



VERSION 3

FEB 08, 2024

## Combinatorial selective ER-phagy remodels the ER during neurogenesis V.3

Melissa Hoyer<sup>1</sup>, Cristina Capitanio<sup>2</sup>, Ian R. Smith<sup>1</sup>, Julia C. Paoli<sup>1</sup>, Anna Bieber<sup>2</sup>, Yizhi Jiang<sup>1</sup>, Joao A. Paulo<sup>1</sup>, Florian Wilfling<sup>3</sup>, Brenda A. Schulman<sup>3</sup>, Harper JW<sup>1</sup>

<sup>1</sup>Harvard Medical School; <sup>2</sup>Max Planck Institute of Biochemistry;

<sup>3</sup>Department of Molecular Machines and Signaling, Max Planck Institute of Biochemistry

Cristina Capitanio: \*Joint second author;

Ian R. Smith: \*Joint second author;

ASAP Collaborative Research Network

Harper

[1 more workspace](#) ↓

OPEN ACCESS



Melissa Hoyer

DOI:

[dx.doi.org/10.17504/protocols.io.81wgbx13nlpk/v3](https://dx.doi.org/10.17504/protocols.io.81wgbx13nlpk/v3)

**Collection Citation:** Melissa Hoyer, Cristina Capitanio, Ian R. Smith, Julia C. Paoli, Anna Bieber, Yizhi Jiang, Joao A. Paulo, Florian Wilfling, Brenda A. Schulman, Harper JW 2024. Combinatorial selective ER-phagy remodels the ER during neurogenesis. **protocols.io** <https://dx.doi.org/10.17504/protocols.io.81wgbx13nlpk/v3> Version created by [Melissa Hoyer](#)

**MANUSCRIPT CITATION:**

Hoyer MJ, Capitanio, C, Smith IR\*, Paoli, JC, Bieber, A, Jiang, Y, Paulo JA, Gonzalez-Lozano, MA, Wilfling, F, Schulman, BA, and Harper JW (2023). Combinatorial selective ER-phagy remodels the ER during neurogenesis.

\*, equal contribution

**License:** This is an open access collection distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited

**Protocol status:** Working

We use this collection and it's working

**Created:** Feb 08, 2024

**Last Modified:** Feb 08, 2024

**COLLECTION integer ID:** 94913

**Keywords:** ASAPCRN, ER-phagy, induced neurons, axons, whole cell proteomics, differentiation, live cell fluorescence microscopy, Keima flux, autophagy

**Funders Acknowledgement:**

ASAP

Grant ID: ASAP-000282

**ABSTRACT**

The endoplasmic reticulum (ER) employs a diverse proteome landscape to orchestrate many cellular functions, ranging from protein and lipid synthesis to calcium ion flux and inter-organelle communication. A case in point concerns the process of neurogenesis, where a refined tubular ER network is assembled via ER shaping proteins into the newly formed neuronal projections to create highly polarized dendrites and axons. Previous studies have suggested a role for autophagy in ER remodelling, as autophagy-deficient neurons in vivo display axonal ER accumulation within synaptic boutons, and the membrane-embedded ER-phagy receptor FAM134B has been genetically linked with human sensory and autonomic neuropathy. However, our understanding of the mechanisms underlying selective removal of the ER and the role of individual ER-phagy receptors is limited. Here we combine a genetically tractable induced neuron (iNeuron) system for monitoring ER remodelling during in vitro differentiation with proteomic and computational tools to create a quantitative landscape of ER proteome remodelling via selective autophagy. Through analysis of single and combinatorial ER-phagy receptor mutants, we delineate the extent to which each receptor contributes to both the magnitude and selectivity of ER protein clearance. We define specific subsets of ER membrane or luminal proteins as preferred clients for distinct receptors. Using spatial sensors and flux reporters, we demonstrate receptor-specific autophagic capture of ER in axons, and directly visualize tubular ER membranes within autophagosomes in neuronal projections by cryo-electron tomography. This molecular inventory of ER proteome remodelling and versatile genetic toolkit provide a quantitative framework for understanding the contributions of individual ER-phagy receptors for reshaping ER during cell state transitions.

## MATERIALS

REAGENT or RESOURCE	SOURCE	IDENTIFIER	RRID
<b>Antibodies</b>			
FAM134B Rabbit Polyclonal Antibody	Proteintech	21537-1-AP	RRID:AB_2878879
FAM134C Rabbit Polyclonal Antibody	Sigma-Aldrich	HPA016492	RRID:AB_1853027
CCPG1 Rabbit Polyclonal Antibody	Cell Signaling Technology	80158	RRID:AB_2935809
TEX264 Rabbit Polyclonal Antibody	Sigma-Aldrich	HPA017739	RRID:AB_1857910
REEP1 Rabbit Polyclonal Antibody	Sigma-Aldrich	HPA058061	RRID:AB_2683591
REEP4 Rabbit Polyclonal Antibody	Sigma-Aldrich	HPA042683	RRID:AB_2571730
REEP5 Rabbit Polyclonal Antibody	Proteintech	14643-1-AP	RRID:AB_2178440
hFAB™ Rhodamine Anti-Tubulin Antibody	BioRad	12004166	RRID:AB_2884950
HSP90 mouse monoclonal Antibody	Proteintech	60318	RRID:AB_2881429
Anti-Keima-Red mAb	MBL international	M182-3M	RRID:AB_10794910
Neurofilament heavy polypeptide antibody	Abcam	ab7795	RRID:AB_306084
MAP2 Guinea Pig Polyclonal Antibody	Synaptic systems	188004	RRID:AB_2138181
Nogo-A (C-4) Mouse Monoclonal Antibody	Santa Cruz	sc-271878	RRID:AB_10709573
Calreticulin Rabbit Polyclonal Antibody	Proteintech	10292-1-AP	RRID:AB_513777

GAPDH (D16H11) XP Rabbit Monoclonal Antibody	Cell Signaling Technology	5174	RRID:AB_10622025
Goat anti-mouse Alexa488	Thermo Fisher Scientific	A-11001	RRID:AB_2534069
Goat anti-chicken Alexa488	Thermo Fisher Scientific	A11039	RRID:AB_2534096
Goat anti-rabbit Alexa568	Thermo Fisher Scientific	A-11011	RRID:AB_143157
Goat anti-rabbit Alexa647	Thermo Fisher Scientific	A27040	RRID:AB_2536101
Goat anti-guinea pig Alexa488	Thermo Fisher Scientific	<b>A-11073</b>	RRID:AB_2534117
Goat anti-guinea pig Alexa647	Thermo Fisher Scientific	A-21450	RRID:AB_141882
<b>Bacterial and virus strains</b>			
DH5 alpha E. coli competent cells	Homemade		
T1R E. coli Competent cells	Homemade		
<b>Chemicals, peptides, and recombinant proteins</b>			
DAPI	Thermo Fisher Scientific	D1306	
TMTpro™ 16plex Label Reagent Set	Thermo Scientific	A44520	
Q5 Hot Start High-Fidelity DNA Polymerase	New England BioLabs	M0493	
QuikChange II Site-Directed Mutagenesis Kit	Agilent	200523	
MiSeq Reagent Nano Kit v2 (300 cycles)	Illumina	MS-103-1001	
Bafilomycin A1	Cayman Chemical	88899-55-2	

DAPI (4',6-Diamidino-2-Phenylindole, Dihydrochloride)	Thermo Fisher Scientific	D1306	
16% Paraformaldehyde, Electron-Microscopy Grade	Electron Microscopy Science	15710	
PhosSTOP	Sigma-Aldrich	T10282	
Protease inhibitor cocktail	Roche	4906845001	
TCEP	Gold Biotechnology	TCEP2	
Formic Acid	Sigma-Aldrich	94318	
Trypsin	Promega	V511C	
Lys-C	Wako Chemicals	129-02541	
Urea	Sigma	U5378	
EPPS	Sigma-Aldrich	E9502	
2-Chloroacetamide	Sigma-Aldrich	C0267	
Trypan Blue Stain Thermo Fisher Scientific	Wako Chemicals	129-02541w	
Bio-Rad Protein Assay Dye Reagent Concentrate	Bio-Rad	5000006	
Urea	Sigma	U5378	
EPPS	Sigma-Aldrich	E9502	
2-Chloroacetamide	Sigma-Aldrich	C0267	
Empore SPE Disks C18 3M	Sigma-Aldrich	66883-U	
Pierce Quantitative Colorimetric Peptide Assay	Thermo Fisher Scientific	23275	
GeneArt Precision gRNA Synthesis Kit	Thermo Fisher Scientific	A29377	
12 Well glass bottom plate with high performance #1.5 cover glass	Cellvis	P12-1.5H-N	
Nunc Cell-Culture Nunclon	Thermo Fisher Scientific	140685	

Delta Treated 6-well			
Nunc Cell-Culture Nunclon Delta Treated 12-well	Thermo Fisher Scientific	150628	
100x21mm Dish, Nunclon Delta	Thermo Fisher Scientific	172931	
Corning Matrigel Matrix, Growth Factor Reduced	Corning	354230	
DMEM/F12	Thermo Fisher Scientific	11330057	
Neurobasal	Thermo Fisher Scientific	21103049	
NEAA	Life Technologies	11140050	
GlutaMax	Life Technologies	35050061	
N-2 Supplement	Thermo Fisher Scientific	17502048	
Neurotrophin-3 (NT-3)	Peprtech	450-03	
Brain-derived neurotrophic factor (BDNF)	Peprtech	450-02	
B27	Thermo Fisher Scientific	17504001	
Y-27632 Dihydrochloride (ROCK inhibitor)	PeprTech	1293823	
Cultrex 3D Culture Matrix Laminin I	R&D Systems	3446-005- 01	
Accutase	StemCell	7920	
FGF3	In-house	N/A	
Insulin Human	Sigma-Aldrich	I9278- 5ML	
TGF-beta	PeprTech	100-21C	
holo-Transferrin human	Sigma-Aldrich	T0665	
Sodium Bicarbonate	Sigma-Aldrich	S5761- 500G	
Sodium selenite	Sigma-Aldrich	S5261- 10G	
Doxycycline	Sigma-Aldrich	D9891	
Recombinant SpCas9	Zuris et al., 2015; Orderu		
Hygromycin B	Thermo Fisher Scientific	10687010	
UltraPure 0.5M EDTA, pH 8.0	Thermo Fisher Scientific	15575020	

	GlutaMAX	Thermo Fisher Scientific	35050061	
	Dulbecco's MEM (DMEM), high glucose, pyruvate	GIBCO / Invitrogen	11995	
	Lipofectamine 3000	Invitrogen	L3000008	
	<b>Experimental models: Cell lines</b>			
	HEK293T	ATCC	CRL-1573	CVCL_0045
	H9	Wicell	WA9	CVCL_9773
	<b>Recombinant DNA</b>			
	pAC150-Keima-RAMP4	This paper		Addgene 201929
	pAC150-Keima-REEP5	This paper		Addgene 201928
	pAC150- FAM134C-GFP	This paper		Addgene 201932
	pAC150- TEX264-GFP	This paper		Addgene 201931
	pAC150-TEX264(deltaLIR, F273A)-GFP	This paper		Addgene 201930
	pHAGE-FAM134C-GFP	This paper		Addgene 201927
	pHAGE-TEX264-GFP	An et al 2019		Addgene 201925
	pHAGE-TEX264(deltaLIR,F273A)-GFP	An et al 2019		Addgene 201926
	pHAGE-mCherry-LC3B	An et al 2019		Addgene 201924
	<b>Software and algorithms</b>			
	Prism	GraphPad, V9	<a href="https://www.graphpad.com/scientificsoftware/prism/">https://www.graphpad.com/scientificsoftware/prism/</a>	SCR_002798
	SEQUEST	Eng et al., 1994	N/A	
	Flowjo	Flowjo, v10.7	<a href="https://www.flowjo.com">https://www.flowjo.com</a>	SCR_008520
	Perseus	Perseus v1.6.15.0 Tyanova	<a href="https://ma">https://ma</a>	SCR_007358

		et al. (2016)	xquant.org/perseus/	
	Fiji	ImageJ V.2.0.0	<a href="https://imagej.net/software/fiji/">https://imagej.net/software/fiji/</a>	SCR_002285
	Imagelab	Biorad, v6.0.1	<a href="https://www.biorad.com/en-us/product/image-lab-software?ID=KRE6P5E8Z&amp;source_wt=imagelabsoftware_surl">https://www.biorad.com/en-us/product/image-lab-software?ID=KRE6P5E8Z&amp;source_wt=imagelabsoftware_surl</a>	SCR_014210
	Cell Profiler	CellProfiler v4.0.6	<a href="https://cellprofiler.org/">https://cellprofiler.org/</a>	SCR_007358
	Nikon Imaging Software Elements	5.21.3 (Build 1489)		SCR_014329
	outknocker.org	<a href="http://www.outknocker.org/outknocker2.htm">http://www.outknocker.org/outknocker2.htm</a>		
	ChopChop	<a href="https://chopchop.cbu.uib.no/">https://chopchop.cbu.uib.no/</a>		SCR_015723
	<b>Instruments</b>			
	Orbitrap Fusion Lumos Tribrid Mass Spectrometer	Thermo Fisher Scientific	IQLAAEGA APFADBM BHQ	CR_020562
	Orbitrap Eclipse Tribrid Mass Spectrometer	Thermo Fisher Scientific	FSN04-10000	SCR_020559
	Attune NxT	Thermo Fisher Scientific		SCR_019590
	Sony Biotechnology SH800S Cell Sorter	Sony Biotechnology	SH800S	SCR_018066
	Neon™ Transfection System	Thermo Fisher Scientific	MPK5000	N/A
	ChemiDoc MP imaging system	BioRad	12003154	SCR_019037
	Yokogawa CSU-X1 spinning disk confocal on a Nikon Ti-E inverted microscope	Yokogawa/ Nikon		




FILES

Q SEARCH

Protocol



NAME

Characterizing spatial and temporal properties of ER-phagy receptors

VERSION 1

CREATED BY



Melissa Hoyer

OPEN →

Protocol



NAME

Analysis of ER structures in Cultured Induced Neuron axons

VERSION 1

CREATED BY



Melissa Hoyer

OPEN →

Protocol



NAME

🔗 Analysis of ER Flux in Cultured Induced Neurons using Keima ER reporters

VERSION 1

CREATED BY



Melissa Hoyer

OPEN →

Protocol



NAME

🔗 Electroporation of Cas9 protein into human pluripotent stem cells

VERSION 1

CREATED BY

Melissa Hoyer



[OPEN](#) →

## Protocol



NAME

🔗 Neural differentiation of AAVS1-TRE3G-NGN2 pluripotent stem cells

VERSION 1

CREATED BY



Melissa Hoyer

[OPEN](#) →

## Protocol



NAME

🔗 Whole-cell proteomics and Analysis by Tandem Mass Tagging-based proteomics

VERSION 1

CREATED BY



Melissa Hoyer

[OPEN](#) →

## Protocol



NAME

Testing ER stress induction in Cultured Induced Neurons via measuring ATF4 protein level or XBP-1 mRNA splicing

VERSION 1

CREATED BY



Melissa Hoyer

[OPEN](#) →

## Protocol



NAME

Neural differentiation on EM grids - iNeurons sample preparation for cryo-ET and CLEM

VERSION 2

CREATED BY



**Cristina Capitanio**  
Max Planck Institute of Biochemistry

[OPEN](#) →

## Protocol



NAME

**Analysis of nuclei integrity in cultured induced neurons by fluorescence microscopy**

**VERSION 1**

CREATED BY



**Melissa Hoyer**

[OPEN](#) →

## Protocol



NAME

**Molecular Cloning- Gibson and LR reactions**

**VERSION C8IGZUBW**

CREATED BY



**Melissa Hoyer**

[OPEN](#) →

## Protocol



NAME

**Human pluripotent stem cell culture**

**VERSION 1**

CREATED BY



**Melissa Hoyer**

[OPEN](#) →