Genetic dissection of neuropeptide cell biology at high and low activity in a defined sensory neuron

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Neuropeptides are ubiquitous modulators of behavior and physiology. They are packaged in specialized secretory organelles called dense core vesicles (DCVs) that are released upon neural stimulation. Unlike synaptic vesicles, which can be recycled and refilled close to release sites, DCVs must be replenished by de novo synthesis in the cell body. Here, we dissect DCV cell biology in vivo in a Caenorhabditis elegans sensory neuron whose tonic activity we can control using a natural stimulus. We express fluorescently tagged neuropeptides in the neuron and define parameters that describe their subcellular distribution. We measure these parameters at high and low neural activity in 187 mutants defective in proteins implicated in membrane traffic, neuroendocrine secretion, and neuronal or synaptic activity. Using unsupervised hierarchical clustering methods, we analyze these data and identify 62 groups of genes with similar mutant phenotypes. We explore the function of a subset of these groups. We recapitulate many previous findings, validating our paradigm. We uncover a large battery of proteins involved in recycling DCV membrane proteins, something hitherto poorly explored. We show that the unfolded protein response promotes DCV production, which may contribute to intertissue communication of stress. We also find evidence that different mechanisms of priming and exocytosis may operate at high and low neural activity. Our work provides a defined framework to study DCV biology at different neural activity levels.

Significance

Neuropeptides are ubiquitous modulators of behavior and physiology. They are packaged in specialized secretory organelles called dense core vesicles (DCVs) that are released upon neural stimulation. Whereas local recycling of synaptic vesicles has been investigated intensively, there are few studies on recycling of DCV proteins. We set up a paradigm to study DCVs in a neuron whose activity we can control. We validate our model by confirming many previous observations on DCV cell biology. We identify a set of genes involved in recycling of DCV proteins. We also find evidence that different mechanisms of DCV priming and exocytosis may operate at high and low neural activity.

Results

Cell Biology of DCVs in the PQR Neuron. We selected the PQR O2 sensor as a defined neuron to study DCV cell biology in vivo because it is genetically tractable and its activity can be dialed up or down by changing the levels of its cognate stimulus, O2 (30). PQR natively expresses multiple neuropeptides (31), and its dendrite, cell body, and axon lie in a single plane, facilitating imaging. PQR O2-evoked Ca2+ responses were largely independent of presynaptic input and were not affected by mutations that

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reduce synaptic vesicle exocytosis (unc-13) (19), DCV exocytosis (unc-31/CAPS Ca\textsuperscript{2+}-dependent activator protein for secretion) (24), or neuropeptide maturation (egl-21/CPE) (22, 23) (Fig. 1 A and B). These data suggest DCV mutant phenotypes in PQR are likely to be cell-autonomous.

To express transgenes selectively in PQR, we used the gcy-32 promoter (32). Since promoter activity was an important variable for our assays, we compared the expression of a pgycy-32::RFP transgene at 21% O\textsubscript{2} across a panel of mutants, including unc-64 (syntaxin), unc-31 (CAPS), unc-2 (P/Q voltage-gated Ca\textsuperscript{2+} channel), gcy-35 (a soluble guanylate cyclase required for the O\textsubscript{2}-evoked Ca\textsuperscript{2+} responses in PQR), and unc-43 (CaMKII). We observed a small decrease in RFP expression in WD repeat and FYVE domain-containing 3 (wdy-3) (see below) mutants, but unaltered expression in the other strains, suggesting the gcy-32 promoter is relatively insensitive to changes in neuroendocrine signaling (Fig. 1C).

Fluorescently tagged proneuropeptides have proven reliable reporters of DCV dynamics and neuropeptide secretion (24, 33, 34). To track neuropeptides and DCVs in PQR, we expressed human neuropeptide Y (NPY) tagged with RFP (NPY-RFP), and the Ce insulin-like peptide INS-1 tagged with VENUS (INS-1-VENUS). Like human proinsulin, INS-1 is predicted to comprise A and B chains processed from a propeptide by cleavage at dibasicle residues, and held together by disulfide bonds (Fig. L4). Previous work showed that a C-terminal GFP tag similar to ours remained attached to mature, oxidized INS-1 even after cleavage by EGL-3/PC2 (35). INS-1-VENUS and NPY-RFP localized to intracellular compartments in the PQR cell body and to puncta along the PQR axon, but were excluded from the dendrite. The two tagged peptides colocalized almost completely (SI Appendix, Fig. S1), suggesting they cosegregated to the same DCVs. In subsequent experiments, we used strains that express low levels of INS-1-VENUS from a low copy, integrated pgycy-32::NS-1-VENUS reporter transgene (SI Appendix, Supplementary Methods).

Neuropeptides are packaged in vesicles that become acidified as they mature into DCVs (13, 30, 32). We expressed INS-1 tagged with pHluorin in PQR to probe DCV acidification. pHluorin fluorescence is quenched below pH 5.5 (38). INS-1-pHluorin was faint and confined to the PQR cell body in wild-type animals (Fig. 1D). Disrupting unc-32, which encodes a conserved, neurally expressed vesicular proton pump subunit (39), increased INS-1-pHluorin fluorescence and revealed an INS-1-VENUS–like subcellular distribution. Thus, INS-1-pHluorin provides a readout of UNC-32–dependent DCV acidification.

To obtain further readouts of DCV biogenesis and maturation, we compared the distribution of INS-1-VENUS to that of a transmembrane protein that selectively labels DCVs, IDA-1/Phogrin (40, 41). In axons, 68% of INS-1-VENUS colocalized with IDA-1-mRFP, whereas in the cell body the two proteins showed only 27% colocalization (Fig. 1E). Thus, ∼75% of IDA-1 in the PQR cell body appears to reside in a compartment devoid of neuropeptides, possibly a recycling pathway (see below). For comparison, 95% of INS-1-VENUS in the axon, and 87% in the cell body, were colocalized with NPY-RFP (Fig. S1).

Axons are not uniform structures but harbor varicosities (42). To characterize INS-1-VENUS localization further, we correlated its fluorescence with a cytoplasmic marker, mKate (Fig. 1F). As expected, the two markers showed high correlation (ρ = 0.640, n = 7); however, after normalization to local cytoplasmic volume, INS-1-VENUS fluorescence was not found enriched in cytoplasmic enlargements. This suggests not all varicosities along PQR axon are presynaptic (Fig. 1F). Varicosities often but not always correspond to presynaptic sites (42).

Electron micrographs (EMs) show ~15 presynaptic specializations distributed along the PQR axon in the ventral nerve cord (wormwiring.org). EMs of Ce motor neurons suggest DCVs are excluded from within ~150 nm of the active zone but are enriched perisynaptically close to the active zone (26, 43). We used the active zone marker GFP-ELKS-1 to locate presynaptic sites, which we defined as local maxima in this marker’s fluorescence. In total, 50 ± 8% of INS-1-mCherry and 62 ± 8% GFP-ELKS-1 total fluorescence in the axon concentrated within 1.5 μm of presynaptic sites (34, 44, 45) (Fig. 1G). As expected, INS-1-mCherry did not colocalize with GFP-ELKS-1 (ρ = 0.252, n = 14) but is enriched around it. These observations are consistent with DCVs being enriched in the proximity of presynaptic sites in active PQR, as observed in EM studies of motor neurons. In summary, INS-1-mCherry/INS-1-VENUS fluorescence puncta likely correspond to DCVs enriched at perisynaptic regions.
High-Dimension Analysis of DCV Distribution in PQR. We defined a set of parameters to describe the fate of INS-1-VENUS in PQR (Fig. 2 A–C and SI Appendix, Supplementary Methods). We measured INS-1-VENUS levels in the cell body as “cell body fluorescence” and calculated the fluorescence along the axon after background subtraction. We extracted the local maxima along the axon (Fig. 2B) and defined the mean of these “puncta” as “puncta fluorescence.” The mean size of these puncta was quantified using the “full width at half-maximum (FWHM)” parameter, and the number of puncta per micrometer of axon with “puncta density per μm.” We quantified the total fluorescence in the axon using the “area under the curve (AUC)” parameter. We also measured accumulation of fluorescence at the “tip of the dendrite” and at the “tip of the axon.” Wild-type animals did not accumulate tagged neuropeptide at these locations, but some mutants did. We quantified these parameters using custom software from >60 images of PQR in animals kept at 21% O2, or at 7% O2 for 1 h, before image capture (Fig. 2 C and D). We also evaluated DCV exocytosis in animals kept at 21% O2 using the established coelomocyte assay (44) (Fig. 2E). Coelomocytes are scavenger cells that endocytose molecules secreted in the pseudocoelemic cavity, including GFP-tagged neuropeptides. Posterior coelomocytes report the activity-regulated secretion of INS-1-VENUS from PQR and suggest INS-1-VENUS is released continuously at 21% O2 (46). This release was significantly reduced in mutants defective in Ca^2+–regulated secretion such as unc-64/ syntaxin and unc-31/CAPS (Fig. 2E).

Despite continuous release of INS-1-VENUS from PQR at 21% O2, only a fraction of INS-1-VENUS redistributed intracellularly when we inhibited POR activity by shifting animals to 7% O2. By 2 h after this shift, cell body fluorescence had slightly but significantly increased, while the “total fluorescence” of the axon (AUC) was unchanged (Fig. 2F). This suggests a decrease in net DCV traffic from the cell body to the axon. The distribution of DCVs in the axon did, however, change: mean puncta fluorescence decreased, while puncta density increased (Fig. 2F). Thus, at low neuronal activity, DCVs spread into multiple smaller puncta instead of a few big puncta (Fig. 2F). The parameters we used allowed all puncta to be detected, both at 7% and 21% O2. At both O2 levels, most neuropeptide fluorescence remained in puncta: the ratio of mean puncta fluorescence to median axon fluorescence was not significantly altered by neuronal activity (Fig. 2F).

The absence of more drastic fluorescence changes suggests that DCV production in POR is adjusted according to neuropeptide release, or that POR releases only a small fraction of its DCV neuropeptide content.

Phenotypic Clustering of Mutants Reveals Functional Groups of Genes. We measured the parameters describing INS-1-VENUS fate in 187 mutant strains harboring defects in proteins with domains implicated in membrane traffic, neuroendocrine secretion, and neuronal or synaptic activity (Dataset S1). For each mutant we used the t statistic to compare parameter values with wild-type controls quantified in parallel (Fig. 2D). The t statistic scores differences between two groups, taking account of their variances and the sample size. The comparisons defined a phenotypic profile for each mutant. Our feature set allowed us to group mutants by profile similarity, using 24 nonsupervised hierarchical clustering methods that used bottom-up comparisons and could reach different conclusions from the same dataset. We used the most consensual of the clustering methods (uncentered correlation) to visualize the phenotypes and relatedness of mutants (Fig. 3 and SI Appendix, Fig. S2).

We were concerned that genetic modifiers in the background, an insufficiently large parameter set, and variability during feature extraction could yield false-positive or false-negative gene clusters. To minimize false positives, even at the expense of discounting genuine gene clusters, we set a conservative threshold. To be considered meaningful, gene groups had to be detected by >10 clustering methods. To test this threshold, we...
functions that are indicated to the intensity. Bold branches in the dendrogram indicate robust clusters detected across multiple samples. The other colored dots indicate genes of interest discussed in the main text.

**Fig. 3.** Phenotypic clustering of mutants. The dataset is visualized using the uncentered correlation method. Each row represents the INS-1-VENUS distribution profile of one mutant strain. For each parameter, positive and negative t statistics (red and blue shading, respectively) indicate an increase or decrease, respectively, in a given parameter in the mutant compared with wild type. The magnitude of the t statistic (from −12 to +12) is indicated by the shading intensity. Bold branches in the dendrogram indicate robust clusters detected across ≥10 clustering methods. Colored lines indicate clusters with predicted functions that are indicated to the Right, based on the identity of genes included in the clusters. The control strains (here written WT II and WT V) are in the N2 genetic background and are compared with each other. The gray dots highlight mutants mentioned in the main text that have profiles similar to the wild-type controls. The other colored dots indicate genes of interest discussed in the main text.
included several independently derived strains bearing the same or different null alleles of the same gene. These strains should group together, whereas different, nonnull (hypomorphic and/or gain-of-function) alleles of the same gene are less likely to cluster. Forty-two percent of the positive controls (15/36 strain pairs bearing nulls) were clustered by ≥10 clustering methods; by contrast, none of six strain pairs bearing nonnull (loss- and/or gain-of-function) alleles were detected at this cutoff (SI Appendix, Fig. S2).

Using this threshold, we identified 62 groups containing two to six genes (Fig. 3, thick branches, and SI Appendix, Fig. S2). The fluorescence profile of mutants provided insights into processes affected by the mutation, while the clustering of mutant phenotypes predicted functionally related genes (34, 44, 47). To better anchor gene groups with biological function, we included in our dataset mutants characterized in previous behavioral, ultrastructural, or electrophysiological studies (Dataset S1). In the next several sections, we discuss gene groups highlighted by our clustering analysis.

**A Baseline UPR Signaling Supports the Production of DCV.** Our analysis clustered *ire-1* and *xbp-1* mutants (Fig. 3, cyan). In these animals INS-1-VENUS and the DCV membrane protein IDA-1/phogrin localized almost exclusively to the PQR cell body (Fig. 4A). IRE-1 and XBP-1 mediate the ER response to misfolded proteins by activating the unfolded protein response (UPR) (48). The UPR relieves ER stress by repressing general translation at the ER, while stimulating the ER ability to fold, export, and degrade proteins. As expected if INS-1 traffic was blocked at the pH-neutral ER, INS-1-pHluorin fluorescence was higher in *xbp-1* mutants than wild-type controls and was excluded from the axon (Fig. 4C). Mutations that disrupt DCV biogenesis after ER exit, for example, *unc-104* kinesin (40) or *hid-1* (see below) (49), did not alter the *xbp-1* phenotype (Fig. 4B). By contrast, VENUS targeted to the ER using a signal peptide was trafficked out of the cell body in *xbp-1* mutants. These data suggest a baseline UPR is required for efficient insulin export and DCV formation in PQR. Artificially increasing neuronal expression of XBP-1s, the isoform that impairs the ability to fold, export, and degrade proteins. As expected if INS-1 traffic was blocked at the pH-neutral ER, INS-1-VENUS fluorescence was higher in *xbp-1* mutants than wild-type controls and was excluded from the axon (Fig. 4C). Mutations that disrupt DCV biogenesis after ER exit, for example, *unc-104* kinesin (40) or *hid-1* (see below) (49), did not alter the *xbp-1* phenotype (Fig. 4B). By contrast, VENUS targeted to the ER using a signal peptide was trafficked out of the cell body in *xbp-1* mutants. These data suggest a baseline UPR is required for efficient insulin export and DCV formation in PQR. Artificially increasing neuronal expression of XBP-1s, the isoform that impairs the ability to fold, export, and degrade proteins. As expected if INS-1 traffic was blocked at the pH-neutral ER, INS-1-VENUS fluorescence was higher in *xbp-1* mutants than wild-type controls and was excluded from the axon (Fig. 4C). Mutations that disrupt DCV biogenesis after ER exit, for example, *unc-104* kinesin (40) or *hid-1* (see below) (49), did not alter the *xbp-1* phenotype (Fig. 4B). By contrast, VENUS targeted to the ER using a signal peptide was trafficked out of the cell body in *xbp-1* mutants. These data suggest a baseline UPR is required for efficient insulin export and DCV formation in PQR.

**Vesicles from the ER fuse with the cis-Golgi and their contents traffic to the trans-Golgi network (TGN).** Neuropeptides exiting the TGN enter a short-lived, poorly characterized compartment commonly called immature dense core vesicles (imDCVs) (50). Apart from alleles that block ER exit or anterograde DCV transport (51), no mutations were detected at this cutoff (Fig. 3, dashed magenta). We identified a group of 23 such genes clustered by eight or more methods. Included were eight genes recently shown to be involved in imDCV remodeling and cargo maintenance: *unc-108*/*Rab2*, *ric-19/ICA69*, *vps-50*, *vps-51*, *vps-52*, *vps-53*, *rund-1*, and *hid-1* (27, 29, 37, 53). Clustering with these eight genes were genes previously implicated in endosomal traffic and synaptic vesicle recycling, including *anph-1*/Anphymysin, *syx-6*/Syntansix, *rab-4*/Rab14, *unc-11*/AP180, and *tax-6*/Calcineurin (54–56) (Fig. 3, dashed magenta). Also in the cluster were five genes not previously implicated in DCV biogenesis in any species: *K02E10.1*: a Rab related to RAB1/8/10; a Rab related to RAB-14; UNC-11: an ortholog of human AP180; *F41H10.4*: orthologous to human GRIPAP1 (also known as GRASP1) and *wdg-3*, encoding a large protein conserved in humans that contains WD40 repeats, and FYVE and BEACH domains (Fig. 3, magenta). We observed a small decrease in expression from the *pgcy-32* promoter in *wdg-3* mutants, but unlabeled activity in the other strains (Fig. 1C).
Double mutants of *unc-108* with *hid-1*, *syx-6*, or *vps-50* did not show additive phenotypes, suggesting genes in this cluster play related roles during DCV biogenesis (Fig. 4D). One proposed function of *UNC-108/Rab2* and *RIC-19* is to prevent loss of soluble imDCV cargo to endolysosomes (57). Previous work in C. elegans motoneurons showed that disrupting EGL-3/PC2 can partially prevent this leak in *unc-108* mutants (27). We found that disrupting *egl-3* rescued the INS-1-VENUS fluorescence phenotypes of *syx-6*, *hid-1*, *unc-101*, *rab-14*, *af-1-1*, *unc-11*, and *vps-52* (SI Appendix, Fig. S3 C and D).

This is consistent with these six genes regulating DCV biogenesis at a step after neuropeptides exit the TGN, when EGL-3/PC2 is activated by imDCV acidification. We therefore refer to the 23 clustering genes as the “maturation clusters.” Consistent with a constitutive leak of neuropeptide from imDCV (28), several mutants that disrupt endocytic traffic toward lysosomes (*cup-5*/mucolipin, *ppk-3*/Fab1p, *vps-39*/HOPS complex, *sand-1*/Mom1) increased the INS-1-VENUS content in PQR. Mutations in *sand-1* and *vps-39* also improved the phenotype of *unc-108* (Fig. 3, purple, and SI Appendix, Fig. S3A).

Maturation clusters include proteins associated with the TGN and/or vesicles located near the TGN e.g., *UNC-108/Rab2*, *RIC-19*/ICA69, *RUND-1*/RUNDIC1, *HID-1*/Dymeclin (27, 29). Other proteins in the maturation clusters are associated with recycling endosome compartments e.g., Syntaxin 6, RAB14, the EAR complex (made of VPS-50, 51, 52, and 53 subunits) and GRIPAPP (58, 59). The EAR complex shares most of its subunits with the GARP complex, but includes the VPS-50 subunit, whereas GARP has VPS-54 (58). EARP mediates traffic toward the recycling endosome, whereas GARP promotes traffic toward the TGN. Disrupting VPS-50 but not VPS-54 perturbed INS-1-VENUS trafficking, consistent with recycling endosomes contributing to DCV biogenesis (53) (Fig. 3, magenta dot, and Fig. 4E). As expected (53), in PQR, mRFP-tagged VPS-50, UNC-108, and SYX-6 localized to the cell body, and to a lesser extent to the axon (Fig. 4 G–I). Together, these observations suggest recycling endosomes promote maturation of DCVs in close proximity to the TGN, but after scission of imDCVs from the TGN.

Maturation Clusters Promote Recycling of DCV Membrane Proteins. Previous work focused on retrieval of peptide cargo as DCVs mature (27, 28, 53). However, several proteins in the maturation clusters, including *UNC-11*/AP180 and amphiphysin, mediate clathrin-dependent recycling of SVs at synapses (55). Like SVs, DCVs harbor many membrane proteins, and at least some can also be recycled after release (60, 61). The physiological role of this process is uncertain, but might contribute to DCV biogenesis.

We speculated that a quality control mechanism matches peptide cargos to available DCV membrane proteins during DCV maturation. In this model, endosomal recycling of DCV membrane proteins prevents the leak of DCV cargo observed in the maturation clusters mutants. Among the many DCV membrane proteins potentially recycled to imDCV through recycling endosomes, we focused on *IDA-1*/Phogrin and PAMN-1/PAM (peptidylglutamate alpha-amidating monoxygenase), both specific markers for DCVs, and on the 

H+/ATP pump required for DCV acidification. If genes in the maturation clusters promote recycling of DCV membrane proteins, their corresponding mutants should misroute DCV membrane proteins, reducing the colocalization of *IDA-1*, PAMN-1 and the H+/ATP pump with INS-1. To test this we focused on the new genes we identified: *F41H10.4*, *wdfy-3*, or *K02E10.1* and on *vps-50*, known to affect recycling toward recycling endosomes.

We first examined the distribution of *IDA-1* and PAMN-1. In the cell body of wild-type PQR, ~25% of *IDA-1* and PAMN-1 colocalized with INS-1-VENUS. Disrupting *vps-50*, *F41H10.4*, *wdfy-3*, or *K02E10.1* reduced this colocalization to 5–15% (Fig. 5 A and B). Moreover, whereas ~65% of *IDA-1* and PAMN-1 colocalized with INS-1-VENUS in wild-type axons, in mutants axon colocalization fell to 20–45%. These data suggest that in these mutants, recycling of DCV membrane proteins is disrupted before the recycling endosomes fuse with peptide-containing imDCV. Second, we monitored imDCVs acidification: if the vesicular H+/ATP pump is not efficiently recycled to imDCVs, then INS-1-PHluorin fluorescence should increase in mutants of the maturation clusters. Consistent with this hypothesis, INS-1-PHluorin fluorescence increased significantly in *vps-50*, *hid-1*, *unc-108*, *F41H10.4*, *wdfy-3*, and *syx-6* mutants, but not in *ida-1* (Fig. 5D). If recycling endosomes are not fusing with peptide-containing imDCV in mutants of the maturation clusters, then these mutants might show an expanded recycling endosome compartment. To investigate this,
we quantified the SYX(+)INS-1(−) compartment, likely reflecting recycling endosomes. In wild type, ~85% of SYX(+) vesicles did not contain INS-1; in hid-1, vps-30, wdy-3, and K02E10.1 mutants, we observed a small but significant increase in this compartment (Fig. 5C). In sum, these data suggest that proteins in the maturation cluster promote recycling of DCV membrane proteins to imDCV through recycling endosomes (Fig. SE).

**Dynemin Maintains the Mobility of DCVs.** Two clusters with opposite phenotypes included genes encoding UNC-104/KINESIN 3 and SYD-2/LIPRIN-α on the one hand, and DHC-1/DYNEIN and UNC-116/KINESIN 1 on the other (Fig. 3, cyan and pink, and Fig. 6A). unc-104/kinesin three mutants showed increased INS-1/VENUS cell body fluorescence, and little or no fluorescence in the axon. Previous studies have shown that mutations in unc-104/ kinesin 3 or syd-2/liprin-α disrupt anterograde traffic of several neural cargoes, including DCVs (40, 62, 63). SYD2 is suggested to activate UNC-104 (62). Consistent with this, unc-104; syd-2 double mutants resembled unc-104 single mutants (Fig. 6A).

The second cluster showed the converse phenotype: reduced cell body fluorescence, but increased fluorescence in puncta and at the axonal tip. This cluster included dhc-1 (dynein heavy chain), dnc-1 (p150 subunit of dynactin), unc-116 (kinesin-1 heavy chain), jnk-1 (c-Jun kinase), and egl-50 (Fig. 3, pink, and Fig. 6A). The dhc-1 phenotype was not altered by reducing neuronal activity (in egl-19 mutants lacking the L-type Ca²⁺ channel), or by disrupting priming/exocytosis in unc-31 mutants (Fig. 6B), suggesting retrograde movement occurs independently of neuronal activity and DCV release. DCV accumulation along the POR axon suggests dynein activity is required either to navigate DCVs around roadblocks along POR axon microtubules or to prevent DCV accumulation at multiple microtubule plus ends along the POR axon.

Kinesin-1 promotes anterograde trafficking, whereas dynein promotes retrograde trafficking. These motors can simultaneously associate with the same cargo (64). Interestingly, mutations in dhc-1/dynein and unc-116/kinesin-1 had similar DCV trafficking phenotypes. To investigate how dynein and kinesin-1 influence DCV transport more closely, we quantified INS-1-RFP trafficking in the ALM mechanosensory neuron. ALM processes run laterally, close to the cuticle, making them ideally suited for visualizing DCV trafficking. We measured the fraction of mobile puncta, as well as their directionality and run velocity, in the proximal and distal portions of the ALM axon. As expected from previous studies (40, 63), unc-104 and syd-2 mutants had few INS-1/VENUS puncta in the axon, and their anterograde run velocity was reduced (Fig. 6D). Only unc-104, syd-2, and dhc-1 mutants affected the mean anterograde DCV run velocities, whereas only dhc-1 affected the mean retrograde DCV run velocity (Fig. 6C and F), suggesting these motors/adaptors are key to DCV fast trafficking.

Consistent with a mostly indirect effect of unc-116/Kinesin-1 on DCV trafficking, an unc-116 mutation had no effect on DCV run velocities but affected the general movement pattern of DCVs. In both dhc-1 and unc-116 mutants, the net movement of DCV was anterograde, while many DCVs were immobile at the distal end, to a lesser extent, the proximal axon (Fig. 6D and E). Kinesin-1 transports dynein anterogradely with the dynactin complex and is required to provide dynein to the distal axon (65). Our results and the accumulation of DCVs at the tip of the axon in POR and ALM support a model in which dynein activity is limiting for the retrograde net movement of DCVs in the distal axon of unc-116, dhc-1, and dnc-1 mutants. Therefore, the dhc-1-like phenotype of Kinesin-1 and Dynactin mutants in POR may reflect defective anterograde transport of the dynein/dynactin complex by Kinesin-1 (Fig. 6G).

**DCVs Production in POR: A Homeostatic System.** Toggling POR activity by changing O₂ levels only weakly altered the INS-1/VENUS fluorescence content of POR (Fig. 2E). Disrupting molecules that mediate O₂-evoked Ca²⁺ responses in POR [the soluble guanylate cyclase gcy-35, the cGMP channel subunit cng-1, the ryanoidine receptor 68, the L-type voltage-gated Ca²⁺ channel egl-19 (30)] also had relatively weak effects on the total amount of INS-1/VENUS fluorescence in POR (Fig. 3, gray dots). Similarly, mutations known strongly to disrupt SV/DCV exocytosis (unc-13, unc-31, others) had relatively weak effects on the total amount of INS-1/VENUS fluorescence in POR (Fig. 3, green and red, and Fig. 7A and B). These observations suggest that, despite tonic release of neuropeptides at 21% O₂, DCV production in POR efficiently adapts to the need of the neuron. Nevertheless, unc-13, unc-31, and other priming and docking mutants changed DCV distribution in the axon (see below).

**Differential Control of Neuropeptide Release at High and Low Neuronal Activity.** EMs of Ce neuromuscular junctions show a small number of SVs and DCVs that touch the plasma membrane and are said to be docked there (26, 66). “Docking” is thought to involve a
reversible interaction of vesicles with the plasma membrane before “priming,” which leads to fusion in response to Ca\textsuperscript{2+} entry (67). For SVs, the proteins involved in these steps include the SNARE complex, formed by \(\alpha\)-helices from syntaxin/UNC-64, SNAP25/RIC-4, and synaptobrevin/SNB-1, and the priming factors UNC-18, UNC-13, and UNC-31/CAPS, all previously characterized in C. elegans (24, 25, 68–72).

Several clusters contained these docking and priming factors: unc-64 clustered with unc-13(null) and ric-4/SNAP25; unc-31/CAPS with pck-1/protein kinase C\(_e\), and pck-1 with aex-6/Rab27 (Fig. 3, red and green). Although mutations in priming and docking factors had a weak effect on the total DCV content of PQR, they changed DCV distribution in the axon. In these mutants, INS-1-VENUS puncta fluorescence was reduced (Fig. 7A). In the same mutants INS-1-VENUS “AUC” weakly increased or remained unchanged (Fig. 3). This axonal phenotype suggests the persynaptic distribution of DCVs was reduced due to spread or noncapture in unc-64, unc-13, ric-4, pck-1, aex-6, and unc-31 mutants. This could be explained by a lack of DCV docking sites, a less stable association with the plasma membrane (priming), or a change in the properties of the DCVs themselves.

Reciprocally, tom-1 mutants, which disrupt Tomosyn, a presynaptic protein that inhibits docking, priming, and exocytosis of SVs and DCVs (73–75), showed increased puncta fluorescence (Fig. 3, orange). The tom-1 phenotype was not altered when we disrupted the priming factor UNC-31, or the L-type voltage-gated Ca\textsuperscript{2+} channel \(\alpha\)-subunit EGL-19, necessary for PQR depolarization (30) (Fig. 7B).

This suggests Tomosyn can alter DCV docking independently of PQR activity and unc-31/CAPS function.

Synaptotagmin 1/SNT-1 triggers SV exocytosis in response to Ca\textsuperscript{2+} entry (76). snt-1 mutants showed a weak increase in fluorescence in cell body and axonal parameters, regardless if animals were kept at 7% O\textsubscript{2} or 21% O\textsubscript{2} (Fig. 3, green dot, and Fig. 7D), suggesting SNT-1 promotes secretion of DCVs across the PQR activity levels we analyzed. To evaluate regulated exocytosis of DCVs in snt-1 and other mutants, we used the coelomocyte assay (44) (Fig. 2E). Mutations in aex-6/rab27, unc-64, and pck-1 attenuated secretion both at 21% and 7% O\textsubscript{2}, suggesting that they reduce docking, priming, and/or exocytosis of DCVs (Fig. 7C). In contrast, tom-1 mutants showed increased coelomocyte fluorescence both at 7% O\textsubscript{2} and 21% O\textsubscript{2} (Fig. 7C). Disrupting unc-31 and snt-1 only reduced secretion at 21% O\textsubscript{2} and 7% O\textsubscript{2}, respectively (Fig. 7C). Therefore, the functions of unc-31 and snt-1 appear more important at high and low neuronal activity, respectively. By comparison, dhc-1 mutants, which also exhibited increased puncta fluorescence and provided a negative control, did not show a secretory phenotype (Fig. 7C). These data suggest different proteins may be involved in DCV exocytosis at high and low neuronal activity.

Specific Machinery Are Involved in SV or DCV Exocytosis. SVs are released at active zones, which contain several SV docking and priming factors including UNC-10 (RIM), RAB-3, CPX-1, and the UNC-13L long isoform that interacts with UNC-10 (19, 66, 77). As DCVs are excluded from the active zone and do not recycle locally, part of the SV machinery may not strongly influence DCV biology. Mutants for unc-10/RIM and rab-3 clustered together but showed a weak INS-1-VENUS phenotype compared with most mutants we studied (Fig. 3, pink, and Fig. 7A). This phenotype suggests these gene products either only have a weak direct effect on DCVs or that the reorganization of the SV cycle in mutants indirectly affects DCV cell biology. Interestingly, mutants selectively defective for UNC-13L, or for SNB-1, did not significantly reduce neuropeptide secretion (Fig. 7C), suggesting UNC-13L and SNB-1 affect SV release more strongly than DCV release (71, 78), at least in PQR.

Are some proteins involved in DCV but not SV exocytosis? Previous reports suggested that PKC-1 (PKC epsilon) and UNC-31 (CAPS) selectively affect DCV release (24, 25), although the selectivity of CAPS is controversial (79). These two mutants clustered with aex-6/RAB27 in our analysis (Fig. 3, green). Also clustering with aex-6/RAB27 mutants are two alleles of rbf-1, which disrupt a protein orthologous to Rabphilin that is present on DCVs (Fig. 3, green) (80). Like rabphilin, RBF-1 has two C2 domains and a FYVE domain. In the coelomocyte assay, rbf-1 mutants showed an unusual secretion phenotype, with reduced secretion at 7% O\textsubscript{2} and increased secretion at 21% O\textsubscript{2}, suggesting opposite effects in active and inactive neurons (Fig. 7C). To assess whether rbf-1 selectively affected DCV exocytosis, or altered both SV and DCV exocytosis, we compared miniature excitatory post-synaptic potentials (mini-EPSPs) from Ce muscle in rbf-1 mutants and wild-type controls. Spontaneous muscular mini-EPSPs reflect spontaneous release of SV at the neuromuscular junction and are affected by mutations in docking or priming factors for SV (81). Neither the frequency nor the size of mini-EPSPs was altered in rbf-1 mutants, suggesting RBF-1 is not involved in SV release and may only affect DCVs in Ce neurons (Fig. 7D).

Discussion

We established a tonic sensory neuron whose physiology we can control as a model to study DCV cell biology in vivo at high and low neural activity. We characterize DCV biogenesis, traffic, and release in 187 mutants that affect 143 genes. We focus our discussion on salient insights but note that we corroborate many observations made previously, validating PQR as a model.
Efficient ER export of INS-1-VENUS and IDA-1-RFP requires a baseline UPR activity, and inducing the UPR increases DCV production. These observations suggest one mechanism by which altering the neuronal UPR could remodel intertissue communication (82).

We identify a set of gene products—located in the maturation clusters (Fig. 3)—that promote recycling of DCV membrane proteins, including IDA-1 and PAMN-1. Mutants of genes in the maturation clusters (apx-50, hid-1, K02E10.1, F41H10.4, wdp-3, syntaxin-6) fail to acidify DCVs appropriately and show reduced colocalization of DCV membrane proteins with neuropeptides. In the PQR cell body, ~25% of IDA-1 and PAMN-1 colocalize with INS-1-VENUS in wild-type animals; this decreases to 10% in the maturation cluster mutants. We speculate that the IDA-1 and PAMN-1 not colocalized with INS-1 are in recycling compartments. In the axon of the maturation cluster mutants we studied, >60% of INS-1-VENUS is depleted of IDA-1, compared with <35% in wild type. These data suggest that a substantial fraction of IDA-1 is recycled rather than provided de novo by the TGN. These findings mirror results in the pancreatic beta-cell line Min6, which show that endogenous phogrin released after stimulation is recycled to an insulin-positive compartment and can be used during subsequent rounds of release (60). The molecular machinery mediating this recycling is unknown, but recycling phogrin is not observed to transit the TGN but transiently colocalizes with syntaptin-6 (60).

Several genes represented in the maturation clusters were implicated previously in DCV biogenesis. These include subunits of the recycling endosome (EARP) complex (37, 53, 58), UNC-108/Rab2, RIC-19, and HID-1 (49, 83). These studies highlighted roles for these genes in retrieving neuropeptides during DCV maturation, rather than in recycling DCV membrane proteins. Several other genes we identify in the maturation clusters were not previously associated with DCV biogenesis, including UNC-11/ AP180, a protein involved in SV endocytosis at the plasma membrane (55); GRIPAP1, a tethering protein involved in endocytic recycling in neurons (59); WDFY3, a member of the BEACH protein family involved in cortical development (84); and Rab14 and RAB1/8/10. A large-scale screen for effectors of Rab-14, GRIPAP1, and WDFY-3 interact almost exclusively with Rab4, Rab14, or Rab2 (SI Appendix, Fig. S4). Rab4 and Rab14 act at the early “sorting” endosome, to assemble multiple classes of cargo into recycling endosome progeny.

Altogether, the molecular identity of genes of the maturation clusters, the defect in DCV transmembrane protein recycling, and the expansion of the Syntaxin-6 positive compartment in some of the maturation clusters mutants support modifications to the current model for DCV biogenesis. We suggest the maturation cluster gene products function in recycling DCV transmembrane proteins from the plasma membrane back to the imDCV exiting the TGN. Evidence exists of post-TGN vesicular fusion events during DCV biogenesis in mammalian endocrine cells (86–88). These vesicular fusion events involve Syntaxin-6 and HID-1, both found in the maturation clusters (61, 87–89). These fusion events are described as “homotypic” because they occur between vesicles containing a dense-core, identified as imDCV. Instead, we suggest some of the observed homotypic fusion events involve recycling vesicles still containing a dense core after exocytosis and imDCVs exiting the TGN. Consistent with this, in lactotroph pituitary cells, many vesicles still containing prolanin after exocytosis colocalize transiently with internalized TfnR and Syntaxin-6, two markers of recycling endosomes (90). Therefore, DCV biogenesis is not a fully de novo process but involves a recycling trafficking pathway.

DCV content and distribution are relatively stable over short periods of PQR activity/inactivity (<1 h), despite evidence of constant neuropeptide release by the activated neuron. Mutants known to chronically reduce PQR activity, or SV and DCV release, showed relatively weak phenotypes. We recently showed that neurosecretion feeds back to increase neuropeptide transcription in tonically active neurons (46). We suggest production of DCVs is also coupled to neurosecretion through unknown feedback mechanisms. Increased availability of recycling endosomes containing DCV membrane proteins, following neurosecretion, may provide one such mechanism, by favoring retention of neuropeptides in maturing DCVs rather than their trafficking to lysosomes for degradation.

Disrupting proteins involved in DCV docking, priming, and exocytosis in PQR, reduces both the axonal puncta fluorescence and exocytosis in PQR; mutations that increase docking and priming have the opposite effect. These effects contrast with the effect of the same mutations on DCVs in motor neurons (44). However, it is consistent with their effects on SV redistribution in motor neurons (73). The differences between PQR and motor neurons might reflect dissimilar neuronal properties, or the non–cell-autonomous effects of the mutations on motor neuron activity. The DCV redistribution observed in docking-defective mutants is thought-provoking, since EM of the central nervous system reveals very few DCVs docked at the plasma membrane at steady state (26). Perhaps DCVs make transient and repeated interactions with the plasma membrane, whose duration/frequency would be determined by neuronal activity and the number of docking/priming sites.

Few genes affect SVs and DCVs differentially. Disrupting the active zone protein UNC-13L affects SVs without substantially altering DCVs in our assays, while RBF-1 (rabphilin) appears to affect only DCV biology.

In summary, our analysis provides a general way to identify and classify new, less-well-described mutants with better understood ones. This procedure allowed us to identify and classify K02E10.1, F41H10.4, wdp-3, and syntaxin-6 mutants, which were not described before. Based on their predicted function, we showed these genes and others in the maturation clusters are involved in DCV membrane protein recycling. Several other significant clusters were not explored here and will likely provide insights into DCV biology.

Methods

Two independent strains with integrated [pgpy-32:ins-1(genomic)-VENUS::unc-54 2′UTR] transgenes were crossed with 187 mutants strains listed in Dataset S1. Detailed methods are provided in SI Appendix, including culture procedure, quantitative imaging, and statistical analysis.

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