HDAC6 Is a Bruchpilot Deacetylase that Facilitates Neurotransmitter Release

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SUMMARY

Presynaptic densities are specialized structures involved in synaptic vesicle tethering and neurotransmission; however, the mechanisms regulating their function remain understudied. In Drosophila, Bruchpilot is a major constituent of the presynaptic density that tethers vesicles. Here, we show that HDAC6 is necessary and sufficient for deacetylation of Bruchpilot. HDAC6 expression is also controlled by TDP-43, an RNA-binding protein deregulated in amyotrophic lateral sclerosis (ALS). Animals expressing TDP-43 harboring pathogenic mutations show increased HDAC6 expression, decreased Bruchpilot acetylation, larger vesicle-tethering sites, and increased neurotransmission, defects similar to those seen upon expression of HDAC6 and opposite to hdac6 null mutants. Consequently, reduced levels of HDAC6 or increased levels of ELP3, a Bruchpilot acetyltransferase, rescue the presynaptic density defects in TDP-43-expressing flies as well as the decreased adult locomotion. Our work identifies HDAC6 as a Bruchpilot deacetylase and indicates that regulating acetylation of a presynaptic release-site protein is critical for maintaining normal neurotransmission.

INTRODUCTION

Synaptic vesicles fuse with the plasma membrane at presynaptic release sites. While SNAREs (soluble NSF attachment receptors) are essential for fusion, the neurotransmitter release process is modulated by numerous additional mechanisms. The presynaptic dense body is an evolutionary conserved structure that is involved in capturing and concentrating synaptic vesicles at release sites (Hallermann et al., 2010a; Mukherjee et al., 2010). In fruit flies, a major constituent of this structure is the cytoskeletal-like protein Bruchpilot (BRP) (Wagh et al., 2006). Although the presynaptic dense body and BRP are critical to maintain normal levels of synaptic transmission, the mechanisms that regulate the function of this structure remain largely unknown.

The BRP protein organizes in parallel strands with their N termini facing the plasma membrane while sending their C termini into cytoplasm to contact and tether synaptic vesicles (Fouquet et al., 2009). BRP is acetylated by the synaptic acetyl transferase (HAT) ELP3 (Miskiewicz et al., 2011), and lysine acetylation is believed to neutralize positive charges at the BRP C-terminal end, thus regulating dense body (T-bar) morphology and function. If acetylation is a regulatory mechanism to modify BRP, it should be reversible; however, the BRP deacetylase is not known.

Here, we report that the cytoplasmic deacetylase HDAC6 is necessary and sufficient for BRP deacetylation. Deacetylation of BRP in animals that overexpress HDAC6 results in larger T-bars that contact more synaptic vesicles resulting in a larger readily releasable vesicle pool, while hdac6 null mutants show the opposite phenotype. Interestingly, HDAC6 is a target of the RNA-binding protein TDP-43 that is mutated in amyotrophic lateral sclerosis (ALS), and both the loss and gain of TDP-43 function phenocopy the loss and gain of HDAC6, respectively. Providing further functional relevance, genetically upregulating BRP acetylation by downregulating HDAC6 or upregulating ELP3 in TDP-43-expressing flies can rescue the synaptic and locomotion defects observed in these animals. Hence, our work in fruit flies suggests that BRP acetylation is under the control of two intersecting pathways: ELP3-dependent acetylation and HDAC6-dependent deacetylation.

RESULTS

HDAC6 Promotes the Formation of Larger T-Bars with More Tethered Synaptic Vesicles

HDAC6 is a cytoplasmic deacetylase expressed in neurons (Fukada et al., 2012). To explore synaptic defects associated
with altered levels of HDAC6, we used hdac6<sup>ko</sup> null mutants and overexpression of hdac6 (Figure S1A) and assessed presynaptic morphology at the Drosophila larval neuromuscular junction using transmission electron microscopy (TEM). We find that many synaptiﬁc features, including the number of T-bars, synaptic vesicles, or mitochondria per boutonic area, are not different from controls (Figures S1B–S1H), indicating proper delivery of these components to synaptic boutons. However, using serial-section electron microscopy, in hdac6<sup>ko</sup> mutants, BRP C rings are smaller compared to controls (Figures 1A–1E). Hence, HDAC6 regulates BRPC immunoreactivity levels, likely as a result of differences in antibody accessibility; in actGAL4/+ mutants, BRP C rings are smaller compared to controls (Figures 1F, 1G, and 1J). These changes at the T-bar top also result in altered BRPC ring strands in T-bars is not disrupted. Taken together, the data indicate HDAC6 promotes the reorganization of the BRP C terminus to form larger T-bar tops.

Presynaptic T-bars coordinate neurotransmission by facilitating vesicle tethering (Hallermann et al., 2010a). We therefore quantiﬁed the number of T-bar-tethered vesicles. Animals that overexpress HDAC6 show an increased number of tethered vesicles, while hdac6<sup>ko</sup> mutants harbor less tethered synaptic vesicles compared to controls (Figure 1P). Hence, in contrast to hdac6 loss of function, the overexpression of HDAC6 causes T-bar tops to expand, enabling them to contact more synaptic vesicles.

**HDAC6 Results in a Larger Readily Releasable Vesicle Pool**

To assess if changes in T-bar morphology and the number of tethered vesicles correlate with defects in neuronal function, we resorted to electrophysiology. First, we recorded neurotransmission in hemolymph-like physiological solution (HL-3) with 0.45 mM CaCl<sub>2</sub> to reveal exocytic defects. At low-frequency stimulation, the excitatory junctional current (EJC) amplitude in hdac6<sup>ko</sup> mutants is marginally smaller. Conversely, EJC amplitudes are significantly increased when HDAC6 is overexpressed (Figure 2A). Given that the mean miniature EJC amplitude is not signiﬁcantly affected (Figure 2B), the quantal content upon overexpression of HDAC6 is increased (Figure 2C). To find a functional correlate for the alterations in T-bar-tethered vesicles, we next assessed the size of the pool of synaptic vesicles that can be released during a very short bout of intense stimulation (1 s, 60 Hz). We performed this experiment in 5 mM CaCl<sub>2</sub>,...
ensuring an invariable high release probability. During the first stimulations, this protocol results in the fusion of ready-to-release vesicles (Hallermann et al., 2010b). Back extrapolation of the cumulative quantal content indicates that in hdac6 mutants 20% (p = 0.05), less vesicles were ready for release than in controls, while in animals overexpressing HDAC6, the size of this vesicle pool is 41% (p < 0.01) increased compared to controls (Figures 2D–2G). To independently measure vesicle fusion during high-frequency stimulation, we resorted to synapto-pHluorin (SpH) (Miesenböck et al., 1998). SpH is a pH-sensitive vesicle-associated probe that increases in fluorescence when exposed to the extracellular environment. The SpH signal upon stimulation of motor neurons at 60 Hz (50 stimuli) increases dramatically. However, in hdac6 mutants, this increase is trumped in comparison to control, while overexpression of HDAC6 results in a larger peak fluorescence level (Figures 2H–2J). Taken together, the morphological and functional data indicate HDAC6 is a positive regulator of a larger ready-to-release pool of synaptic vesicles.

HDAC6 Is Necessary and Sufficient to Deacetylate BRP

Reduced BRP acetylation levels at fly neuromuscular junctions (NMJs) result in T-bars with larger top sizes and increased neurotransmitter release (Miśkiewicz et al., 2011), phenotypes very reminiscent of those we observe in animals overexpressing HDAC6. We therefore tested the hypothesis that HDAC6 mediates BRP deacetylation in vivo. We immunoprecipitated BRP from heads of controls, hdac6ko flies, and flies overexpressing HDAC6 and probed western blots with antibodies recognizing acetylated lysines (ac-K). Compared to controls, we observed a stronger ac-K band that migrates at the height of BRP in hdac6ko mutants and a weaker ac-K band in BRP immunoprecipitates.
from animals overexpressing HDAC6 (Figures 3A and 3B). Hence, HDAC6 is necessary to promote BRP deacetylation in vivo. To test if HDAC6 can deacetylate BRP directly, we immunoprecipitated BRP from wild-type fly heads and incubated these BRP-enriched fractions with recombinant HDAC6. Probing western blots for ac-K shows a time-dependent deacetylation of BRP by HDAC6 (Figures 3C and 3D). Thus, HDAC6 is also sufficient for BRP deacetylation in vitro.

The RNA-Binding Protein TDP-43 Regulates HDAC6 Expression and Induces T-Bar Morphology Defects

To independently manipulate HDAC6 levels and assess T-bar morphology, we resorted to TDP-43, an RNA-binding protein that is found in a complex with HDAC6 mRNA and regulates HDAC6 expression (Kim et al., 2010). Flies mutant for tbph, the TDP-43 homolog, show reduced HDAC6 mRNA levels (Fiesel et al., 2010), indicating HDAC6 expression is regulated by TDP-43. Using quantitative RT-PCR, we confirm the reduced HDAC6 mRNA levels in tbph mutants, and we also find an upregulation of HDAC6 mRNA in animals overexpressing wild-type human TDP-43 (nSyb-Gal4, p < 0.001; D42-Gal4, p = 0.05; Figure S2A) or TDP-43 harboring mutations that cause ALS in patients (TDP43<sup>A315T</sup> or TDP-43<sup>A382T</sup>; nSyb-Gal4, p < 0.001 not shown; D42-Gal4, p < 0.001; Figure 3E). Indicating specificity, the expression of HDAC4, another cytoplasmic deacetylase not targeted by TDP-43, is not altered (Figure 3F). Expression of TDP43<sup>A315T</sup> and TDP-43<sup>A382T</sup> yield a more robust increase in HDAC6 expression compared to TDP-43, and we therefore tested if expression of TDP43<sup>A315T</sup> and TDP-43<sup>A382T</sup> would reduce BRP acetylation levels by immunoprecipitating BRP and probing the western blots using anti-ac-K. As shown in Figures 3G and 3H, we observe a much weaker ac-K band in TDP-43 mutant-expressing animals. The developmental lethality associated with tbph null mutations precluded us from examining BRP acetylation in the heads of these animals. Nonetheless, our data indicate that BRP is deacetylated in animals that express mutant TDP-43, a defect that correlates with upregulated HDAC6 expression levels.

TDP43- and HDAC6-Induced T-Bar Defects Are Similar

If HDAC6 regulates T-bar morphology in a dosage-sensitive manner, we expect altered TDP-43 function to also show structural defects at the level of T-bars. We therefore overexpressed TDP-43 using neuronal drivers of different strength and found that the intensity of BRP<sup>C</sup> immunolabeling relates in
a dosage-sensitive manner to the strength of the GAL4 driving TDP-43 expression (nSyb-Gal4 > Elav-Gal4 > D42-Gal4; Figures S2B–S2D) (Khuong et al., 2010). Similarly, overexpression of TDP-43 pathogenic mutants triggered increased BRP C labeling (Figures S2E–S2G), indicating this defect is the result of a gain-of-function mechanism. Note that under the same conditions, BRP assembly is not affected, because BRP N labeling intensity is not different (data not shown). While expression of wild-type TDP-43 or the pathogenic TDP-43 mutants all cause more intense BRPC labeling compared to controls (Figures S2B–S2G), when expressed at similar levels, the pathogenic mutants cause the strongest increase, again correlating with the level of increase in HDAC6 expression (compare Figure S2D to Figures S2E and S2F). One possibility explaining the less severe effects we observe upon expression of wild-type TDP-43 is that wild-type TDP-43 autodownregulates the expression of endogenous TDP-43 (tbph), thus compensating for the increased HDAC6 levels (Ayala et al., 2011). Another possibility is that the pathogenic TDP43 proteins localize differently in comparison to the wild-type TDP-43, harboring additional or stronger effects on HDAC6 mRNA (Estes et al., 2011; Kim et al., 2010). The extent to which either of these mechanisms is at play in fly motor neurons needs to be further explored in the future.

Given that the TDP-43 pathogenic mutants already show a strong effect on BRPC labeling when expressed with the weaker D42-Gal4 driver (Figures S2E–S2G), we used this condition to further study the T-bar defects. First, we used PiMP (Figures S2H–S2N) and TEM (Figures 4A, 4B, and 4D) to assess T-bar top size. We measure larger T-bar top sizes in animals expressing TDP-43 pathogenic mutants, and these T-bars show an increased number of tethered vesicles (Figure 4E). Other synaptic features, including the number of synaptic vesicles, mitochondria, and T-bars, are not different, indicating that these components are properly delivered to the nerve terminals (Figures S3A–S3F). Opposite to animals that express pathogenic TDP-43, tbph mutants harbor T-bars with significantly increased T-bar top sizes (Figures S3A–S3F).
smaller top sizes (Figures S2K, S2L, and S2N and Figures 4C and 4D), and these T-bars harbor less tethered synaptic vesicles than control T-bars (Figure 4E). Hence, T-bar top size and vesicle tethering are oppositely affected in tbph mutants compared to animals expressing TDP-43 pathogenic mutants, and these defects correlate with HDAC6 expression levels (see also below).

To determine if the morphological changes at the T-bar top upon expression of TDP-43 correlate with functional defects, we measured the size of the ready-to-release vesicle pool using two electrode voltage clamps. First, we measured EJCs in 0.45 mM CaCl$_2$ at 0.2 Hz and find the EJC amplitude and quantal content is increased in animals expressing TDP-43 pathogenic mutants, but not affected in tbph mutants (Figures S2K, S2L, and S2N and Figures 4C and 4D). The smaller readily releasable pool we measure in tbph mutants seems at odds with the unaffected basal release measured at 0.2 Hz (Figures S3G–S3J).

While more work is needed, we surmise that deregulation of additional targets of TBPH may affect EJC amplitudes independent of the effects on the ready-to-release vesicle pool. To further scrutinize vesicle release during intense stimulation, we also used SpH in animals that express pathogenic TDP-43 or in tbph mutants and stimulated their motor neurons using 50 stimuli at 60 Hz. We find a significantly higher SpH peak fluorescence level in neurons expressing TDP-43 pathogenic mutants, while tbph mutants only show a marginal change in SpH signal (Figures 4I and 4J). Hence, the increased HDAC6 levels in animals expressing TDP-43 pathogenic mutants correlate with more tethered vesicles and an increased size of the readily releasable vesicle pool, while the decreased levels of HDAC6 in tbph mutants correlate with less tethered vesicles and a smaller readily releasable vesicle pool.

HDAC6 and ELP3 Genetically Interact to Regulate BRP Acetylation

To scrutinize the in vivo role of HDAC6 as a BRP deacetylase, we performed genetic interaction experiments. We reasoned that either increased levels of ELP3 or reduced levels of HDAC6 would antagonize the defects seen upon expression of TDP-43 pathogenic mutants. First, we assessed BRP acetylation levels. While overexpression of the TDP-43 pathogenic mutants alone leads to a less BRP acetylation (Figures 3G and 3H), co-overexpressing ELP3 or removing one copy of hdac6 rescues this defect (Figures 5A and 5B). Next, we tested if gain of ELP3 or partial loss of HDAC6 rescues T-bar morphology in flies expressing pathogenic TDP-43 and found, using PiMP, that both these conditions rescue the larger T-bar tops (Figures 5C–5G). Furthermore, increasing ELP3 or decreasing HDAC6 also rescued the excessive vesicle fusion seen upon intense stimulation in TDP-43-expressing animals, as gauged by SpH imaging (Figure 5H). Hence, ELP3 and HDAC6 antagonistically regulate BRP acetylation, T-bar top size, and the size of the pool of vesicles that is ready for fusion during intense stimulation.

Aged flies expressing pathogenic TDP-43 show reduced motor activity in an automated 24 hr monitoring system (Figure 5I) as well as reduced negative geotaxis (Figure 5J) (Voigt et al., 2010; Estes et al., 2011). We wondered if correcting BRP acetylation levels in animals that express pathogenic TDP-43 would correlate with improved motor performance in these animals. While overexpression of ELP3 or heterozygosity for hdac6 alone has no effect on activity or negative geotaxis (data not shown), these conditions both significantly rescue the activity and geotaxis defects in pathogenic TDP-43-expressing animals (Figures 5I and 5J). These data suggest that excessive BRP deacetylation contributes to TDP-43-induced motor defects in flies and that promoting synaptic BRP reacetylation alleviates these disabilities.

**DISCUSSION**

Here, we find that HDAC6 controls vesicle tethering and synaptic transmission by regulating BRP deacetylation, thereby antagonizing ELP3, a BRP acetyltransferase (Miśkiewicz et al., 2011). Our work defines BRP as a deacetylation target of HDAC6. Acetylation of the C-terminal end of BRP results in more condensed T-bars, while deacetylation leads the protein to send excessive tentacles into the cytoplasm to contact more synaptic vesicles. Similar to chromatin structure being regulated by electrostatic mechanisms at the level of histone acetylation, we propose that electrostatic interactions between acetylated and deacetylated lysines in individual BRP strands regulate presynaptic density structure and function.

While many HDAC-like proteins are present in the nucleus to deacetylate histones, HDAC6 predominantly localizes to the cytoplasm, where it has been implicated in the modification of different proteins, including $\alpha$-tubulin, contractin, and HSP90 (Hubbert et al., 2002; Kovacs et al., 2005; Zhang et al., 2007). In neurons, HDAC6-dependent $\alpha$-tubulin deacetylation may affect axonal transport by promoting kinesin-1 and dynein binding to microtubules (Reed et al., 2006). However, hdac6 null mutant flies did not show overt changes in synaptic features other than T-bar morphology as gauged by electron microscopy, suggesting that axonal transport as a consequence of tubulin defects was not massively affected, although we do not exclude more subtle transport defects.

BRP is a presynaptic density structural component important to cluster calcium channels at release sites while tethering synaptic vesicles at its C-terminal end (Kittel et al., 2006; Wagh et al., 2006). The regulation of BRP by HDAC6-dependent deacetylation indicates the BRP C-terminal end is important to sustain neurotransmitter release during intense (60 Hz) stimulation by orchestrating vesicle tethering. Corroborating these results, mutations in the BRP C-terminal end (brp$^{null}$) cause defects in vesicle tethering and the maintenance of release during intense 60 Hz stimulation (Hallermann et al., 2010a). Similarly brp-isoform mutations that leave calcium channel clustering intact but result in a much more condensed T-bar top show a smaller readily releasable vesicle pool (Matkovic et al., 2013), very similar to the defects we observe when BRP is excessively acetylated (this study and Miśkiewicz et al., 2011). The brp$^{null}$ mutation shows somewhat less severe defects to maintain synaptic transmission, possibly because more vesicles still manage to tether in

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these mutants during stimulation compared to the conditions that result in strong shrinking of the T-bar top. Nonetheless, the data indicate that in flies, BRP orchestrates efficient synaptic transmission during intense activity.

In the model we present, ELP3 and HDAC6 antagonistically control presynaptic function. TDP-43, a gene mutated in ALS, positively regulates HDAC6 expression, and in flies, increased HDAC6 activity or expression of pathogenic TDP-43 results in the deacetylation of active zone material and increased synaptic release. Remarkably, the presence of an ALS risk-associated ELP3 allele in humans correlates with reduced ELP3 expression in ALS patient spinal cords (Simpson et al., 2009). In flies, elp3 mutants also cause active zone deacetylation and more synaptic release. Together with genetic interactions in fruit flies, the data suggest that decreased HDAC6 function and increased ELP3 function act antagonistically, both in flies and humans. However, the target(s) on which these enzymes converge in humans remains to be discovered. In flies, our data are consistent with ELP3-dependent acetylation to occur at the C-terminal tail of the BRP protein (this work and Miśkiewicz et al., 2011). However, the mammalian BRP counterpart, ELKS/CAST, that resides in the presynaptic density (Ohtsuka et al., 2002), does not contain a long C-terminal tail (Wagh et al., 2006). ELKS/CAST in mammals has been found to be associated with filamentous structures (Sik-sou et al., 2007), and the activity to concentrate synaptic vesicles near release sites may thus be executed by binding partners of ELKS/CAST such as Picollo or Bassoon (Mukherjee et al., 2010). Hence, it will be interesting to test if ELP3 and HDAC6 regulate acetylation at the much shorter ELKS/CAST tail or whether ELKS/CAST binding partners are acetylated also in the context of ALS. It is in this perspective interesting to note that another active zone-associated protein, UNC13A, is implicated in ALS as well (Diekstra et al., 2012), but the pathomechanism of how UNC13A is implicated remains to be elucidated.
Electrophysiology
Excitatory junctional currents were recorded in HL-3 at 0.2 Hz or at 60 Hz as described previously (Miskiewicz et al., 2011) and in the Supplemental Experimental Procedures.

RT-PCR
RNA was isolated using TRI Reagent (Sigma-Aldrich), and 1 μg of total RNA was used for oligo(dT)-primed double-stranded cDNA synthesis (SuperScriptIII; Invitrogen). A total of 20 ng cDNA was used for oligonucleotide primed reverse transcription polymerase chain reaction (RT-PCR) and behavior, and P.V. (electrophysiology and SpH), K.M., L.E.J., W.M.Y., J.S., and P.V. performed experiments, and J.S.V., S.M., F.F., and B.D. provided reagents or tools.

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Miescnböck et al., 1999, UAS-HELP3 (Miskiewicz et al., 2011), tbph232, tbph1422, tbph5 (Feigun et al., 2009; Fiesel et al., 2010), hdac655 (Du et al., 2010), w1118, Elav-Gal4, D42-Gal4, nSyb-Gal4, Act-Gal4 and y1 w51123 P(EpGF2) HDAC6Evrogen to overexpress HDAC6 (Bloomington Stock Center).

Microscopy
Larvae were dissected HL-3 and fixed in 4% formaldehyde and incubated at 1:100 with anti-BRP (NC82) or at 1:200 with anti-BRP5 (Fouquet et al., 2009), followed by 1:1,000 anti-mouse Alexa Flour 555 or anti-rabbit Alexa Fluor 555 antibodies (Invitrogen). The mean intensity of BRP was measured per bouton area using ImageJ in confocal images taken on a Nikon A1R confocal microscope using a 60× 1.35 numerical aperture (NA) oil lens and calculated following background subtraction. For PiMP, BRP C dots were calculated at 60 Hz 50 AP in HL-3 with 2 mM CaCl2 and imaged at 100 ms intervals where (Munck et al., 2012). The surface areas of BRP C-labeled objects parallel to the optical view (seen from the top) were manually traced using ImageJ.

Electrochemistry
Immunoprecipitation of BRP was performed as described elsewhere (Miskiewicz et al., 2011) and in Supplemental Experimental Procedures. For deacetylation reactions, immunoprecipitated BRP (from ~300 heads) (Miskiewicz et al., 2011) was incubated with 4 μg HDAC6 (Sigma-Aldrich) in acetylation buffer at 25°C for the times indicated, and acetylation was assessed using western blotting. Antibodies used were 1:500 anti-acetylated lysine (ac-K; rabbit, ABB0178; Abcam), 1:1,000 anti-BRP55 (Fouquet et al., 2009), 1:1,000 anti-BRP5 (Developmental Studies Hybridoma Bank), and 1:1,000 horseradish peroxidase-coupled secondary antibodies (Jackson ImmunoResearch). Blots were imaged using a digital imager, and the mean intensity of bands was measured and the background subtracted using ImageJ.

Electroactivity assays
For negative geotaxis, 22-day-old flies were tested for the ability to climb 8 cm in 10 s. For activity measurements, 21-day-old male flies were monitored using the Drosophila activity monitor system (Trikinetica) (Gielstro, 2012). The average activity starting at 1 hr before the lights were turned on until 1 hr after they were turned on is reported; we call this average activity in this 2 hr interval the “morning peak.”

Statistics
Data sets were tested for normality of the distribution. A multiple-comparison parametric test (ANOVA) was used when comparing multiple groups. Not-normally distributed data were analyzed using a nonparametric test (Kruskal-Wallis). Significance in comparison to controls was tested using Dunnett’s test for normal distribution or Dunn’s test for nonnormal distributions, and each group was also compared to the corresponding control with an unpaired t test. For genetic interactions, rescue groups were compared with corresponding mutants with an unpaired t test.

SUPPLEMENTAL INFORMATION
Supplemental Information includes Supplemental Experimental Procedures and three figures and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2014.05.051.

AUTHOR CONTRIBUTIONS
K.M., L.E.J., and P.V. designed the study and wrote the paper. Data were analyzed by K.M. (immunohistochemistry, TEM, and PiMP), L.E.J. (biochemistry, RT-PCR, and behavior), and P.V. (electrophysiology and SpH). K.M., L.E.J., W.M.Y., J.S., and P.V. performed experiments, and J.S.V., S.M., F.F., and B.D. provided reagents or tools.


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