans*. These results will facilitate further mechanistic studies of LDs in this powerful genetic system, *C. elegans*. *Molecular & Cellular Proteomics* 11: 10.1074/mcp.M111.016345, 317–328, 2012.

Cells store neutral lipids in lipid droplets (LDs)¹. Recent studies demonstrate that LDs are heterogeneous and dynamic in size and metabolic state (1–5). Moreover, studies, especially proteomic studies, have uncovered a large set of proteins that bind to the surface of LDs. Functional studies have yielded insights into, or implied how some of these proteins regulate the dynamic metabolic state of LDs (6–8).

Early studies on mammalian cells identified the PAT family proteins, now renamed as PLIN 1–5 (9), as the major LD-proteins. With PLINs as marker proteins, advances in the purification of LDs and proteomics have made possible the

identification of most if not all LD-associated proteins. Such study was conducted in the budding yeast *Saccharomyces cerevisiae* and identified many lipid metabolism enzymes (10). A similar study was conducted using mammary gland cells and the protein profile of LDs was almost identical to that of the milk fat globule membrane (11). As a result of a better purification method, later studies of LDs in Chinese hamster ovary (CHO) cells discovered many functional proteins that are involved in lipid synthesis, membrane trafficking, signal transduction, and protein degradation (12). Similar findings were soon reported using HuH7 cells, 3T3-L1 adipocytes, and A-431 cells (13–15). The first comprehensive LD proteomic study of CHO cells identified 125 proteins, seven phosphorylated proteins, and several dynamic proteins such as Arf1 and its coatomers (16). In addition, a detailed lipidomic study was carried out using purified LDs (17). In genetically altered *Drosophila* strains with distinct fat metabolic activities, and in different *Drosophila* cell types, LD-protein compositions are different (18, 19). These works suggest that LDs are not simply fat storage inclusions, but rather that they are active cellular organelles (20).

The genetic model organism *C. elegans* is an attractive system for studying LDs and fat metabolism because of its advantages such as its mutations that are used as genetic tools, it is a simple system with about 1000 cells, it is easily to grown and examined, and there is accumulated data from previous studies. Through combined genetic, biochemical, and imaging approaches, *Caenorhabditis elegans* has recently been shown to utilize LDs rather than lysosome-related organelles (LROs) to store fat (21, 22). This work clarified the question of the organelle nature of *C. elegans* fat-storage structures and provided conceptual support for the notion that post-fix Nile Red/Oil Red O staining serves as a more accurate proxy for fat levels in *C. elegans* than vital Nile Red/BODIPY staining (23–25).

The structural LD-proteins, the PLINs, are expressed in eukaryotes from humans through to *Drosophila*. However, there are no genes for apparent PLIN homologs in the *C. elegans* genome, raising the question whether *C. elegans* LDs and higher eukaryotic LDs share conserved proteins and

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¹ The abbreviations used are: LD, lipid droplet; CHO, Chinese hamster ovary; PNS, postnuclear supernatant; TAG, triacylglycerol; TLC, thin layer chromatography.

mechanisms of regulation. Identifying *C. elegans* LD-proteins by biochemical purification and proteomic studies is necessary to address this question. *C. elegans* LDs, which are free of LRO contamination, have previously been isolated using a density centrifugation approach (22), however, the quantity and purity of the isolated LDs were not tested for further proteomic studies. Therefore, it is critical for lipid metabolic study using *C. elegans* to purify high quality and quantity LDs, analyze their proteome, and identify their marker proteins.

In order to identify *C. elegans* LD-proteins, especially some specific marker proteins, we developed a purification method based on our previous work (12, 17, 22) to purify LDs from this organism. Proteomic analysis identified 306 proteins, including 193 proteins that were previously found to be present in the LD proteomes of other organisms. Through both *in vivo* imaging and *in vitro* biochemical approaches, we found that DHS-3 is localized and highly enriched on the surface of LDs, indicating that it can be used as a specific marker protein for LDs in *C. elegans*.

EXPERIMENTAL PROCEDURES

Materials—A Colloidal Blue stain kit was purchased from Invitrogen (Carlsbad, CA). PDH-E1 α monoclonal antibody was from MitoSciences (Eugene, OR). RME1 and Dyn1 monoclonal antibodies were purchased from the Developmental Studies Hybridoma Bank (Japan). Na-K⁺ATPase was from Upstate Biotechnology (Charlottesville, VA). Bip monoclonal antibody and caveolin polyclonal antibody were from BD Biosciences. Actin monoclonal antibody and Rab7 was from Santa Cruz Biotechnology (Santa Cruz, CA). Rab18 was from Calbiochem (San Diego, CA). Gelatin and tannic acid were from Sigma-Aldrich (Missouri, USA). Formvar was from BDH Chemicals. Ltd. (Poole, UK). Uranyl acetate, 25% glutaraldehyde solution (EM grade), and a low viscosity embedding media Spurr's Kit were all from Electron Microscopy Sciences (Hatfield, PA). Osmium tetroxide (EM grade) was purchased from Nakalai Tesque Co. (Kyoto, Japan). Phosphotungstic acid was from Zhongjingkeyi Technology Co., Ltd. (Beijing, China).

Strains and Culture Conditions—The N2 Bristol strain and VS20 (pATGL-1::ATGL-1::GFP) were used in this study. Animal culture was conducted essentially the same as previously described (22). Briefly, *E. coli* strain OP50 was cultured in LB medium and seeded onto 9-cm and 15-cm Nematode Growth Medium plates. Synchronized L1 stage animals were then seeded onto the plates. Animal density was ~50 per cm². Animals were harvested for LD isolation at the young adult stage (24 h post L4 stage).

Isolation of Lipid Droplets—LDs were isolated using a modified method previously described (12). First, about 4×10^5 worms were harvested and washed three times with 50 ml PBS/0.001% Triton-X100. Worm pellets were then washed with 50 ml buffer A (25 mM Tricine, pH 7.6, 250 mM sucrose, and 0.2 mM phenylmethylsulfonyl fluoride), homogenized using a polytron (Cole-Parmer® Labgen™ 125 and 700 Tissue Homogenizers) in 10 ml buffer A, and centrifuged at $1000 \times g$ for 30 s. The supernatant was homogenized again by nitrogen cavitation (Ashcroft Duralife Pressure Gauge) at 500 psi for 15 min on ice, and then centrifuged at $1000 \times g$ for 10 min. Nine milliliters of this postnuclear supernatant (PNS) was loaded into an SW40 tube, and 3 ml buffer B (20 mM HEPES, pH 7.4, 100 mM KCl, and 2 mM MgCl₂) was overlaid on top. The tube was then centrifuged at $12,628 \times g$ for 1 h at 4 °C. The LD fraction was carefully collected from the top layer and washed three times with 200 μ l buffer B.

Protein Preparation and Western Blotting—Proteins were extracted and analyzed using Western blotting by a method described in our previous study (16).

Mass Spectrometry Analysis—The protocol used was the same as previously described (39). LD-proteins were subjected to reduce with 10 mM dithiothreitol by incubating at 56 °C for 1 h and then alkylated for 45 min by 55 mM iodoacetamide in the dark. Proteins were then incubated with 10 μ l trypsin solution (10 ng/ μ l in 25 mM ammonium bicarbonate) for 30 min on ice. After removing excess enzyme solution, 30~40 μ l 25 mM ammonium bicarbonate was added, and digestion was allowed to proceed at 37 °C overnight. Five percent formic acid was added to stop the digestion reaction, which was then vortexed and centrifuged. A C₁₈ trap column was used to add the peptide solution, eluted and then subjected to nano-LC-ESI-LTQ Orbitrap XL MS/MS analysis. The Orbitrap mass spectrometer was operated under data-dependent mode and was set at an initial 300~1800 Da MS scan range. All MS/MS data were searched against the WormBase database Wormpep218, which was released on August 22, 2010, and contains 24761 protein sequences. The BioWorks (3.31 sp1) Sequest search parameters were as follows: enzyme: trypsin; precursor ion mass tolerance: 2.0 Da; and fragment ion mass tolerance: 1.0 Da. The variable modification was set to oxidation of methionine (Met +15.99 Da). The fixed modification was set to carboxyamidomethylation of cysteine (Cys +57.02 Da). The search results were filtered with Xcorr versus Charge values of, Xcorr (+2) > 2.5, and Xcorr (+3) > 3.5. Two times peptide FDR: FDR₁ = 0.434%, FDR₂ = 0.426%. peptide mass accuracy < 5ppm, SP score > 500, RSp < 5. distinct peptides \geq 2, missed cleavages 2.

Transmission Electron Microscopy—The purity of LDs was examined by transmission electron microscopy. Negative staining, whole mount EM, and ultra-thin sectioning methods were used. For negative staining, the sample of purified LDs was loaded onto a carbon-coated, Formvar-covered copper grid and stained for 1 min by 0.5% neutral phosphotungstic acid. To view the isolated LDs by whole mount EM, a carbon-coated, Formvar-covered copper grid was placed onto a drop of isolated LD suspension. The grid was then placed onto a drop of 2.5% glutaraldehyde solution (0.1 M PBS, pH 7.2) for 10 min and subsequently onto a drop of 2% osmium tetroxide solution (0.1 M PBS, pH 7.2) for 10 min to fix the LDs. After fixation, LDs were stained with 0.1% tannic acid for 10 min and 2% uranyl acetate for 10 min. After each step, the grid was washed with deionized water three times, 1 min each time. For ultra-thin sectioning of purified LDs, the LD sample was first embedded in 10% gelatin (0.1 M PBS, pH 7.2). After solidification, the sample was cut into small blocks and prefixed in 2.5% glutaraldehyde (0.1 M PBS, pH 7.2) for 12 h at 4 °C and post-fixed in 2% osmium tetroxide for 24 h at 4 °C. The sample was then dehydrated in an ascending series of ethanol concentrations at room temperature and embedded in Spurr. Sections of a thickness of 70 nm were prepared with a Leica EM UC6 Ultramicrotome (Leica Germany) and loaded onto Formvar-covered copper grids. Grids were then stained with 2% uranyl acetate for 15 min at room temperature before viewing with a FEI Tecnai 20 (FEI Co., Netherlands) electron microscope.

Nile Red Staining of C. elegans—Fixed Nile Red staining of *C. elegans* was performed as previously described (24). Approximately 200~1000 nematodes were suspended in 1 ml of water. Fifty microliters of freshly prepared 10% paraformaldehyde solution was added, mixed, and worms were rocked for 1 h at room temperature. Worms were allowed to settle, and then the paraformaldehyde solution was replaced by 1 ml of 1 μ g/ml Nile Red in M9 and incubated for 15~30 min at room temperature, with occasional gentle agitation. After most of the staining solution was removed, the fixed worms were mounted onto 2% agarose pads for microscopic observation and photography.

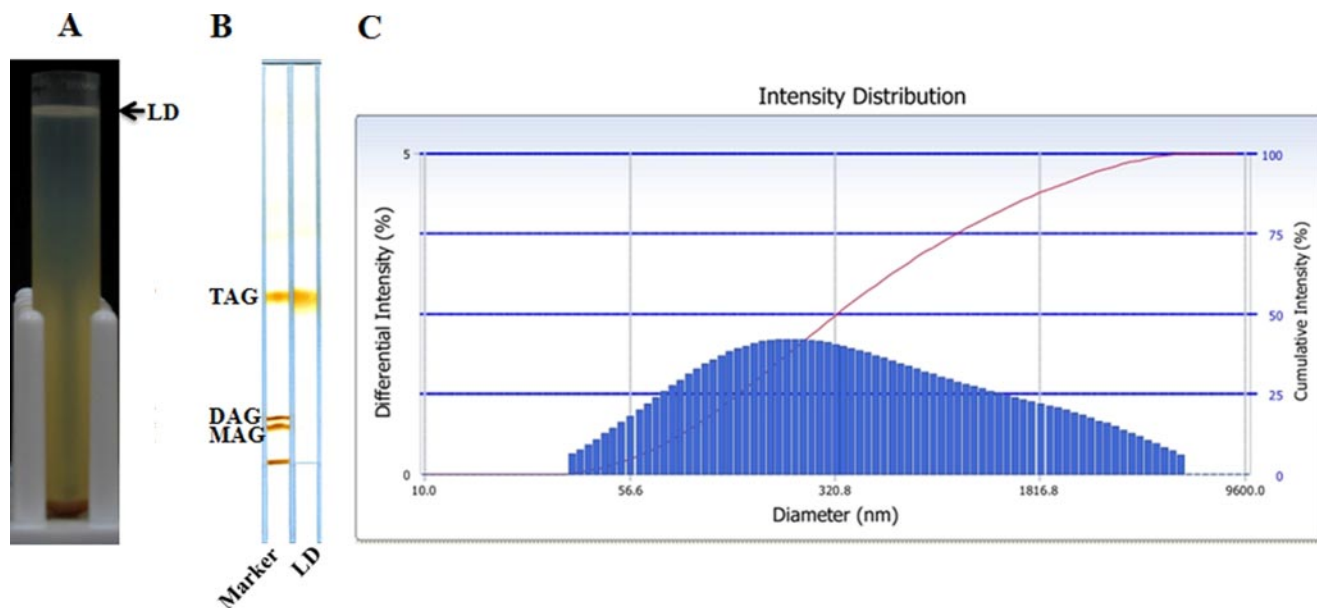


FIG. 1. **Isolation of lipid droplets from *C. elegans*.** *A*, 4×10^5 young adult wild-type *C. elegans* worms were harvested, washed, and homogenized. The PNS was centrifuged at $12,628 \times g$ for 1 h. The top white layer was the lipid droplet (LD) fraction. *B*, Total lipids were extracted from the LD fraction with chloroform:acetone (1:1, v/v) and separated by thin layer chromatography (TLC) in a hexane:diethyl ether:acetic acid (80:20:1, v/v/v) solvent system. The LD fraction contained mainly TAG. *C*, The size of the purified LDs was measured by a Delsa Nano C particle analyzer. The diameters of LDs were in the range of 50 nm to 3000 nm.

Confocal Microscopy—Purified LDs were stained with Nile Red and viewed with an Olympus Fluoview1000 as described previously (39).

Confocal microscopy images of fixed worms were obtained using a Spinning Disk Confocal Microscope (Zeiss). The figures were produced using a 100×1.45 numerical aperture oil objective (Olympus PLAN APO) and an electron-multiplying charge-coupled device (EMCCD) camera (Andor iXon DV-897 BV). The fluorescence signals were analyzed by Image J software (NIH).

For photobleaching experiment, the worms were anesthetized in 0.01% tetraisoole hydrochloride in PBS for 30 min and mounted on 2% agarose pads. We identified the area of interest on the Olympus Fluoview1000, brought it to the desired focus, defined a region of interest for the photobleach, and chose photobleaching conditions so that after photobleaching the fluorescent signal of the photobleached area decreases to background intensity levels. The bleaching conditions require a 100–1000-fold increase in laser power for 20 bleach iterations (roughly 2 s) with 100% transmission of a 488 nm laser. After bleaching, the image of the selected area was captured every 2 min for 10 min.

Thin Layer Chromatography (TLC)—Lipids were extracted and analyzed using TLC by a method described in our previous study (17).

RESULTS

Isolation of Lipid Droplets from *C. elegans*—Using our newly established method, we successfully isolated LD fraction in large quantity on top of a density gradient (Fig. 1A). The LD fraction was then washed three times to remove co-isolated cytosolic proteins and other cellular organelles. To test its lipid composition, we extracted total lipids from the LD fraction by chloroform and acetone, and then separated different lipid species by TLC. TLC results showed that triacylglycerol (TAG) was highly enriched in the fraction (Fig. 1B). We also measured the size of isolated LDs by a Delsa Nano C particle analyzer. As shown in Fig. 1C, the size of LDs was

distributed in the range of 50 nm to 3,000 nm. All these characterizations such as density, lipid composition, and size were agreed with previous isolated lipid droplets from other sources (1, 17, 26, 27).

Verification of the Purity of Isolated Lipid Droplets—To further test the purity of isolated LDs, transmission electron microscopy (TEM) images were taken. The results showed that all the isolated LDs appeared as spherical structures and, importantly, that membrane debris and other cellular organelles were barely detected (Fig. 2A, upper panels). With Nile red staining and DIC imaging, purified LDs appeared to be a bead structure (Fig. 2A, lower panels), similar to purified LDs from CHO K2 cells (12, 17). We then analyzed the LD-protein profile using gel electrophoresis. The protein pattern of isolated LDs was significantly different from the other three cellular fractions (Fig. 2B). In addition, three independent isolations were analyzed and their protein profiles were almost identical, suggesting the reproducibility and quality of the purification method (supplemental Fig. S1). Immunoblotting was used to further verify the purity of the LDs (Fig. 2C). Equal amounts of proteins from LD, total membrane (TM), cytosol (Cyto), and PNS fractions were separated by SDS-PAGE and detected by the antibodies indicated. Fig. 2C shows clearly that the isolated LDs had little contamination with mitochondria (PDH-E1 α), endosomes (RME), ER (Bip), plasma membranes (Na-K⁺ ATPase), cellular membranes (Dyn), or cytosol (actin). In the LD fraction we observed the enrichment of Rab 18 and Rab 7, proteins previously identified (12, 17) in LDs isolated from CHO cells (Fig. 2C).

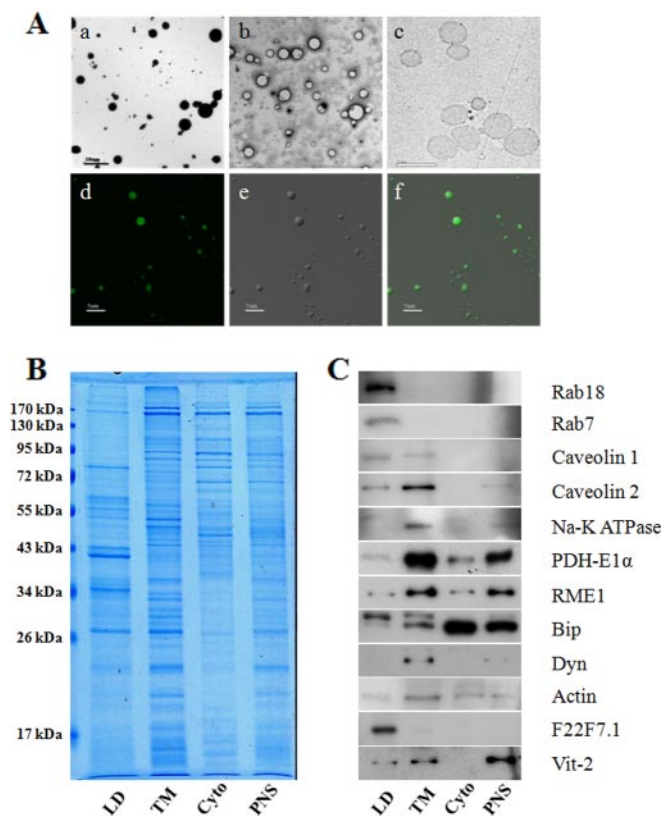


FIG. 2. Verification of purified lipid droplets. *A*, Isolated LDs were first analyzed by TEM with positive-staining (a), and negative-staining (b) and by ultra-thin sectioning (c), and then by light microscopy with Nile red staining (d) by DIC microscopy (e), and by merging images (f). *B*, Proteins extracted from isolated lipid droplet (LD), total membrane (TM), cytosol (Cyto), and PNS fractions were separated by SDS-PAGE and stained by Colloidal blue. Note the distinct banding pattern of LDs. *C*, The same protein samples were also subjected to Western blotting to test for contamination from other cellular fractions. Specific antibodies were used to probe for marker proteins of different cellular organelles/fractions; Rabs and caveolins (LD proteins), caveolins and Na-K ATPase (plasma membrane), PDH-E1 α (mitochondrion), RME1 (endosome), Bip (endoplasmic reticulum), Dyn (membrane), actin (cytosol), F22F7.1 and Vit-2 (lipid droplet-associated proteins).

Proteomic and Bioinformatic Analyses of Lipid Droplet Proteins—Having verified the purity of isolated LDs by biochemical and morphological examinations, we extracted proteins from the purified LDs and subjected them to nano-LC-ESI-LTQ Orbitrap XL MS/MS analysis. From two independent proteomic studies, we identified 306 proteins that were presented in both analyses (Table I and Fig. 3A), and Table S1 shows the top 50 abundant proteins. It was found that 63% of these proteins had been identified in previous LD proteomic studies (Fig. 3B). When this proteome was compared with one previous proteomic study that was done using Chinese hamster ovary cells (CHO K2) (16), 28 of 125 LD proteins of CHO cells were overlapped with LD-associated proteins from *C. elegans* (Fig. 3C). We classified these proteins into nine groups by function or localization: lipid metabolism, other

metabolism, transcription, ribosome, membrane trafficking, chaperone, signal transduction, cytoskeleton, and proteins with unknown function (Fig. 3D). The enrichment (41%) of proteins involved in metabolism further indicates the similarity of *C. elegans* LDs to other eukaryotic LDs.

To determine the relationships between these 306 proteins, we analyzed our data with STRING 9.0 using default parameters (28). supplemental Fig. S2 summarizes the network of predicted associations for these proteins. Some of these proteins showed close relationships and formed two main clusters. The densest cluster (upper cluster) consists of 53 ribosome proteins. Identification of ribosome proteins on LDs has also been reported in some early LD proteomic studies in humans (12), yeast (10), and *Drosophila* (18). This finding suggests that LDs may provide a surface for ribosomes where certain proteins can be efficiently synthesized. The other cluster (lower cluster) mainly consists of metabolic proteins that are involved in processes such as lipid metabolism, energy generation, and nucleotide biosynthesis. These results are consistent with early reports that LDs are not only centers for lipid synthesis, storage and metabolism, but also provide extra membrane surface area for protein synthesis and intracellular reactions.

Identification of DHS-3 as a C. elegans Lipid Droplet Marker Protein—Because dehydrogenases are found in most of previous LD proteomes, we constructed a transgenic line that expresses the fusion protein DHS-3::GFP under the control of a *daf-22* promoter in gut epithelial cells. Interestingly, DHS-3::GFP formed ring structures *in vivo*, typical of the localization pattern of PLIN proteins (Fig. 4A). To validate this result biochemically, we probed the distribution of the DHS-3::GFP protein in the transgenic line using a GFP antibody and an anti-DHS-3 antibody that was generated in our lab. The Western blotting result (Fig. 4B) shows that the two antibodies recognized a single band of molecular weight ~63 kDa, verifying the specificity of the DHS-3 antibody and GFP-fusion protein expression. Using the DHS-3 antibody, we detected DHS-3 in the purified LD fraction but not in the total membrane (TM), cytosol (Cyto), or PNS fractions of wild-type *C. elegans* with equal protein loading (Fig. 4C). To further analyze the enrichment of DHS-3 in the LD fraction, we tested an excess of the PNS fraction (10 \times and 50 \times) using the DHS-3 antibody (Fig. 4D). A very weak DHS-3 signal was detected in the PNS fraction at 10-fold excess loading (Fig. 4D). Although 50-fold excess protein loading, the DHS-3 signal of PNS fraction was still much lower than the signal of LD (Fig. 4D). In addition, to determine if DHS-3 is a dynamic protein on LDs, selected regions of the worm were photo-bleached and then the fluorescent signal in those regions was detected in every 2 min, up to 10 min after bleaching (Fig. 4E). Recovery of fluorescent signals was not observed, indicating that neither DHS-3 was recruited to the bleached LDs from other cellular compartments (arrow-pointed regions) nor translocated to the bleached part from non-bleached part of

TABLE I
C. elegans Lipid Droplet-associated Proteins

Sequence name	Protein ID	Gene name	Citations	Sequence name	Protein ID	Gene name	Citations
Lipid Metabolism							
E04F6.5a	CE01217	acdH-12	(16)	T05F1.10	CE26900	dhs-4	(16, 40)
F49H12.6a	CE23754	acl-4	(39)	Y32H12A.3	CE21514	dhs-9	(16)
Y65B4BL.5	CE24550	acs-13	(13, 41)	C29F3.1	CE08435	ech-1	
C46F4.2	CE30907	acs-17	(10, 13, 41)	Y56A3A.12a	CE24467	faah-4	(19)
F37C12.7	CE29312	acs-4	(13, 41)	ZK973.10	CE40009	lpd-5	
Y76A2B.3	CE19275	acs-5	(13, 41)	Y66H1B.4	CE20348	spl-1	
T11F9.11	CE06423	dhs-19		T25G3.4	CE14180		(16)
T02E1.5a	CE41004	dhs-3		Y53G8B.2	CE25428		(19)
Other Metabolism							
F40F9.6a	CE05855	aagr-3		K12G11.3	CE12212	sodh-1	(16, 40)
Y50D7A.7	CE26144	ads-1		Y47G6A.10	CE34400	spg-7	(11, 16)
T05H4.13a	CE27441	alh-4	(16)	F23H12.2	CE05705	tomm-20	
F13D12.4a	CE02183	alh-8	(15)	F56D2.1	CE11226	ucr-1	(41, 42)
T27E9.1a	CE14263	ant-1.1	(19)	VW06B3R.1a	CE20123	ucr-2.1	(41, 42)
W02D3.6	CE14428	ant-1.2	(19)	T10B10.2	CE23962	ucr-2.2	(41, 42)
K01H12.2	CE03454	ant-1.3	(19)	T24C4.1	CE19592	ucr-2.3	(16, 41, 42)
T01B11.4	CE12898	ant-1.4	(19)	Y38F2AL.3a	CE29997	vha-11	(11, 13, 16, 43)
F08C6.6	CE27925	apy-1		Y49A3A.2	CE22210	vha-13	(11, 13, 16, 43)
F01G4.2	CE03127	ard-1	(16, 40, 43)	T14F9.1	CE07497	vha-15	(11, 13, 16, 43)
F35G12.10	CE00968	asb-1	(13, 43)	M03C11.5	CE43540	ymel-1	
F02E8.1	CE07016	asb-2	(11, 13, 43)	T26C12.1	CE26009		
K07A12.3	CE11868	asg-1	(13, 43)	B0303.3	CE00561		(15)
C53B7.4	CE06974	asg-2	(13, 43)	T22B11.5	CE28486		(16)
R12H7.2	CE03567	asp-4		T08B2.7a	CE13431		(16)
F54B3.3	CE35878	atad-3	(11, 16)	F09E5.2	CE32364		
C34E10.6	CE29950	atp-2	(13, 43)	H28O16.1a	CE18826		(13, 43)
F27C1.7a	CE09719	atp-3	(11, 16)	F58F12.1	CE01976		(13, 43)
T05H4.12	CE13291	atp-4	(13, 43)	R53.4	CE03574		(13, 43)
C06H2.1	CE15602	atp-5	(13, 43)	F32D1.2	CE09866		(13, 43)
T06D8.6	CE02327	cchl-1		W10C8.5	CE18353		
Y37D8A.14	CE20218	cco-2		LLC1.3a	CE31971		(16)
K01D12.12	CE06051	cdr-6		ZK829.4	CE06652		(16)
R07H5.2a	CE18907	cpt-2	(12)	T22D1.4	CE33704		
C54G4.8	CE05514	cyc-1	(18, 42)	F48E3.3	CE02751		
W02D3.2	CE14420	dhod-1	(16)	F59C6.5	CE11464		(15)
F46E10.9	CE20819	dpy-11		D2030.4	CE09081		(16)
B0365.3	CE07721	eat-6	(11, 16)	T05H4.5	CE13277		(15, 41, 42)
K09A9.5	CE11980	gas-1	(15)	F53F4.10	CE10972		(15, 41, 44)
T14G11.3	CE33696	immt-1		C33A12.1	CE05347		(15)
W06H3.1	CE36215	immt-2		C16A3.5	CE04005		(15)
F42G8.12	CE17071	isp-1	(18, 41, 42)	F37C4.6	CE17049		
C05D11.12	CE29662	let-721	(45)	T05H10.6a	CE01643		(11, 16)
Y22F5A.4	CE16605	lys-1		F47B10.1	CE03351		
B0546.1	CE16792	mai-2	(16)	T02H6.11	CE21147		(16, 41, 42)
F20H11.3	CE09512	mdh-1	(16)	Y53G8AL.2	CE26163		
T26A5.3	CE00702	nduf-2.2	(15)	Y69A2AR.18a	CE27514		
Y54E10BL.5	CE22460	nduf-5	(15)	Y51H1A.3a	CE20284		
F22D6.4	CE05685	nduf-6	(15)	B0491.5	CE02107		
W10D5.2	CE14780	nduf-7	(15)	W09C5.8	CE20171		
C09H10.3	CE02132	nuo-1	(15)	Y71H2AM.5	CE22939		
T10E9.7a	CE37406	nuo-2	(15)	C34B2.8	CE16896		
Y57G11C.12b	CE14948	nuo-3	(15)	R04F11.2	CE06233		
K04G7.4a	CE01361	nuo-4	(15, 44)	C25H3.9a	CE44829		
Y45G12B.1a	CE21933	nuo-5	(15)	C27D8.4	CE30618		
T09A5.11	CE01081	ostb-1		F45H10.2	CE10544		
F27D9.5	CE04451	pcca-1	(42)	R07E4.3	CE04818		
F52E4.1a	CE07269	pccb-1	(42)	Y53F4B.18	CE22408		
K11D9.2a	CE18884	sca-1	(11, 16)	F52H2.6	CE10874		
C01F1.2	CE06743	sco-1		ZK550.3	CE37464		

C. elegans Lipid Droplet Proteome and Marker Protein

TABLE I—continued

Sequence name	Protein ID	Gene name	Citations	Sequence name	Protein ID	Gene name	Citations
C03G5.1	CE03917	sdha-1	(16)	F23B12.5	CE09597		
C34B2.7	CE16895	sdha-2	(16)	Y47D3B.10	CE20261		
F42A8.2	CE01579	sdhb-1	(16)	MTCE.11	CE34065		
C54H2.5	CE06987	sft-4		F45H10.3	CE10546		
Trafficking and Transport							
F44B9.5	CE24973	aup	(41, 42, 44)	Y66D12A.22	CE28800	tin-10	
M03F4.7a	CE12368	calu-1		C18E9.6	CE05298	tomm-40	
Y38A10A.5	CE21562	crt-1		F53F10.4	CE10986	unc-108	(40)
D2013.5	CE42493	eat-3	(42)	K09F5.2	CE04746	vit-1	(11, 39)
B0432.4	CE32102	misc-1		C42D8.2a	CE06950	vit-2	(11, 39)
C17E4.9	CE08258	nkb-1	(11, 16)	F59D8.1	CE20900	vit-3	(11, 39)
C02E11.1a	CE28528	nra-4		F59D8.2	CE26817	vit-4	(11, 39)
M117.2	CE06200	par-5		C04F6.1	CE03921	vit-5	(11, 39)
C39F7.4	CE16905	rab-1	(15, 40)	K07H8.6a	CE28594	vit-6	(11, 39)
F53G12.1	CE11006	rab-11.1	(40)	T08G11.1a	CE13443		
Y92C3B.3b	CE27340	rab-18	(13, 41)	R05G6.7	CE29443		(43)
W03C9.3	CE03777	rab-7	(13, 40–42)	F01G4.6a	CE09162		
D1037.4	CE30373	rab-8	(40)	Y7A5A.1	CE21326		
Y51H4A.3	CE25369	rho-1	(16, 40)	T20H4.5	CE00832		
W06H8.1a	CE25146	rme-1		T10F2.2	CE02041		
T21C9.12	CE06481	scpl-4	(19)	W02D3.1	CE14418		(18, 41, 42)
W08E3.3	CE14708	tag-210	(42)	K11H3.3	CE00474		
Chaperone							
C47E8.5	CE05441	daf-21	(41, 44)	H06O01.1	CE11570	pdi-3	(15, 41, 44)
F26D10.3	CE09682	hsp-1	(41, 44)	Y37E3.9	CE26775	phb-1	(12, 13, 16)
C15H9.6	CE08177	hsp-3	(41, 44)	T24H7.1	CE40718	phb-2	(12, 13, 16)
F43E2.8	CE07244	hsp-4	(41, 44)	F43D9.4	CE00994	sip-1	(41, 44)
Y22D7AL.5b	CE42184	hsp-60	(39, 41, 44)	B0403.4	CE03880	tag-320	(15, 41, 44)
C14B1.1	CE00897	pdi-1	(15, 41, 44)	T05E11.3	CE06362		(40)
C07A12.4a	CE03972	pdi-2	(15, 41, 44)				
Cytoskeleton							
T04C12.6	CE13148	act-1	(40)	ZK154.3	CE15257	mec-7	(13, 40)
T04C12.5	CE13150	act-2	(40)	F26E4.8	CE09692	tba-1	(13, 40)
T04C12.4	CE13148	act-3	(40)	C47B2.3	CE17563	tba-2	(13, 40)
M03F4.2a	CE12358	act-4	(40)	F44F4.11	CE18680	tba-4	(13, 40)
T25C8.2	CE16463	act-5	(40)	T28D6.2	CE16521	tba-7	(13, 40)
C54C6.2	CE33770	ben-1	(13, 40)	K01G5.7	CE16197	tbb-1	(13, 40)
W09H1.6a	CE16576	lec-1		C36E8.5	CE00913	tbb-2	(13, 40)
ZC8.4a	CE31264	lfi-1		B0272.1	CE00850	tbb-4	(13, 40)
Signal Transduction							
T20G5.1	CE00480	chc-1	(16)	W10D9.5	CE14794	tomm-22	
ZK632.6	CE00423	cnx-1	(13, 44)	Y56A3A.32	CE31841	wah-1	
F40E10.3	CE05839	csq-1		ZK856.8	CE06665		
F52H3.7a	CE32894	lec-2		Y54G2A.2a	CE26776		
F58G11.1a	CE11400	letm-1		Y54G2A.18	CE25462		
K04D7.1	CE06090	rack-1		K01G5.5	CE16195		
Transcription							
F31E3.5	CE01270	eef-1A.1	(16, 19)	B0035.9	CE03252	his-46	(19, 42)
R03G5.1a	CE01270	eef-1A.2	(16, 19)	F07B7.9	CE03252	his-50	(19, 42)
F25H5.4	CE15900	eef-2	(16, 19)	F54E12.3	CE03252	his-56	(19, 42)
T01C3.7	CE12920	fib-1		F55G1.11	CE03252	his-60	(19, 42)
F45F2.12	CE10538	his-8	(19, 42)	F22B3.1	CE03252	his-64	(19, 42)
K06C4.10	CE03252	his-18	(19, 42)	K07A1.8	CE11854	ile-1	
K06C4.2	CE03252	his-28	(19, 42)	F57B9.6a	CE01341	inf-1	
F17E9.12	CE03252	his-31	(19, 42)	R74.1	CE16317	lars-1	
C50F4.7	CE03252	his-37	(19, 42)	W01A8.1b	CE06531	mdt-28	
K03A1.6	CE03252	his-38	(19, 42)	F10G7.2	CE02626	tsn-1	
Ribosome							
F25H2.10	CE09655	r1a-0	(19, 46)	R13A5.8	CE01380	rpl-9	(19, 46)
Y37E3.7	CE26658	r1a-1	(19, 46)	B0393.1	CE00854	rps-0	(19, 46)
Y62E10A.1	CE22694	r1a-2	(19, 46)	F56F3.5	CE00664	rps-1	(19, 46)

TABLE I—continued

Sequence name	Protein ID	Gene name	Citations	Sequence name	Protein ID	Gene name	Citations
Y71F9AL.13a	CE25552	rpl-1	(19, 46)	D1007.6	CE09041	rps-10	(19, 46)
F10B5.1	CE01543	rpl-10	(19, 46)	F40F11.1	CE05860	rps-11	(19, 46)
T22F3.4	CE13968	rpl-11.1	(19, 46)	F54E7.2	CE26896	rps-12	(19, 46)
F07D10.1	CE07033	rpl-11.2	(19, 46)	C16A3.9	CE04009	rps-13	(19, 46)
JC8.3a	CE17986	rpl-12	(19, 46)	F37C12.9	CE00821	rps-14	(19, 46)
C32E8.2a	CE08526	rpl-13	(19, 46)	F36A2.6	CE09945	rps-15	(19, 46)
K11H12.2	CE12148	rpl-15	(19, 46)	T01C3.6	CE12918	rps-16	(19, 46)
Y48G8AL.8a	CE22195	rpl-17	(19, 46)	T08B2.10	CE26948	rps-17	(19, 46)
Y45F10D.12	CE16650	rpl-18	(19, 46)	Y57G11C.16	CE14956	rps-18	(19, 46)
C09D4.5	CE08034	rpl-19	(19, 46)	T05F1.3	CE13265	rps-19	(19, 46)
B0250.1	CE18478	rpl-2	(19, 46)	C49H3.11	CE04237	rps-2	(19, 46)
C14B9.7	CE00078	rpl-21	(19, 46)	F53A3.3a	CE10884	rps-22	(19, 46)
B03B6.10	CE00778	rpl-23	(19, 46)	K02B2.5	CE04691	rps-25	(19, 46)
C53H9.1	CE19381	rpl-27	(19, 46)	Y41D4B.5	CE21842	rps-28	(19, 46)
F13B10.2a	CE05598	rpl-3	(19, 46)	C23G10.3	CE01810	rps-3	(19, 46)
Y106G6H.3	CE44850	rpl-30	(19, 46)	C26F1.4	CE06878	rps-30	(19, 46)
W09C5.6a	CE20168	rpl-31	(19, 46)	Y43B11AR.4	CE24278	rps-4	(19, 46)
T24B8.1a	CE03709	rpl-32	(19, 46)	T05E11.1	CE06360	rps-5	(19, 46)
ZK652.4	CE00450	rpl-35	(19, 46)	Y71A12B.1	CE24592	rps-6	(19, 46)
F37C12.4	CE30781	rpl-36	(19, 46)	ZC434.2	CE06577	rps-7	(19, 46)
B0041.4	CE07669	rpl-4	(19, 46)	F42C5.8	CE04561	rps-8	(19, 46)
F54C9.5	CE02255	rpl-5	(19, 46)	K07C5.4	CE06114	Ribosome	(19, 46)
F53G12.10	CE11024	rpl-7	(19, 46)	C37A2.7	CE30433	Ribosome	(19, 46)
Y24D9A.4a	CE27398	rpl-7A	(19, 46)				
Unknown							
M176.3	CE12464	chch-3		F42G8.10a	CE17069		
K02F3.10	CE01346	moma-1		F54A3.5	CE25901		
F30A10.5	CE32397	stl-1		W04C9.2	CE18333		
Y56A3A.21	CE22589	trap-4		B0513.5	CE37309		
K03H1.4	CE00475	ttr-2		Y57A10A.23	CE22626		
Y51A2D.10	CE19206	ttr-25		Y54F10AM.5	CE34127		
T28B4.3	CE14325	ttr-6		Y111B2A.2	CE26622		
C31E10.7	CE37487			F29C4.2	CE17720		
Y39B6A.10	CE21698			ZK809.3	CE03831		
C25A1.12	CE41871			R53.5	CE03575		
F22F7.1a	CE17691			Y57G7A.10a	CE19639		
Y67H2A.5	CE28376			F49H12.5	CE20835		
C10G11.7	CE08086			ZK1055.7	CE18476		
F36A2.7	CE09946			K02F3.2	CE39385		
F43E2.7a	CE41652			Y92H12BR.3a	CE29936		
F32A11.1	CE17737			F59D6.7	CE11488		
F44E5.1	CE18676			C41G7.9a	CE42828		

the same LD (arrowhead-pointed region). After 20 min DHS-3::GFP signal was still not detected in the bleached region (supplemental Fig. S3). The notable position shift of LDs indicates that these LDs were still active during these 20 min. These results demonstrate that DHS-3 can be used as a protein marker for *C. elegans* LDs.

Verification of Lipid Droplet Proteins—To further confirm DHS-3 as a LD resident protein, we then constructed a transgenic line expressing the fusion protein pDHS-3::DHS-3::GFP under the control of its own promoter and observed that similar to pDAF22::DHS-3::GFP, pDHS-3::DHS-3::GFP also formed ring structures *in vivo* (Fig. 5A). To determine that these ring structures were LDs, purified LDs from DHS-3::GFP strain were analyzed using fluorescence and DIC microscopy (Fig. 5B). Almost all purified LDs detected by DIC were over-

lapped with fluorescence images. A few of DIC-detected LDs were not surrounded by GFP signals (Fig. 5Bb, arrows), suggesting that not all LDs contain DHS-3. In addition, LDs in DHS-3::GFP strain were labeled using Nile Red fixed staining and merged with DHS-3::GFP fluorescence signals (Fig. 5C). Most Nile Red signals were surrounded with DHS-3::GFP (Fig. 5Cc). These experiments proved that DHS-3::GFP ring structures are LDs.

More experiments were carried out to verify this LD proteomic study in *C. elegans*. Because ATGL was previously found in LDs of mammalian cells (12) and *C. elegans* (21, 29), it was chosen to do so. First, ATGL was indeed identified in the proteomics (Table I). Second, fluorescence study represented that pATGL::ATGL::GFP was colocalized with LDs stained by Lipid Tox (Fig. 5D). In addition, an unknown function protein F22F7.1

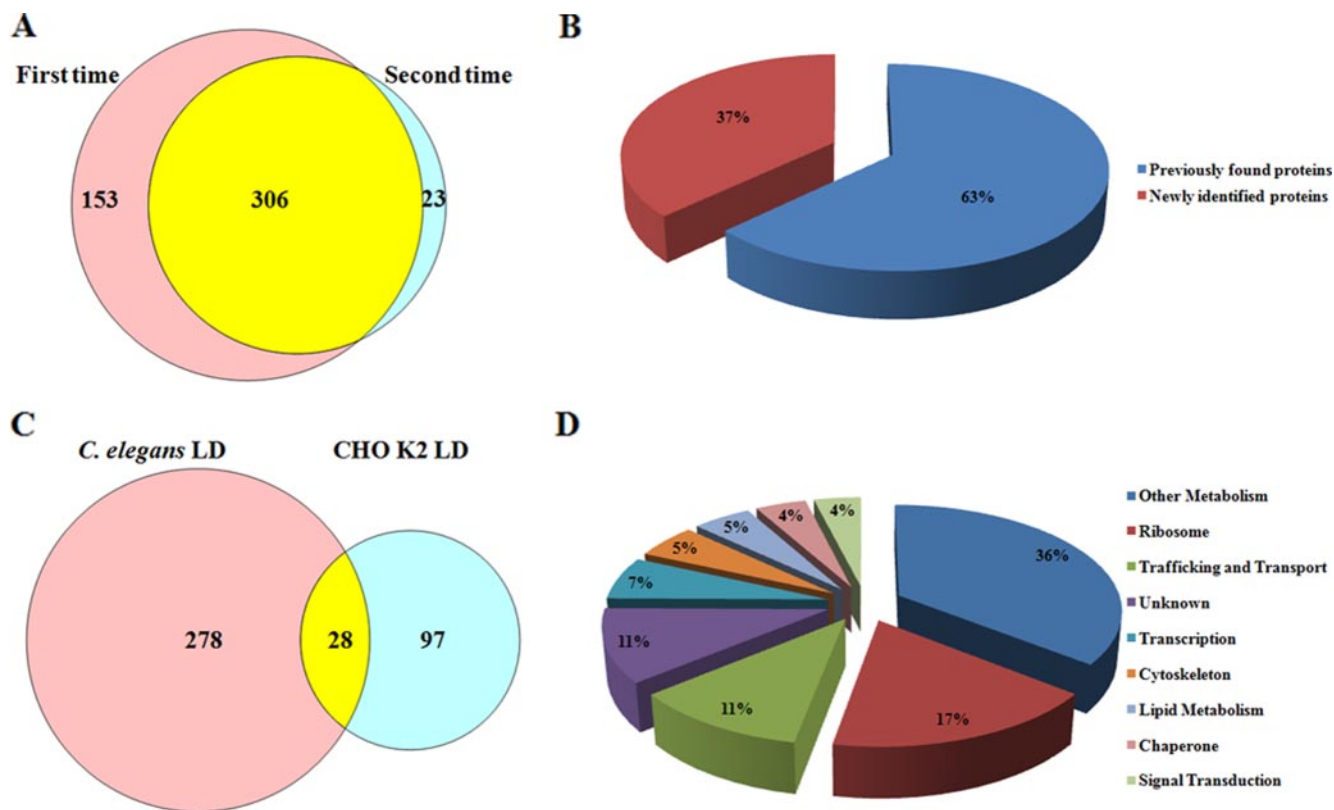


FIG. 3. **Proteomic and bioinformatic analyses of lipid droplet proteins.** A, LD proteins were precipitated by acetone and digested by trypsin then subjected to nano-LC-ESI-LTQ Orbitrap XL MS/MS analysis. The Venn Diagram showed the overlap of two independent mass spectrum results. B, LD proteins identified by mass spectrum were categorized to previously found proteins and newly identified proteins. C, The Venn Diagram showed the LD proteins identified in both *C. elegans* and Chinese hamster ovary K2 (CHO K2) cells. D, The 306 identified LD proteins were classified into 9 groups: lipid metabolism, other metabolism, transcription, ribosome, membrane traffic, chaperone, signal transduction, cytoskeleton, and unknown function.

and an apolipoprotein Vit-2 that were also identified by the proteomics were further verified. Western blotting experiments also showed that F22F7.1 was very enriched in LDs and Vit-2 was partially associated with LDs (Fig. 2C).

DISCUSSION

We reported the purification and proteomic characterization of *C. elegans* LDs. Because of lack of LD marker proteins in *C. elegans*, we had to test the purity of our LD preparations by several other approaches. First, we demonstrated that the LD preparation was floated on top of gradient and highly enriched in TAG but not other lipid species. Second, our EM results showed that isolated LDs contained minimal contamination of other cellular organelles. Third, the protein pattern of LDs in SDS-PAGE was markedly different with TM, Cyto, and PNS. Fourth, using antibodies to detect specific marker proteins for each fraction, we detected only minimal mitochondrial, endosomal, ER, plasma membrane, and cytosolic contamination. Taken together, our results indicate that our LD preparations were relatively pure and suitable for proteomic analysis.

Results from our proteomics study suggest that *C. elegans* LDs and other eukaryotic LDs are conserved in that they share

a large number of homologous proteins involved in lipid metabolism, membrane trafficking, and signal transduction. Of particular interest are the acyl-CoA synthetase (ACS) family, the homologue of mammalian adipose triglyceride lipase ATGL-1, and the short chain fatty acid dehydrogenases (DHS) family. *C. elegans* ACS-20 and ACS-22 are implicated in the incorporation of very long chain fatty acids into sphingomyelin, which may be linked to cuticle barrier formation (30). DHS-28, a peroxisomal dehydrogenase, has been shown to regulate long chain fatty acid β -oxidation and LD size (21). These proteins have also been identified in the LD proteome of other species (Table I). Another interesting category of LD-proteins shared between *C. elegans* and other species is proteins involved in trafficking and transport. We identified Rab1, 7, 8, 10, 11, and 18 in the *C. elegans* LD proteome. The small GTPase Rab18 localizes to LDs and promotes their close apposition to rough ER in human and mouse cells (2, 31). Rab10 and Rab35 have been shown to positively regulate LD size in *Drosophila* S2 cells (32). Vit-1, 2, 3, 4, 5, and 6 were also present (Table I). Vit proteins are apolipoprotein homologs believed to transport lipids to growing oocytes during yolk deposition (33). Western blotting analysis showed that

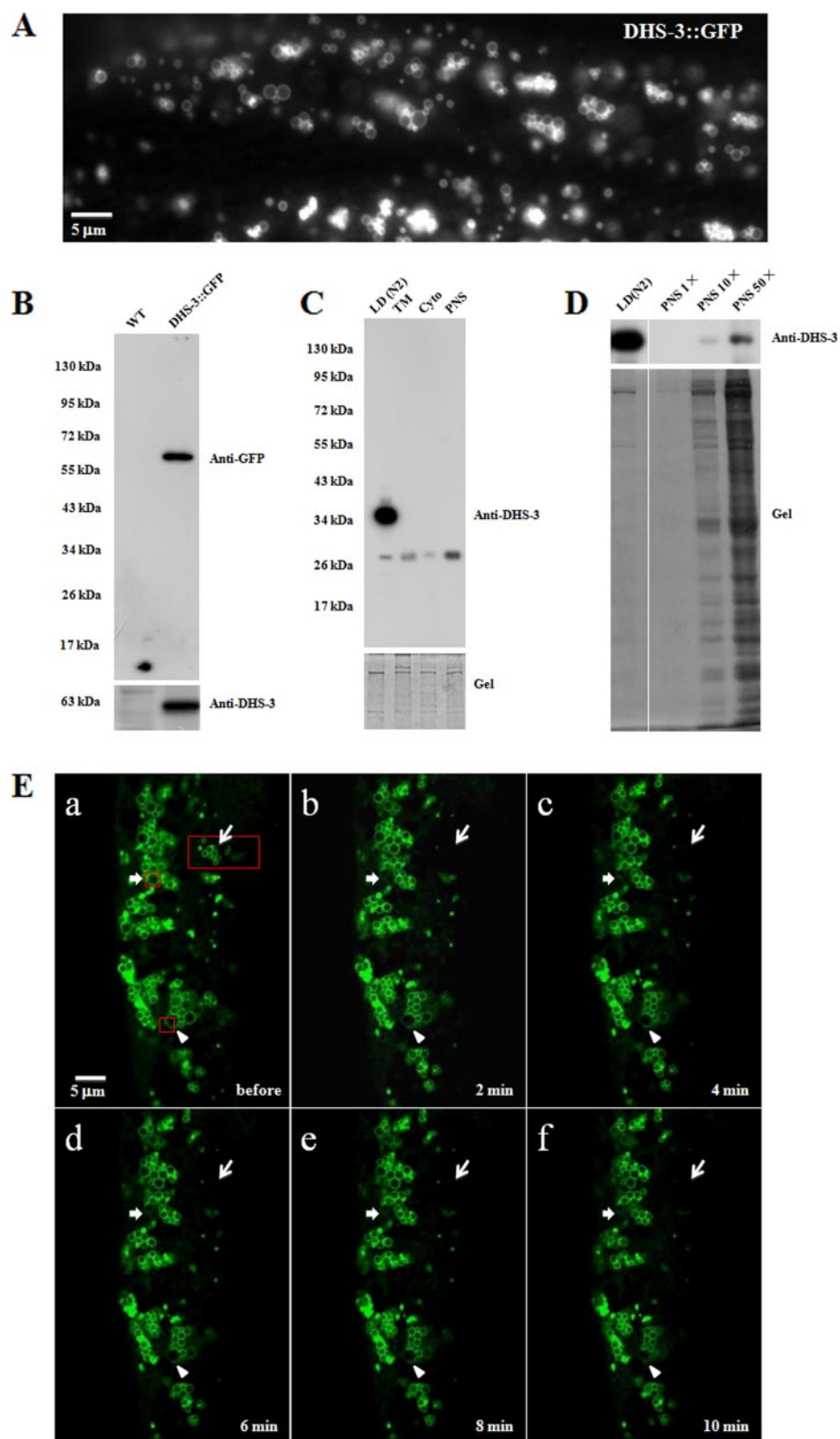


FIG. 4. Identification of DHS-3 as a lipid droplet marker protein. *A*, A DHS-3::GFP strain was used to observe the localization of DHS-3 using fluorescence microscopy. *B*, Western blotting of the WT and DHS-3::GFP strains using GFP (*upper panel*) and DHS-3 (*lower panel*) antibodies. *C*, Western blotting results confirmed that DHS-3 is mainly localized on LDs (*upper panel*). The original gel showing equal protein loading (*lower panel*). *D*, DHS-3 in LDs was dramatically enriched compared with the PNS (*upper panel*). The original gel (*lower panel*). *E*, The DHS-3::GFP strain was observed by fluorescence microscopy before photobleaching (*a*), after photobleaching (*b*/2 min, *c*/4 min, *d*/6 min, *e*/8 min, and *f*/10 min). The red boxes were the selected photobleaching regions: aggregated LDs (thin arrow), single LD (thick arrow), and partial LD (arrowhead).

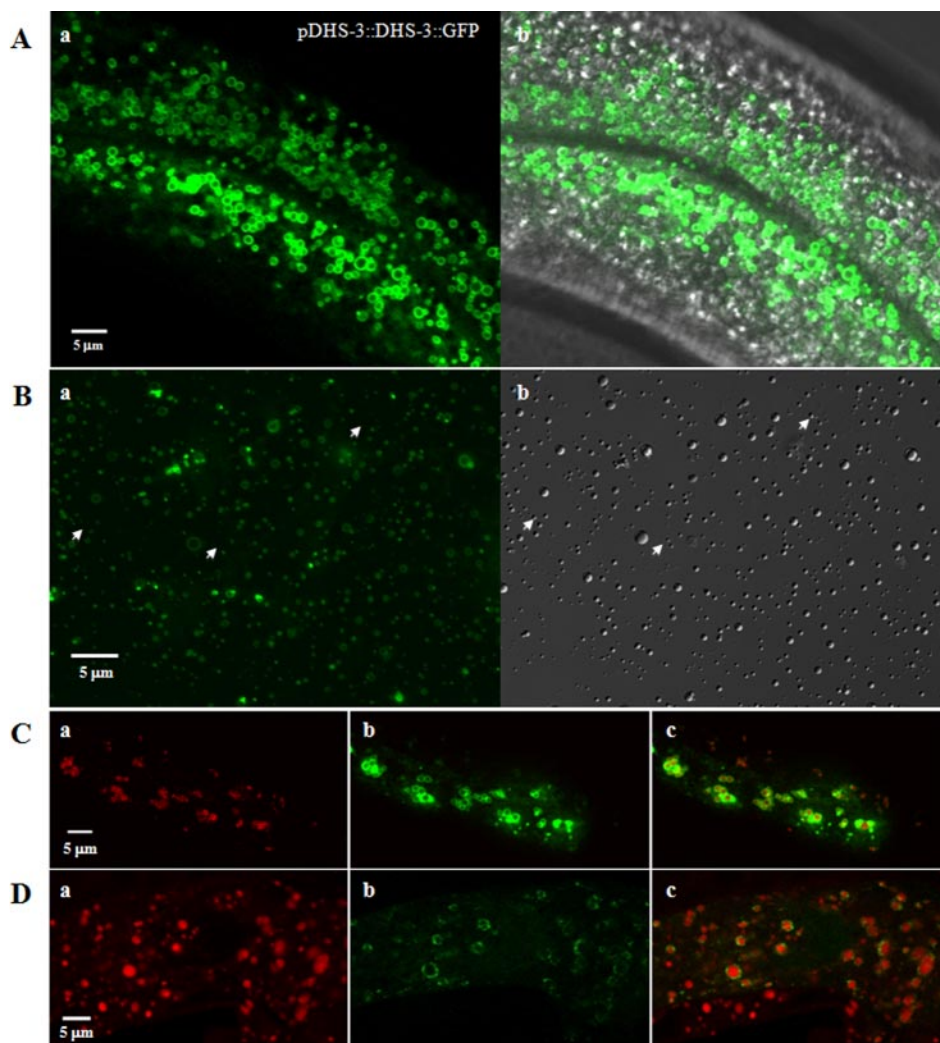


FIG. 5. **Verification of lipid droplet proteins.** A, A pDHS-3::DHS-3::GFP strain was used to observe the localization of endogenous DHS-3 using fluorescence microscopy (a) and merged with bright field. (b). B, Purified DHS-3::GFP lipid droplets were observed by fluorescence microscopy (a) and by DIC microscopy (b). C, Nile Red fixed staining of *C. elegans* in DHS-3::GFP strain. The fluorescence of fixed Nile Red (a), the fluorescence of DHS-3::GFP (b) and the merge of these two images (c). D, Lipid Tox deep Red staining of pATGL-1::ATGL-1::GFP strain (VS20). The fluorescence of Lipid Tox deep Red (a), the fluorescence of ATGL-1::GFP (b) and the merge of these two images (c).

Vit-2 was only partially associated with LDs and the main signal was in total membrane fraction (Fig. 2C), suggesting there are at least two types of lipid storage structures in *C. elegans*, Vit containing lipoprotein particles with higher density and lipid droplets with lower density. Their functions and relationship are worth to be investigated.

It is not clear at present why there are so many mitochondrial metabolism proteins (e.g. mitochondrial respiratory chain proteins) in our LD proteome (Table I). Similar results have been reported before in LD proteomes for other organisms. It has been proposed that mitochondria, peroxisomes, ER membranes, and endosomes may be physically associated with LDs (5, 34) or may even be continuous with LDs in terms of phospholipid membrane topology (35). Recently, we conducted an interactomic study on interaction between LDs and mitochondria and identified several pairs of proteins that may

be involved in this interaction (36).

Our purification and proteomic study has uncovered many bona fide LD-proteins. Using morphological and biochemical analyses, we also identified DHS-3 as a good LD marker protein. These results prove the benefits of purifying LDs and using proteomic approaches over commonly-used genetic approaches to study *C. elegans* LDs. More importantly, this work provides a tool for establishing *in vitro* assays for the study of LDs in *C. elegans*.

As a direct LD detection, our approach may also be used to assess whether the Raman signals of live *C. elegans* captured by Coherent anti-Stokes Raman Spectroscopy and Stimulated Raman Spectroscopy come from LDs or other types of organelles (37–39). For example, the level of colocalization between LD marker proteins and the Raman signals from Coherent anti-Stokes Raman Spectroscopy and Stimulated

Raman Spectroscopy may determine whether these signals can reliably act as a proxy for TAG levels in live *C. elegans*. Furthermore, an *in vitro* assay using isolated LDs and other cellular organelles may help to resolve the issue of the specificity of the Raman signals that are detected by Coherent anti-Stokes Raman Spectroscopy and Stimulated Raman Spectroscopy.

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§ This article contains supplemental Figs. S1 to S3 and Table S1.

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