COPI Activity Coupled with Fatty Acid Biosynthesis Is Required for Viral Replication

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Introduction

Viruses, because of their small genome size, are dependent on a multitude of cellular factors to replicate within their hosts. Not only do they have to co-opt cellular factors in order to complete their replication cycle, but also they must efficiently and simultaneously coordinate many steps of their replication cycle using host-encoded machinery. This can require complicated compartmentalization of various steps in their lifecycle. For example, single-strand RNA viruses must simultaneously coordinate transcription, RNA replication, and RNA packaging activities using the same genomic RNA template.

One example of subcellular separation of these activities is the observation that all positive-strand RNA viruses, a group that includes poliovirus, undergo RNA replication in association with membranes of infected cells [1]. Depending on the specific virus, these membranes can be derived from a variety of sources within the host cell, including the endoplasmic reticulum (ER), Golgi apparatus, mitochondria, chloroplasts, or from the endolysosomal compartment [2]. While the purpose of this compartmentalization has not been definitively established, several models have been discussed. One model suggests that this process provides a structural framework for replication, fixing the RNA replication machinery onto a confined two-dimensional space [3]. This compartmentalization of RNA replication may be important due to the fact that the viral RNA must be used for competing enzymatic activities: replication and transcription must both access templates using different machines. The separation of RNA templates into defined compartments may prevent interference between these processes. Another model postulates that the compartment may be generated by a cellular autophagic process. This may allow for the nonlytic release of virions [4], which in vivo could allow the virus to circumvent presentation by the immune system. Another possibility is that autophagy may play an antiviral role in clearing the cytoplasm of infectious virus. Therefore, the purpose of this targeted localization has yet to be understood.

Poliovirus, and picornaviridae in general (nonenveloped, positive-strand RNA viruses), do not use native organelle membranes for replication but instead actively induce the formation of a novel cytoplasmic vesicular compartment in infected cells [5,6]. During replication of these viruses, there is a massive rearrangement of intracellular membranes whereby the cytoplasm of the cell becomes densely packed with vesicles of nonuniform size [7]. Immunoelectron microscopy has revealed that the cytoplasmic surfaces of these vesicles are the sites of viral RNA replication and that a membrane compartment is essential for replication [8]. The mechanisms whereby these viruses induce this vesicular compartment and direct their RNA replication complex to the observation that all positive-strand RNA viruses, a group that includes poliovirus, undergo RNA replication in association with membranes of infected cells [1]. Depending on the specific virus, these membranes can be derived from a variety of sources within the host cell, including the endoplasmic reticulum (ER), Golgi apparatus, mitochondria, chloroplasts, or from the endolysosomal compartment [2]. While the purpose of this compartmentalization has not been definitively established, several models have been discussed. One model suggests that this process provides a structural framework for replication, fixing the RNA replication machinery onto a confined two-dimensional space [3]. This compartmentalization of RNA replication may be important due to the fact that the viral RNA must be used for competing enzymatic activities: replication and transcription must both access templates using different machines. The separation of RNA templates into defined compartments may prevent interference between these processes. Another model postulates that the compartment may be generated by a cellular autophagic process. This may allow for the nonlytic release of virions [4], which in vivo could allow the virus to circumvent presentation by the immune system. Another possibility is that autophagy may play an antiviral role in clearing the cytoplasm of infectious virus. Therefore, the purpose of this targeted localization has yet to be understood.

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Synopsis
In order to successfully invade and replicate within their hosts, viruses hijack cellular factors. In the case of many RNA viruses, including a Drosophila picorna-like virus Drosophila C virus, they must undergo the essential step of genomic replication on the surface of cytoplasmic membranes. Specifically, for picornaviruses, these vesicles are induced in the infected cell, and the ontology and cellular factors required to form this compartment have been unclear. Circumstantial evidence has implicated coat protein complex I (COPI), COPII, and autophagy. Here, Cherry and colleagues present their findings using a genome-wide RNA interference screening approach using a picorna-like virus that COPI and fatty acid biosynthesis are critical host pathways required to generate this intracellular vesicular compartment. Furthermore, they show that loss of COPI, but not COPII, is protective both in adult flies and in human cells infected with the related picornavirus, poliovirus. These novel and exciting findings have broad-scale implications for picornavirus replication and for the potential use of these pathways as novel antiviral targets.

Results
Gene Ontology Analysis Reveals Overrepresented Cellular Functions Necessary for Viral Replication

Genome-wide RNAi screening in Drosophila cells using high-throughput imaging identified 66 ribosomal proteins and 45 nonribosomal genes as required for DCV replication [20]. In our first study, we showed that knock-down of these ribosomal proteins blocked translation of IRES-containing viruses, including poliovirus, due to a requirement for higher levels of ribosomal function than for host messages, showing a unique sensitivity of this class of viruses to ribosome attenuation [20]. To identify roles for the remaining genes in viral replication, we analyzed Gene Ontology (GO) associations of the 45 nonribosomal genes required for DCV replication in Drosophila cells. This analysis showed that these genes fall into a small number of functional categories (Figure 1A). In addition, Table 1 lists the 45 genes, their effects on viral replication, GO category, and whether the double-strand RNA (dsRNA) amplicons identified have potential off-target effects as predicted by 21-base pair overlaps with other annotated genes. Based on the associations with Gene Ontology (GO) categories, some biological processes were significantly overrepresented. Specifically, statistical analysis revealed that vesicular trafficking processes were overrepresented while Drosophila-specific genes were underrepresented (30% of genome, 4% of set), suggesting that DCV selectively targets conserved features of the host cells, and not species-specific functions.

One notable group of genes within the vesicle trafficking category included five of the seven COPI coatamer proteins: alphaCOP, betaCOP, beta’COP, gammaCOP, and zetaCOP (Figure 1B, p < 0.001 for enrichment relative to representation in the genome, by Fisher exact test). To confirm that loss of COPI was responsible for the phenotype and to determine whether the two COPI genes (deltaCOP and epsilonCOP [CG9543]) not identified in the screen were erroneously missed (i.e., false negatives), we synthesized additional dsRNAs for the seven COPI coatamer genes and tested them for their role in DCV replication. These analyses revealed that dsRNAs against all COPI components except epsilonCOP blocked DCV replication, although some differences in the extent of the effect were observed, possibly reflecting variability in the efficiency of the gene silencing mediated by the dsRNAs (Figure 1B).

Thus, we can conclude that deltaCOP was a false negative in the primary screen. However, neither of the dsRNAs directed against epsilonCOP had an effect on DCV replication. RT-PCR analysis demonstrated that epsilonCOP mRNA was depleted, demonstrating that the dsRNA was functional (Figure S1).

These specific intracellular membranes, and the cellular components involved in this process, are not established. Previous studies have implicated a number of different trafficking processes including coat protein complex I (COPI), COPII, and autophagy-mediated processes, with the membrane being derived from the ER via a COPII coatamer-mediated process or the Golgi via either COPI or autophagic vesicles [4,9–12]. Studies investigating how picornas and related viruses induce the formation of cellular membranes have used small molecule inhibitors such as Brefeldin A, which have pleiotropic effects, or have used steady-state localization experiments that are complicated by the fact that markers from many different intracellular organelles can be found residing on virus-induced membranes, making it difficult to assign a specific role for specific cellular components in the ontogeny of the vesicles.

To overcome some of these limitations, we used a genome-wide loss-of-function analysis to identify factors required for the generation of this compartment and viral RNA replication. To accomplish this, we studied Drosophila C virus (DCV), a natural pathogen of Drosophila that readily infects the cells and animals [13]. DCV is a dicistrovirus that is in small molecule inhibitors such as Brefeldin A, which have pleiotropic effects, or have used steady-state localization experiments that are complicated by the fact that markers from many different intracellular organelles can be found residing on virus-induced membranes, making it difficult to assign a specific role for specific cellular components in the ontogeny of the vesicles.

Vesicles induced by picornavirus replication must undergo the essential step of genomic replication on the surface of cytoplasmic membranes. Specifically, for picornaviruses, these vesicles are induced in the infected cell, and the ontology and cellular factors required to form this compartment have been unclear. Circumstantial evidence has implicated coat protein complex I (COPI), COPII, and autophagy. Here, Cherry and colleagues present their findings using a genome-wide RNA interference screening approach using a picorna-like virus that COPI and fatty acid biosynthesis are critical host pathways required to generate this intracellular vesicular compartment. Furthermore, they show that loss of COPI, but not COPII, is protective both in adult flies and in human cells infected with the related picornavirus, poliovirus. These novel and exciting findings have broad-scale implications for picornavirus replication and for the potential use of these pathways as novel antiviral targets.
However, the protein may be long-lived—something we could not assess due to the absence of antibodies directed against either this or the other *Drosophila* COPI proteins. Nevertheless, these data suggest that it may have an unknown homolog which can substitute for its function. It should be noted that in yeast only six of the seven coatamer components are essential—only epsilonCOP is dispensible [21]. This suggests that epsilonCOP may be dispensable for COPI function in both yeast and *Drosophila*.

**COP1, but Not Secretion, Is Required for DCV Replication**

Two vesicular coat complexes, COPI and COPII, are required for trafficking between the ER and Golgi [22]. Formation of transport vesicles is dependent on the recruitment of these cytosolic coat proteins to the surface of the donor compartment membrane from which they bud. Whereas the COPII coatamer is required for the anterograde transport of proteins from the ER to the Golgi, the COPI coatamer is required for retrograde transport of recycled proteins and membrane from the Golgi to the ER [23]. Blocking either the COPI or the COPII coatamer pathways blocks protein secretion, as observed in yeast mutants for the orthologous genes and in studies using RNAi screening for genes required for general secretion [24]. However, we only identified COPI-associated genes and none of the COPII coatamer components (Sec13, Sec31, Sec23, and Sec24 [CG1472]) in our screen, suggesting that either the COPII coatamer proteins are refractory to RNAi-mediated depletion in our cells or DCV replication specifically requires COPI function but not COPII.
To rule out a role for COPII in DCV replication, we modified a microscopy-based assay to quantitatively monitor secretion of a plasma membrane reporter protein, Delta, to test whether the dsRNAs directed against COPII components were effective [25]. Using Drosophila cells that were stably transformed with an inducible membrane-bound form of Delta (DeltaNdeMyc cells [26]), we were able to assess the effects of different dsRNAs on the secretory pathway using flow cytometry. We pretreated cells with dsRNAs for 3 d and then induced the transgene with the addition of copper.
sulfate for 2 h. Cell surface levels of Delta were measured by staining unpermeabilized cells with an antibody that recognizes extracellular Delta. Using this assay on control cells, we detected a large increase in surface Delta expression as compared to uninduced cells (Figure 2A, compare green and purple). Treatment of the cells with dsRNA against COPI (betaCOP) or COPII (sec23) components significantly decreased the extracellular levels of Delta as expected (Figure 2A). While dsRNA treatment against sec23 did not block secretion as much as knockdown of betaCOP, treatment with dsRNA against Syntaxin 5 (Syx5), a t-SNARE required at the Golgi for secretion [27], was able to block secretion to a similar extent as COPI. Despite this, treatment with dsRNA against sec23 or Syx5 had no effect on viral replication (unpublished data). These data suggest that DCV replication does not require a functional secretory pathway per se but instead specifically requires COPI (but not COPII) coatamer function.

COPI Is Required Downstream of Entry

We next sought to determine which step in the viral lifecycle requires COPI function, and so we first determined whether depletion of COPI by dsRNA treatment affected DCV entry in tissue culture cells. We had previously determined that viral entry requires clathrin-mediated endocytosis and thus did not anticipate a requirement for COPI during entry. Nevertheless, we tested whether pretreatment with dsRNAs against control (GFP [green fluorescent protein]), COPI (betaCOP), or COPII (sec23) affected viral entry. To do this, the cells were pretreated with dsRNAs for 3 d and, then incubated at 4 °C to block endocytosis. Next, virions were added at a multiplicity of infection of 10 and allowed to bind to the surface of these dsRNA-treated cells. After 1 h of binding, the cells were washed to remove unbound virions and then returned to 25 °C to allow endocytosis to resume. After 3 h, the cells were immunostained to visualize virions during entry through the endocytic compartment. Using this assay, and quantitation with automated image analysis, we found that depletion of COPI (or COPII) did not block viral entry (Figure 2B).

To verify that this assay is sensitive to genes required for DCV entry, we tested the effect of Rab5, another cellular factor identified in our screen. Rab5 encodes a small GTPase required for endocytosis, and as such should be required for DCV uptake [28]. Indeed, we found that treatment with Rab5 dsRNA resulted in a 4-fold decrease in viral entry (Figure 2B). We did not identify other genes involved in clathrin-mediated endocytosis in this screen, suggesting that genes such as clathrin may be difficult to deplete in the Drosophila cell lines used. However, our RNAi screen was able to uncover a component of the endocytic apparatus required for viral entry (Rab5) and further underscores the role for COPI as required for a step in the viral lifecycle postentry.

DCV Induces a Cytoplasmic Vesicular Compartment that Is the Site of RNA Replication

All positive-strand RNA viruses undergo RNA replication on the surface of intracellular membranes [1]. Picornaviruses, which are similar in many respects to DCV, induce the formation of cytoplasmic vesicles of nonuniform size; and it is on the surface of these vesicles that viral RNA replication occurs [5–7]. We used ultrastructural analysis to test whether DCV might induce a similar vesicular compartment and found that, indeed, vesicles were induced in the cytoplasm of infected cells but not in the uninfected control cells (compare Figure 3A to Figure 3B). While the vesicles were nonuniform in size, they averaged 115 nm in diameter.

We next determined whether DCV uses these vesicles as a site for RNA replication. To this end, we generated an antibody against the DCV helicase, an integral component of the RNA replication machinery. We stained cells that were either uninfected or infected with DCV with the anti-helicase antibody and monitored localization using immunoelectron microscopy. We found that the DCV helicase was localized to the surface of these vesicles and did not stain the uninfected cells (Figure 3F–3G and unpublished data). Greater than 90% of the gold labeling was vesicle associated, demonstrating that the RNA replication machinery is indeed compartment bound. Importantly, the vesicles were detectable by 10 h postinfection but not at an earlier time point (unpublished data), consistent with our previous findings that new viral protein synthesis begins at approximately 7 h postinfection [13]. Because these viruses do not encapsidate the RNA polymerase, RNA replication cannot begin until the genomic RNA is translated to produce the viral factors required for RNA replication including the helicase. Altogether, our data demonstrate that the vesicles form postentry and posttranscription and are the site of RNA replication.

Vesicle Formation Is COPI Dependent

Because DCV induces a cytoplasmic vesicular compartment and requires the COPI coatamer for replication, we tested whether depletion of COPI by dsRNA affected DCV-dependent vesicles by treating cells with dsRNAs against COPI (betaCOP), COPII (sec23), or a control (GFP) followed by DCV infection. At 10 h postinfection, both control cells (Figure 3B) and COPII-treated cells (sec23, Figure 3D) were densely packed with the newly formed vesicles, despite the fact that dsRNA against sec23 reduced transport of Delta to the cell surface. Randomly selected cells were quantitated in terms of the presence or absence of the characteristic cytoplasmic vesicles; 87% of control cells and 83% of sec23-depleted cells were filled with the vesicles. In contrast, the COPI-depleted cells had a 2.5-fold reduction in the percentage of cells that contained vesicles (34%, Figure 3C), suggesting that the COPI coatamer is required to generate this vesicular compartment during DCV replication.

DCV Replication Disrupts the Golgi Apparatus

Since the COPI coatamer normally buds vesicles from the Golgi apparatus [22,29], we reasoned that the virus-induced vesicular compartment might be generated by COPI-mediated budding of vesicles from the Golgi during DCV replication. Although the COPI machinery required for trafficking is conserved between yeast, mammals, and insects, there are striking differences in the morphologies of the Golgi apparatus. In Drosophila, the Golgi cisternae are not interconnected to form a single copy organelle that is typically juxtanuclear. Instead, the vesicles are stacked and dispersed throughout the cytoplasm, as is the case in plants and yeast [30, 31]. We tested whether the morphology of the
Figure 2. COPI Is Specifically Required for DCV Replication Postentry

(A) FACS analysis demonstrates that COPI (betaCOP) and COPII (sec23) are required for Delta secretion. DeltaWTNdeMYC cells were treated with dsRNA and subsequently Delta expression was induced for 2 h. Extracellular Delta expression was monitored by FACS. The bar was set such that 98% of the total uninduced cells were negative for Delta staining. Induction leads to a shift in the population to express surface Delta, such that only 31% of the cells remain negative. Under these conditions, COPI, COPII, and SREBP block surface staining.

(B) DCV entry requires endocytosis (Rab5) but not COPI (betaCOP) or COPII (sec23) function. Cells were pretreated with dsRNA, infected at 4°C to allow surface binding, followed by 3 h at 25°C to allow endocytosis, and monitored viral trafficking. Viral uptake was measured by determining the percentage of cells (red) that contained virus (green). Green, anti-DCV; red, Alexa-fluor-568-phalloidin.

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Golgi was altered during DCV replication by infecting Drosophila cells with DCV and monitoring the structure of the Golgi using an antibody to a membrane-bound Golgi resident protein. Using confocal microscopy, we found, as has been observed by others, that the Golgi has a punctate morphology in uninfected Drosophila cells [30,32] (Figure 4A, uninfected cells). In contrast, the morphology of the Golgi was altered in the infected cells. The punctae seemed smaller and increased in number throughout the cytoplasm of the cell (Figure 4A, infected cells). This disruption resembles the large number of dispersed vesicles observed by electron microscopy. These observations were made using two different antibodies against the Golgi (anti-Golgi and DG13). Moreover, we co-stained infected cells with antibodies to DCV helicase and a Golgi marker (DG13) using immunoelectron microscopy. We found that the DCV-induced vesicles that are coated by the viral helicase (5-nm gold particles) are also positive for the Golgi marker (12 nm) (Figure 3H). This demonstrates that these vesicles are indeed derived from the Golgi apparatus.

Because Golgi morphology was disrupted by DCV during replication, and depletion of the COPI coatamer blocked DCV replication; we reasoned that the Golgi morphology of COPI-depleted cells might be altered. Indeed, treatment of cells with dsRNA to COPI (betaCOP) led to a decrease in Golgi staining (Figure 4B), which was distinct from the change in Golgi morphology observed upon infection (compare the signal levels in uninfected cells in Figure 4A and 4B). The absolute levels of Golgi markers were decreased in COPI-treated cells, whereas the signal was dispersed in DCV-infected cells as observed by confocal microscopy. In contrast, treatment with dsRNA to a ribosomal protein, RpS6, which blocks DCV translation, and thus replication at a different step in the lifecycle, had no effect on Golgi morphology (unpublished data). Moreover, depletion of Sys5 (t-SNARE) or COPII (sec23) led to a loss in Golgi staining but had no effect on viral replication (Figure 4C and 4D). This demonstrates that loss of Golgi per se is not sufficient to block viral replication. Instead, the specific loss of COPI results in a loss of the Golgi, a defect in vesicle formation, and a block in viral replication. Together, this suggests that the vesicular compartment is formed by COPI coatamer-mediated disassembly from the Golgi during infection and that the Golgi disruption mediated by the loss of COPII does not block COPI access to the appropriate target for vesicle formation.

Fatty Acid Biosynthesis Is Required to Generate This Vesicular Compartment

The apparent requirement for the generation of a COPI-dependent vesicular compartment for DCV replication led us to investigate the role of fatty acid biosynthesis in the formation of this compartment. Fatty acid biosynthesis is essential for the generation of membrane lipids, which are required for the formation of vesicle membranes. We found that depletion of the fatty acid biosynthesis pathway using dsRNA to the sterol regulatory element-binding protein (SREBP) or the COPII coatamer (sec23) led to a decrease in Golgi staining (Figure 4C and 4D). This demonstrates that the formation of the vesicular compartment is dependent on fatty acid biosynthesis.
to hypothesize that there might be additional genes identified in our genome-wide RNAi screen that might also be required to generate this vesicular compartment. Therefore, we tested whether any of the other genes had a phenotypic effect on the morphology of the Golgi, and thus might be required for the generation of the vesicular compartment. We screened the 45 genes and found that while the majority had no effect on the Golgi as monitored by immunofluorescence microscopy, two additional genes led to a loss in Golgi staining similar to that seen on treatment with dsRNAs against the COPI coatamer components. Both of these (HLH106 and CG3523) encode factors required for fatty acid biosynthesis (Figure 4F and unpublished data).

HLH106, also known as sterol regulatory element binding protein (SREBP), is the master transcriptional regulator of fatty acid metabolism, and directly controls the transcription of CG3523 which encodes fatty acid synthase, the first rate-limiting enzymatic step in the pathway [33]. These results indicate that fatty acid biosynthesis is required both for DCV replication and for maintenance of the Golgi compartment. Additionally, we found that depletion of these factors had no effect on viral entry (unpublished data). Instead, depletion of these factors blocked the formation of the virus-induced vesicular compartment as measured by electron microscopy (Figure 3, unpublished data).

Our finding that fatty acid biosynthesis was required for the formation of this compartment is consistent with the observation that infected cells have a net increase in membrane due to the large number of cytoplasmic vesicles (2-fold increase in total membrane). Our results are also supported by the observation that cerulenin, a fatty acid synthase inhibitor, blocks positive-strand RNA virus (including poliovirus) replication in tissue culture [34]. While SREBP in mammals is cholesterol responsive and as such regulates both fatty acid metabolism and cholesterol biosynthesis, in insects SREBP responds to palmitate levels (Drosophila is a cholesterol auxotroph [35]). Nevertheless, Drosophila SREBP controls many of the same regulators of fatty acid biosynthesis, suggesting conserved functions in viral replication.

SREBP, COPI, and Fatty Acid Biosynthesis Are Limiting for Viral Replication in Animals

To test the dependence of DCV infection on host fatty acid biosynthesis in vivo, we infected Drosophila SREBP mutants with DCV. SREBP-null adults were generated by rescuing the larval lethality of the mutation with an RU486-inducible wild-type SREBP transgene that is expressed exclusively during larval development [36]. Withdrawal of RU486 results in adults that do not express the rescue construct and as such are null for SREBP as measured by Western blot analysis (Figure 5A). Therefore, SREBP is dispensable in adult flies. We challenged these mutants or their heterozygous siblings with DCV and monitored viral replication using two methods. First, we used immunoblot analysis to monitor viral capsid production as a function of time postinfection. Consistent with the cell-based results, SREBP mutant flies had reduced levels of viral antigen production as compared to heterozygous matched siblings normalized to cellular tubulin levels (Figure 5B). Second, we monitored viral RNA production by RT-PCR and found that loss of SREBP severely attenuated viral replication (Figure 5C). This demonstrates that the transcriptional master regulator of fatty acid biosynthesis, SREBP, is required and limiting for viral replication in animals.

We also found that there was a synthetic interaction between fatty acid biosynthesis and COPI activity in vivo.
While heterozygous mutants of gammaCOP or fatty acid synthase (CG3523) were unaffected in their ability to support DCV replication, flies carrying mutant alleles for both gammaCOP and fatty acid synthase were attenuated in their ability to support DCV replication as measured by viral antigen production (Figure S2). Therefore, the pathways that were limiting in vitro for viral replication were also limiting in animals.

Poliovirus Infection Is Also Sensitive to Depletion of COPI but Not COPII

Because attenuation of COPI, but not COPII, blocked DCV replication, we hypothesized that this effect may be generalizable to mammalian picornaviruses such as poliovirus. To test whether attenuation of these pathways protected human cells from poliovirus replication, we infected human cells pretreated with small interfering RNAs (siRNAs) against control, alphaCOP or sec23B with poliovirus. We assayed infection by immunofluorescence staining of infected cells using an antibody against VP1, a capsid protein (Figure 6A). We quantitated these images and observed a significant reduction of viral infection in cells transfected with siRNAs against alphaCOP as compared to control siRNA or siRNA against sec23B (Figure 6B). To confirm that the siRNA against sec23B was functional, we measured the levels of sec23B and alphaCOP by RT-PCR. We found that treatment with either sec23B or alphaCOP siRNA led to a depletion of the cognate mRNA, demonstrating that sec23B is depleted yet dispensable for poliovirus replication in human cells (Figure 6C). Therefore, these data suggest that poliovirus replication in human cells, like DCV replication in Drosophila cells, requires COPI, while COPII activity is dispensable.

Discussion

In this work, we have shown the dependence of DCV replication on an array of host-encoded factors. Using an unbiased loss-of-function screen, we identified a number of factors involved in different stages of the viral lifecycle. Moreover, because this RNAi methodology does not result in null alleles, but instead in hypomorphic phenotypes, we were able to identify the limiting components for viral replication in the cell. Interestingly, these host factors are significantly biased toward conserved genes as opposed to species-specific factors, demonstrating that DCV specifically, and perhaps viruses more generally, may selectively target conserved functions in the cell. This may help explain how some viruses can readily infect disparate hosts (mosquitoes, humans, etc.) and parsimoniously expand their range to new species. Moreover, because these required, but limiting, genes are essential for DCV replication in Drosophila cells, one may presume that related viruses may be dependent on similar cellular factors for replication. Indeed, we confirmed that poliovirus replication in mammalian cells is also dependent on COPI.

We found that DCV, like picornaviruses, induces the formation of a cytoplasmic vesicular compartment in
infected cells and that this compartment is the site of viral RNA replication. Among the conserved genes whose disruption significantly reduced DCV replication were a group of vesicular trafficking genes including the COPI coatamer. Our data show that COPI was required downstream of viral entry and was essential for the production of this vesicular compartment. However, we cannot rule out the possibility that COPI is required postentry, prevesicle formation for a step in the viral lifecycle independent of its role in secretion. In contrast, our data clearly show that both COPII and autophagy were dispensable for both viral replication and vesicle formation. For autophagy, we directly tested the roles of Beclin-1, Atg5, Atg18, and Atg12 and found no defect in DCV replication (unpublished data). This is important because there has been much debate on the ontogeny of vesicles that arise during picornavirus replication. This is due, at least in part, to the experimental approaches used to determine the factors involved. For example, it is difficult to discern cause from effect in studies utilizing marker co-localization strategies, as many different cellular factors and compartments may be associated with the vesicles. By undertaking a loss-of-function study, we were able to identify specific factors required to form the vesicular compartment, rather than simply identifying factors found associated with the membranous compartment under steady state conditions. While it is possible that some of the vesicles associated with viral replication are generated via a COPII or an autophagic process, our data clearly demonstrate that these latter processes are not essential for bulk vesicle formation or for viral replication.

Because the COPI coatamer normally targets and buds from the Golgi and DCV-induced vesicles required COPI activity, we analyzed the state of the Golgi during infection. We found that normal Golgi morphology was disrupted during viral replication with many small punctae distributed throughout the cytoplasm of the cell, consistent with the disassembly of

Figure 6. Attenuation of COPI but Not COPII Protects Human Cells from Poliovirus Infection
(A) Poliovirus infection of Caco-2 cells pretransfected with siRNAs against alphaCOP results in inhibition of viral replication but not control siRNA or siRNA against sec23B as measured by immunofluorescence analysis of infected cells (nuclei [blue] = DAPI, infected cells [green] = FITC-conjugated mouse anti-enterovirus VP1).
(B) Percent infection (FITC-positive cells/DAPI * 100) is shown for two independent experiments performed in triplicate where error bars represent one standard deviation. *p < 0.05.
(C) Plaque-forming units/mL (pfu/mL) are shown for the experiments performed in (B). *p < 0.05.
(D) RT-PCR on Caco-2 cells treated with siRNA against alphaCOP or sec23B demonstrates that treatment with either siRNA leads to a significant depletion of the cellular mRNA and amplification of GAPDH was used as loading control.
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the Golgi by the COPI coatamer and the formation of the vesicles used for RNA replication. We also demonstrated that a Golgi marker co-localizes with the RNA replication machinery at the DCV-induced vesicles. At present, we cannot determine if this compartment is formed directly by the conversion of the Golgi into a novel specific structure or whether membrane is derived from other cellular structures. This is in part because an intact Golgi was not required for vesicle formation, suggesting that the COPI coatamer targets a specific membrane component that remains accessible even if the Golgi is apparently disrupted by the loss of cellular factors including COPII or Sar5. This raises the possibility that DCV may derive membranes from other structures that are targets for COPI-dependent vesicle formation or that DCV may in some way redirect COPI to other sites. Possible explanations for the source of COPI-mediated membrane recruitment include the ER-intermediate compartment, as COPI has also been localized to this area, or the possible anterograde transport activity of the COPI coatamer. DCV, which is clearly dependent on COPI for the generation of its virogenic organelle and must in some way interdict normal COPI trafficking pathways, may prove to be a useful tool for dissecting COPI functions and the complex relationships between COPI, the Golgi, and the generation of vesicular structures upon which viral replication occurs.

Under normal circumstances, in order to drive the formation of COPI vesicles, the COPI coatamer complex is bound by the small GTPase ADP-ribosylation factor 1 (Arf1). These coatamer-GDP bound Arf1 complexes are activated by guanine nucleotide exchange factors to induce vesicle formation (reviewed in [37]). Our screen and additional factors required for viral replication. This may be due to some functional redundancy between Arfs. Recent work on poliovirus demonstrated that a number of different Arfs were recruited to the poliovirus replication complexes [12]. Moreover, in a screen for factors involved in general secretion in Drosophila cells, two Arfs were essential [38]. Together, this may point to functional redundancy of Arfs under certain conditions in a variety of systems.

Once we identified the COPI complex as necessary for vesicle formation and Golgi maintenance, we reexamined the additional factors identified during the initial screen and found that suppression of fatty acid metabolism (SREBP and CG3523) decreased viral replication in vitro and in vivo and also prevented the formation of the vesicular compartment. Thus, we were able to assign a functional role for fatty acid metabolism in viral replication. This is perhaps not surprising since morphometric analysis of membrane profiles in DCV-infected cells indicated that there was a 2-fold increase in membrane surface area within 10 h of infection. Thus, virus infection leads to membrane redistribution involving both the Golgi and COPI as well as membrane expansion through de novo lipid biogenesis. Because the size of the virally induced vesicles (mean = 115 nm) was significantly larger than that of normal COPI vesicles (mean = 50 nm), they may be formed in part by active membrane biosynthesis at the budding site. Nevertheless, this coupling of fatty acid biosynthesis with COPI coatamer budding from the Golgi results in Golgi disassembly and the formation of a novel cytoplasmic vesicular compartment upon which viral RNA replication takes place.

More generally, it is not clear why it would be beneficial for a virus to generate a new membranous structure rather than use preexisting membranes for replication. Indeed, some viruses (e.g., flock house virus) use preexisting membranes for RNA replication instead of generating new structures [39]. Moreover, how viruses such as DCV coordinate and activate these cellular processes has yet to be shown, making this Drosophila-DCV system an ideal model both to identify cellular factors required for viral replication and to study how virus-dependent cellular structures and organelles are generated de novo from preexisting components within a cell.

Importantly, the work presented herein confirms the relevance of the cell culture model used to perform the initial RNAi screen by demonstrating a requirement in vivo for the machinery which produces the virogenic organelle. Moreover, we found that both COPI and fatty acid biosynthetic machinery were essential for viral replication in adult animals. This additional evidence supports the generality of the findings and is the first demonstration of the importance of the virus-induced membranous organelle for infection of the native host of a virus of this class. In addition, we extended our finding to the related picornavirus, poliovirus. Using a similar loss-of-function strategy in human cells, we found that, like DCV infection of Drosophila cells, poliovirus infection of human cells required COPI while COPII appeared dispensable. Therefore, our screen for host factors in this Drosophila model system provides insight into cellular genes required for viral replication in higher organisms.

More work will be necessary to identify the mechanistic aspects of vesicle formation and viral functions dependent thereon. Nevertheless, our results form a basis for investigation of virus–host interactions, the limiting cellular components required for the viral lifecycle, and potential antiviral targets in a system that is amenable to both forward and reverse genetic analysis and thus is uniquely suited to rapid and comprehensive dissection.

Materials and Methods

Cells, antibodies, and reagents. SL2 cells, DL2 cells, and DeltaWT-deMYC cells were grown and maintained as described previously [13,26], as were the production and purification of DCV [13]. Amplicons were obtained from the following sources: anti-DCV [13], anti-Golgi (Calbiochem, San Diego, California, United States), DG13 (anti-Golgi, gift of Vivek Malhotra, University of California San Diego), anti-Delta (C594.9B, Iowa Hybridoma Bank, University of Iowa, Iowa City, Iowa, United States), anti-tubulin (Sigma, St. Louis, Missouri, United States), and anti-dSREBP (IgG 3B, prepared as described [35]). Polyclonal anti-DCV helicase antibodies were generated in rabbits against a peptide corresponding to residues 483–498 of the replicase polyprotein within the helicase domain. Fluorescently labeled secondary antibodies against chicken were obtained from Jackson ImmunoResearch (West Grove, Pennsylvania, United States), and additional antibodies were from Molecular Probes (Eugene, Oregon, United States). Additional chemicals were obtained from Sigma.

RNAi. dsRNAs for RNAi were generated and used for RNAi for 5 d as described [28]. Amplicons used were generated by the DRSC and are described at http://hrnai.org.

Secretion assay. DeltaWT-deMYC cells were treated with dsRNA and pulsed with 0.5 mM CuSO4 for 2 h. All subsequent steps were performed at 4 °C. The cells were washed in FACS buffer (2% fetal calf serum, azide, PBS) and stained with anti-Delta (1:200) for 45 min. The cells were washed and stained with Alexa-488 anti-mouse for 45 min. Cells were analyzed on a FACScan flow cytometer with Cell Quest software (Becton-Dickinson, Palo Alto, California, United States), live cells were gated using forward scatter and side scatter, and propidium iodide was used to exclude dead cells.
Viral entry, infection, and immunofluorescence. Entry experiments were performed as described [13]. Cells were pretreated with dsRNA and placed at 4 °C. Virions were added (multiplicity of infection = 10) and incubated for 2 h. The cells were washed and incubated at room temperature for 3 h. Cells were then stained with anti-DCV as described and counterstained with Alexa-594 phalloidin (Invitrogen, Carlsbad, California, United States). For other experiments, cells were infected and stained as previously described [20]. Cells were imaged using automated microscopy [20] or confocal microscopy (Leica TCS SP2 AOBS) as indicated, and percent infection was measured. Image quantitation was performed using MetaMorph software (Molecular Devices, Sunnyvale, California, United States).

Electron microscopy. Cells were fixed on the dish in 2% PFA/2.5% glutaraldehyde in 0.1 M sodium cacodylate buffer (pH 7.4) for 1 h at RT, postfixed in 1% osmium tetroxide/1.5% potassium ferrocyanide in water, and stained in 1% uranyl acetate in cacodylate buffer (pH 5.2) for 30 min at RT. After dehydration in a graded ethanol series, cells were removed from the dish in propyleneoxide and pelleted at 3,000 rpm for 3 min. Pellets were embedded in Epon. Ultrathin sections (approximately 80 to 90 nm) were mounted on copper grids, stained with 2% uranyl acetate in acetate followed by 0.7% lead citrate, and examined in a JEOl 1200EX transmission electron microscope, and images were recorded at a primary magnification of x9,700.

For preparation of cryosections, cells were fixed in 4% paraformaldehyde in 0.1 M sodium phosphate buffer (pH 7.4) in a microfuge tube and pelleted for 3 min at 3,000 rpm. The supernatant was carefully removed, and fresh 4% paraformaldehyde was added. After 2-h fixation at room temperature, the cell pellets were washed with PBS containing 0.2 M glycine. Cells pellets were infiltrated with 2.3 M sucrose in PBS for 15 min and frozen in liquid nitrogen. Frozen samples were sectioned at −120 °C, transferred to formvar-carbon-coated copper grids, and floated on PBS. Gold labeling was carried out at room temperature on a piece of parafilm. All antibodies and Protein A-gold were diluted 1% BSA. Grids were floated on drops of 1% BSA for 10 min, transferred to 3× drops of primary antibody, and incubated for 30 min. The grids were then washed in PBS for a total of 15 min and transferred to drops of Protein A-gold or gold-labeled secondary antibody. Embedding of the labeled grids was carried out on ice in 0.5% uranyl acetate in 2% methyl cellulose. The grids were examined in a JEOl 1200EX transmission electron microscope, and images were recorded at a primary magnification of x25,000 [40].

The total amount of membrane per cell was calculated by measuring the linear amount of membrane of similar sized sections of cells using MetaMorph software for uninfected (n = 6) and infected (n = 6) cells.

Fly stocks and viral infections. All flies were obtained from the Bloomington stock center unless stated otherwise and were maintained on standard medium at 24 °C. RU486-inducible Gal4 (S106) was used to rescue the larval lethality of the SREBP-null allele (189) by feeding larvae 200 μM RU486 which induced the expression of the UAS-SREBP rescue construct as described [36]. Following eclosion, adults were maintained on standard medium. The 4- to 5-d-old adults of the stated genotypes were inoculated with DCV as previously described [13].

Immunoblotting and RT-PCR. Flies were collected at the time points indicated. The flies were lysed in radioimmunoprecipitation buffer supplemented with a protease inhibitor cocktail (Boehringer-Ingelheim, Ingelheim, Germany). Samples were separated by 10% SDS-PAGE and blotted as previously described [13]. For RT-PCR, flies were homogenized in total RNA was extracted using TRIzol (Invitrogen) according to the manufacturer. cDNA was prepared using AMV reverse transcriptase (Invitrogen) and the virus-specific primer DCV2 according to the manufacturer’s protocol (Qiagen, Valencia, California, United States). For other experiments, cells were incubated with PV at a multiplicity of 1 PFU/cell in virus binding buffer (DMEM supplemented with 1 mM HEPS for 1 h at 4 °C). Following washing, virus infection was initiated by shifting cells to 37 °C in tissue culture medium for 7 h. Cells were fixed and permeabilized before staining with ice-cold methanolacetone (3:1) for 10 min at room temperature. Cells were incubated with FITC-conjugated mouse anti-enteroivirus VP1 (Ncl-Enterov; Novocastra Laboratories, Newcastle upon Tyne, United Kingdom) for 1 h, washed, and mounted with Vectashield (Vector Laboratories, Burlingame, California, United States) containing DAPI. Images were captured with a confocal laser-scanning microscope (Leica, Exton, Pennsylvania, United States). Plaque-forming assays were performed in HeLa cells as described [42].

Statistical analysis. Statistical analyses for Figure 1 were performed using the Fisher exact test for small samples; the χ² test was used in situations where all counts are above five. Student’s t-test was performed on the data from Figure 6.

Supporting Information

Figure S1. RNAi against epsilonCOP and sec27 Leads to Depletion of mRNA
RT-PCR of cells treated with the indicated dsRNA. Total RNA was purified 3 d post treatment, used as a template for cDNA, and amplified using primers specific for the indicated genes. The amount of input cDNA was varied to assess the linearity of the PCR conditions.

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Figure S2. DCV Replication Requires High Levels of COPI and Fatty Acid Synthase in Adults

The flies carrying a mutant allele of gammaCOP (gammaCOP [S057302a]) and fatty acid synthase AU: Make CG3523 italic? If so, also gammaCOP(GG3525 [Df(2L)S17]) are resistant to viral infection as measured by viral antigen production post infection. Flies heterozygous for each mutant or the compound mutants were challenged with DCV, and viral antigen production was measured by Western blot 24 h post infection. Protein lysates were generated and probed with anti-DCV or anti-tubulin for normalization.

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Author contributions. SC conceived, designed, and analyzed the experiments and wrote the manuscript. SC and HW performed the experiments. AK and RBR contributed reagents and data for Figure 5. CC generated the data for Figure 6. NP contributed to experimental design and the drafting of the manuscript.

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References
