The ciliopathies are a group of phenotypically overlapping disorders caused by structural or functional defects in the primary cilium. Although disruption of numerous signaling pathways and cellular trafficking events have been implicated in ciliary pathology, treatment options for affected individuals remain limited. Here, we performed a genome-wide RNAi (RNA interference) screen to identify genetic suppressors of BBS4, one of the genes mutated in Bardet-Biedl syndrome (BBS). We discovered 10 genes that, when silenced, ameliorate BBS4-dependent pathology. One of these encodes USP35, a negative regulator of the ubiquitin proteasome system, suggesting that inhibition of a deubiquitinase, and subsequent facilitation of the clearance of signaling components, might ameliorate BBS-relevant phenotypes. Testing of this hypothesis in transient and stable zebrafish genetic models showed this posist to be true; suppression or ablation of usp35 ameliorated hallmark ciliopathy defects including impaired convergent extension (CE), renal tubule convolution, and retinal degeneration with concomitant clearance of effectors such as β-catenin and rhodopsin. Together, our findings reinforce a direct link between proteasome-dependent degradation and ciliopathies and suggest that augmentation of this system might offer a rational path to novel therapeutic modalities.
Conflict of interest: NK and ICT are paid consultants of Rescindo Therapeutics Inc. NK also holds founder stock of the same commercial entity. PLT was a paid employee of Rescindo Therapeutics Inc. at the time of this research.

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expression significantly (Supplemental Figure 2). Therefore, to validate the 29 hits, we transfected activation of Wnt/\(\beta\)-cat recapitulated quantitatively in vivo with this article; https://doi.org/10.1172/jci.insight.130516DS1), whose luciferase activity will cell factor (TCF) binding sites (Figure 1A and Supplemental Figure 1; supplemental material available line that stably expresses an shRNA against \(BBS4\) (20) and a luciferase reporter with 8 concatenated T cell factor (TCF) binding sites (Figure 1A and Supplemental Figure 1; supplemental material available online with this article; https://doi.org/10.1172/jci.insight.130516DS1), whose luciferase activity will be elevated when increased \(\beta\)-cat binds to TCF and turns on the expression of luciferase. Cells selected clonally for reproducibility and dynamic range (Supplemental Figure 1) were then transfected with the Qiagen human whole-genome siRNA library, targeting about 22,000 genes. To improve the reproducibility of the screen and to reduce the false positive/false negative rate, the library was designed to contain 2 half libraries, in which 4 nonrelated siRNAs (2 siRNAs in each half library) target 1 gene (25). At 72 hours after transfection, cells were stimulated with WNT3a and collected for luciferase and lactate dehydrogenase (LDH) assays (for cell viability; Figure 1A). With the expectation that some contain 2 half libraries, in which 4 nonrelated siRNAs (2 siRNAs in each half library) target 1 gene (25). At 72 hours after transfection, cells were stimulated with WNT3a and collected for luciferase and lactate dehydrogenase (LDH) assays (for cell viability; Figure 1A). With the expectation that some suppressors whose products can prevent cell death from the toxicity of dipeptide-repeat (DPR) protein (17).

An prominent role of primary cilium is to act as a signaling center (18, 19), facilitating the communication between extra- and intracellular signaling effector molecules during development and disease progression (2). To date, this organelle has been linked to several paracrine pathways crucial for development, including Wnt, Shh, and Notch (20). We posited that the identification of genes whose suppression could rescue aberrant signal transduction caused by ciliary dysfunction might have therapeutic value. To identify such targets, we designed a genome-wide RNAi screening paradigm, with the aim of isolating genes whose suppression can rescue hyperactive Wnt/\(\beta\)-catenin (\(\beta\)-cat) signaling in the absence of \(BBS4\) (a ciliary gene mutated in patients with BBS, an archetypal ciliopathy; refs. 21, 22).

Here, we report the findings of our screen, in which 10 of 29 in vitro hits were found to rescue \(bbs4\)-dependent convergent extension (CE) defects in vivo. Considering the druggable potential and our previous finding that suggests the perturbation of proteasome-mediated protein degradation, we focused on USP35, a negative regulator of ubiquitin-proteasome protein degradation. Deeper characterization of USP35 (and its orthologue USP38) showed that suppression or ablation in vivo rescued a host of ciliopathy-associated anatomical pathologies, with concomitant rescue of the overabundance of key signaling molecules. These data further support a central role for the ubiquitin proteasome system (UPS) in the pathogenesis of ciliopathies and suggest that targeting this pathway via inhibiting USP35/USP38 deubiquitinase provides a rational route for the development of novel therapeutic modalities.

Results

Genome-wide suppressor screen identifies genes that reduce aberrant Wnt signaling caused by loss of \(BBS4\). We reported previously that loss of \(BBS4\) expression leads to the hyperactivation of Wnt/\(\beta\)-cat signaling (23). Since that study, increased Wnt/\(\beta\)-cat activity has been reported in \(Kif3a^{−/−}\), \(Ift88^{kopk/kopk}\), and \(Ofd1^{−/−}\) mice (24). Importantly, the canonical Wnt activation phenotype could be rescued by WT \(BBS4\) and be recapitulated quantitatively in vivo (23). Therefore, we used this assay to design and execute a genome-wide RNAi suppressor screen. We first generated a human retinal pigmented epithelium (RPE) cell line that stably expresses an shRNA against \(BBS4\) (20) and a luciferase reporter with 8 concatenated T cell factor (TCF) binding sites (Figure 1A and Supplemental Figure 1; supplemental material available online with this article; https://doi.org/10.1172/jci.insight.130516DS1), whose luciferase activity will be elevated when increased \(\beta\)-cat binds to TCF and turns on the expression of luciferase. Cells selected clonally for reproducibility and dynamic range (Supplemental Figure 1) were then transfected with the Qiagen human whole-genome siRNA library, targeting about 22,000 genes. To improve the reproducibility of the screen and to reduce the false positive/false negative rate, the library was designed to contain 2 half libraries, in which 4 nonrelated siRNAs (2 siRNAs in each half library) target 1 gene (25). At 72 hours after transfection, cells were stimulated with WNT3a and collected for luciferase and lactate dehydrogenase (LDH) assays (for cell viability; Figure 1A). With the expectation that some siRNAs may target genes that influence cell viability, leading to false positives, luciferase readouts were normalized to LDH activity. Through this platform, we identified 29 genes that can reduce significantly (z < −3; P < 0.05, replicated) the hyperactivation of Wnt/\(\beta\)-cat signaling in replicate wells (Figure 1C).

\(AXIN2\) expression is a direct target of Wnt/\(\beta\)-cat signaling (26) and has been used to evaluate the activation of Wnt/\(\beta\)-cat signaling (27). Consistent with the Wnt-reporter assay, \(BBS4\) depletion enhances \(AXIN2\) expression significantly (Supplemental Figure 2). Therefore, to validate the 29 hits, we transfected cholesterol by inhibiting the activity of the Niemann-Pick C1-like 1 (NPC1L1) protein (12); sequencing of a CHD cohort reported inactivating mutations in \(NPC1L1\) associated with lower LDL levels and a lower risk of CHD (13). Finally, protein-truncating variants in SLC30A8 have been shown to reduce the risk of type 2 diabetes (14), encouraging the exploration of new therapeutic targets.

Because of such paradigms, suppressor screens have been proposed as a useful agnostic method to both understand disease pathomechanism and also to identify candidate genetic targets, around which novel therapeutics can be developed. For example, an ENU-mediated mutagenesis suppressor screen in \(Mecp2\)-null mice, the gene responsible for Rett syndrome, identified a loss-of-function mutation in squalene epoxidase that ameliorates the symptoms caused by loss of \(Mecp2\) (15). Additionally, a genome-wide screen in yeast found that knockdown of \(Dbr1\), an RNA debranching enzyme, can alleviate the toxicity of TDP43 aggregates in Amyotrophic Lateral Sclerosis (16). More recently, a genome-wide CRISPR/Cas9 deletion screen uncovered several suppressors whose products can prevent cell death from the toxicity of dipeptidyl-peptidase (DPP) protein (17).

An prominent role of primary cilium is to act as a signaling center (18, 19), facilitating the communication between extra- and intracellular signaling effector molecules during development and disease progression (2). To date, this organelle has been linked to several paracrine pathways crucial for development, including Wnt, Shh, and Notch (20). We posited that the identification of genes whose suppression could rescue aberrant signal transduction caused by ciliary dysfunction might have therapeutic value. To identify such targets, we designed a genome-wide RNAi screening paradigm, with the aim of isolating genes whose suppression can rescue hyperactive Wnt/\(\beta\)-catenin (\(\beta\)-cat) signaling in the absence of \(BBS4\) (a ciliary gene mutated in patients with BBS, an archetypal ciliopathy; refs. 21, 22).
siRNA of each of the 29 genes into the same cell type used for the primary screen and performed quantitative PCR (qPCR) to quantify AXIN2 message. In the context of BBS4 knockdown, suppression of 14 of 29 genes led to significant reduction of AXIN2 message in comparison with control siRNA (Figure 1B). Although the roles of some of these genes are unclear, the identified hits are involved in different cellular mechanisms (Supplemental Table 1). These results suggest the link of ciliopathies to both existing and potentially new cellular mechanisms. Given that these hits are identified through in vitro Wnt/β-catenin reporter, we next asked whether the rescue of hyperactive Wnt/β-catenin signaling can also be observed in vivo. During early development, hyperactivation of the Wnt/β-catenin pathway perturbs planar cell polarity, impairing proper CE (23, 28). Therefore, we investigated the in vivo -cat pathway perturbs planar cell polarity, impairing proper CE (23, 28). Therefore, we investigated the in vivo effects of the 14 candidate genes by assessing their effects on the CE phenotype observed in bbs4 zebrafish morphants (20, 23). We designed morpholinos (MO) targeting 11 of the 14 candidates (DTX1, PITPNM2, ENTPD6, C14orf166B, TDRD3, ZIC1, PTMA, ENGASE, ENPP7, TDRD12, and USP35) and guide RNA targeting 2 candidates (DRD5 and PCF11; lack of appropriate splicing blocker site) to perturb the expression of candidate genes (RHOXF1 was excluded from further analysis due to the lack of a zebrafish ortholog) (Supplemental Figure 6). We scored the phenotypic effects resulting from suppression of these 13 candidates by CE analysis; we found that suppression of 10 of 13 rescued significantly the CE defects of bbs4 morphants (Figure 1C, Figure 2A, and Supplemental Figure 4).

**In vivo assessment of rescue efficacy by USP35 suppression.** We and others have shown previously the existence of a functional relationship between ciliopathy proteins and the UPS (20, 23, 29). Importantly, prior in vitro studies motivated by protein-to-protein interaction between BBS4 and RPN10 showed that ciliary deficits can abolish proteasome-dependent protein degradation. Moreover, UPS-mediated protein degradation is also necessary for regulating multiple signaling pathways (30). Among our 10 candidate genes, we noted USP35, a ubiquitin-specific peptidase. Human USP35 belongs to the USP family of deubiquitinases and has been reported in the context of several cellular mechanisms, including the regulation of Park2-mediated mitophagy and Aurora B stability (31, 32). USP35 contains 2 USP catalytic domains that are conserved with USP38 (Supplemental Figure 5A), suggesting that USP35 and USP38 may play similar physiological roles. The orthologous roles of USP35 and USP38 are supported further by the fact that some species only have either USP35 (e.g., D. melanogaster) or USP38 (e.g., D. rerio) (33). Given these observations, we tested the rescue effects of each of USP35 and USP38 in human cells and usp38 in zebrafish. As a first test, we used a BBS4-depleted RPE cell line and transfected it with siRNA targeted to either USP35 or USP38, followed by assessment of their respective ability to ameliorate the hyperactivation of Wnt/β-catenin (Supplemental Figure 5, B and C). Suppression of either USP35 or USP38 attenuated AXIN2 expression (Supplemental Figure 5D), with USP38 having a more modest effect, likely explaining why this molecule was not detected in our primary screen. Cosilencing of both USP genes led to a more significant reduction of AXIN2 expression than either transcript alone, suggesting overlapping functions (Supplemental Figure 5D).

The zebrafish genome has a sole copy of usp38 with no detectable usp35 ortholog. We therefore generated both transient (morphants, MOs) and genetic (CRISPR/Cas9) models (Supplemental Figure 6 and Methods). We then asked whether suppression or deletion of usp38 could promote proteasome-dependent protein degradation, facilitating the clearance of signaling molecules and rescue of developmental phenotypes. As a first test, we asked whether suppression of usp38 can rescue CE defects of bbs4 morphants (20, 23, 34). To obtain quantitative data for this experiment, we measured the angle between the tip of the head and the tail of 8–10 somite embryos, a measurement that captures body length in early embryos (23), and binned them into 3 categories: normal (under 2 SDs from control); Class I (2–4 SDs from control) and Class II (>4 SDs from control).

While suppression of bbs4 led to approximately 80% embryos with CE defects, coinjection with usp38-MO reduced the incidence of pathology and the severity of the phenotype (25% Class I and 15% Class II compared with 35% Class I and 45% Class II in bbs4 morphants; P < 0.0001; Figure 2A). This observation indicates that in vivo suppression of usp38 can ameliorate the hyperactivation of the Wnt/β-catenin pathway, consistent with our in vitro screen.

A common feature of many ciliopathy patients is abnormal renal morphology, including but not limited to calyceal malformation, cyst formation, and fetal lobulation (35). Therefore, we next evaluated the effects usp35/usp38 suppression on renal development in 4-day postfertilization (dpf) zebrafish larvae. Consistent with other studies in ciliary morphants and mutants (36), bbs4 morphants displayed atrophy and...
diminished convolution in proximal renal tubules (~65%), a phenotype reminiscent of renal immaturity of BBS patients and 1 possible source of cysts (ref. 37 and Figure 2B). In line with our CE studies, suppression of \textit{usp38} improved — but did not fully rescue — the renal abnormalities of \textit{bbs4} morphants by about 20% (Figure 2B). Since a functional assay would be more straightforward to statistically assess the rescue efficacy, we performed extensive experiments to develop a proteinuria assay in our zebrafish models. However, likely due to (a) the detection limitation and (b) high assay variability, this experiment was not possible in a zebrafish system. A murine model will be required to address this aspect of the work.

The use of MOs to target genes of interest is more homogenous and less time-consuming but can be confounded by off-target effects (38). To test the specificity of our MO-induced findings, we implemented a CRISPR/Cas9 genome-editing approach. Guide RNAs targeting exon 3 of \textit{bbs4} and exon 1 of \textit{usp38} induced efficient (~99%) Cas9-mediated genome editing (Supplemental Figure 6). Expression of human BBS4 and USP35 mRNA in the \textit{bbs4} gRNA/Cas9 and \textit{usp38} gRNA/Cas9 significantly rescue the phenotypic defects,
suggesting the specificity of the CRISPR agents (Supplemental Figure 7). Furthermore, a newly accepted paper shows negligible off-target effects in the zebrafish exome by CRISPR manipulation (39). Similar to the phenotypes of bbs4 morphants, injection with bbs4 gRNA/Cas9 led to quantitatively measured CE defects; coinjection with a likewise efficient (Supplemental Figure 8) usp38 gRNA/Cas9 into bbs4 gRNA/Cas9 led to significant amelioration of CE (Supplemental Figure 8). Additionally, similar to morphants, ~55% of the F0 generation of bbs4 mutant embryos mutant embryos had atrophy and deficient convolution of their proximal renal tubules (Figure 2C); this defect was also improved upon the introduction of usp38 deletions (Figure 2C).

Figure 2. Suppression of usp38 (USP35 ortholog in zebrafish) ameliorates the defects caused by depletion of bbs4. (A) Morpholinos were injected as described in the Methods. Depletion of bbs4 results in CE defects, including wider anterior-posterior body gap, somite, and loss of eyes (mostly in Class II). To quantitatively determine the CE phenotype, the angle of body gap was measured in each embryo, and the embryos were classified as described in Methods. Coinjection of usp38-MO reduces both Class I and Class II embryos. Arrowheads represent the tip of anterior and posterior body axis. Brackets represent the width of somite. (χ² analysis, *P < 0.05, ****P < 0.0001). (B) Depletion of bbs4 leads to the atrophy and deficient convolution in the proximal tubules, a phenotype that is related to cyst formation. Knockdown of usp38 expression ameliorates renal defects seen in bbs4 morphants (χ² analysis, ***P < 0.001). Scale bar: 100 μm. (C) While bbs4 CRISPR (mosaic) mutant exhibit defects in the convolution of proximal tubules, deletion of usp38 ameliorates these defects (χ² analysis, **P < 0.01, ****P < 0.0001).
we see a milder effect by CRISPR than MO, which suppressed more uniformly. We used both approaches in this study. In our view, the focus is not the magnitude of rescue efficacy of both techniques but the direction of effect. Together, the results by using both approaches suggest that suppression of usp38 can ameliorate the defects of BBS suppression or ablation in zebrafish.

Exploring the molecular mechanism of USP35 suppression mediated rescue. We next probed the molecular basis of the observed rescue using our in vitro and in vivo tools. Specifically, we asked whether USP35/USP38 regulates the stability or deubiquitination of signaling components known to be perturbed by bbs4 depletion, such as the Wnt/β-cat pathway.

First, we returned to the in vitro model. We have shown previously that suppression of BBS4 leads to accumulation of β-cat in the HEK293 cells (23). Therefore, we cultured BBS4-depleted HEK293 cells, pulled down endogenous β-cat by immunoprecipitation, and assessed the effects of USP35 suppression on its ubiquitination. We found that the ubiquitination of β-cat increases in cells depleted of USP35 (Figure 3A), suggesting that suppression of USP35 will facilitate the degradation of β-cat. Next, we asked whether USP35 also affects the stability of other ciliopathy-relevant signaling pathways, such as Notch. We have reported previously that depletion of bbs4 in the HEK293 cells leads to accumulation of Notch intracellular domain (NICD), a key component of Notch signaling (20). We reproduced the previous finding, with BBS4 suppression causing the accumulation of NICD in our cell-based model (Supplemental Figure 9 and Figure 3B). Consistent with a candidate rescue mechanism, cosuppression of USP35 with BBS4 facilitated the degradation of NICD (Figure 3B), suggesting that improved degradation of aberrantly accumulated proteins is a strong candidate rescue mechanism.

Hedgehog (HH) signaling is also a major pathway regulated by both the primary cilium and the proteasome (40). We therefore asked whether disruption of USP35 affects HH signaling transduction. HH signaling plays important roles during retina differentiation, as well (41). To assess the activation of HH, we perform qPCR in RPE cells for PTCH1 and BCL2, whose expression increases when HH is activated (42, 43). We found that the expression level of PTCH1 and BCL2 were elevated in BBS4-depleted RPE cells compared with nonsilencing control cells (7- and 3-fold of increase, respectively; Supplemental Figure 10A and 10B). However, knockdown of USP35 attenuated this phenotype (Supplemental Figure 10, A and B). Although which HH component might be targeted by USP35 is unknown, these results suggest that USP35 suppression in not restricted to Wnt-mediated defects.

Next, we asked if the deubiquitination function of USP35 is involved in the rescue mechanism of USP35, as opposed to hitherto unknown functions of this molecule. For this experiment, we generated a dominant negative mutant of USP35, in which Cys450 is mutated to alanine, blocking its activity to cleave the ubiquitin chain (31, 33). If deubiquinase activity of USP35 is required for rescue, expression of USP35 dominant negative mutant of USP35, in which Cys450 is mutated to alanine, blocking its activity to cleave suppression in not restricted to Wnt-mediated defects.

Although which HH component might be targeted by USP35 is unknown, these results suggest that USP35 comparison with nonsilencing control cells (7- and 3-fold of increase, respectively; Supplemental Figure 10A and 10B). We found that the expression level of PTCH1 and BCL2 were elevated in BBS4-depleted RPE cells compared with nonsilencing control cells (7- and 3-fold of increase, respectively; Supplemental Figure 10A and 10B). However, knockdown of USP35 attenuated this phenotype (Supplemental Figure 10, A and B). Although which HH component might be targeted by USP35 is unknown, these results suggest that USP35 suppression in not restricted to Wnt-mediated defects.
Investigating the efficacy of USP35 suppression/ablation in retinal degeneration. Our screening and validation data, together with prior studies that implicated proteasomal function in the pathomechanism of ciliopathies (20, 23), suggested that suppression of USP35 might offer a rational therapeutic route. However, our data measured efficacy in systems whose therapeutic implementation would not be useful because they affect early developmental processes. We thus turned our attention to retinal degeneration, a postnatal, progressive phenotype pathognomonic of BBS (46–49) and other ciliopathies (50–52).
Mislocalization of rhodopsin in the inner segment is a hallmark of Bbs4\(^{-/-}\) retinas, a molecular pathology also associated with the progression of retinal degeneration (7, 53). A recent report suggests that enhanced proteasome activity might be a therapeutic target for dominant retinal degeneration caused by mislocalization of the p.Pro23His rhodopsin mutant (54). Therefore, we considered mislocalization of rhodopsin as an attractive target, especially since accumulation of unstable GFP, a reporter of proteasome activity, was also reported in a Bbs4\(^{-/-}\) mouse mutant (20). We examined the retinas of 5 dpf zebrafish larvae and assessed whether mislocalization of rhodopsin can be detected in a bbs4 CRISPR/Cas9 model. We generated retinal sections, stained them with an anti-rhodopsin antibody, and quantified the amount of rhodopsin in the cytoplasm of the outer nuclear layer (ONL).

**Figure 4. Rescue of the bbs4 CRISPR mutant phenotype with coablation of usp38 in 5dpf zebrafish larvae.** (A) Mislocalization of rhodopsin staining (green) is trapped in the cytoplasm of the outer nuclear layer (ONL) cells in bbs4 mutants (arrowheads), but localization is restored to normal in double bbs4/usp38 mutants. Blue, DAPI. Top- and bottom panels of images were taken at 20×; midpanel of images were taken at 40×. (B) The rhodopsin located in the cytoplasmic region (indicated by dashed red line in A) of ONL cells was quantified by ImageJ (NIH). Ablation of bbs4 causes a significant increase of rhodopsin mislocalization. Coablation of usp38 rescues this defect (1-way ANOVA). ***P < 0.001; ****P < 0.0001. (C) Assessment of visual function by visual startle response (VSR). Loss of bbs4 leads to deficient startle response upon light stimulation. However, the visual ability can be improved by coablation of usp38 (1-way ANOVA). *P < 0.05; **P < 0.01; ****P < 0.0001.

Mislocalization of rhodopsin in the inner segment is a hallmark of Bbs4\(^{-/-}\) retinas, a molecular pathology also associated with the progression of retinal degeneration (7, 53). A recent report suggests that enhanced proteasome activity might be a therapeutic target for dominant retinal degeneration caused by mislocalization of the p.Pro23His rhodopsin mutant (54). Therefore, we considered mislocalization of rhodopsin as an attractive target, especially since accumulation of unstable GFP, a reporter of proteasome activity, was also reported in a Bbs4\(^{-/-}\) mouse mutant (20). We examined the retinas of 5 dpf zebrafish larvae and assessed whether mislocalization of rhodopsin can be detected in a bbs4 CRISPR/Cas9 model. We generated retinal sections, stained them with an anti-rhodopsin antibody, and quantified the amount of rhodopsin in the cytoplasm of the outer nuclear layer (ONL). Compared with WT embryos, bbs4 CRISPR mutants (>99% mosaicism, Supplemental Figure 6) had
significantly increased rhodopsin mislocalization ($P < 0.01$; Figure 4, A and B). In contrast, injection of CRISPR gRNAs targeting usp38 (>99% mosaicism, Supplemental Figure 6) alone had no impact on retinal morphology. However, coinjection of bbs4 and usp38 gRNAs with Cas9 rescued rhodopsin mislocalization significantly ($P < 0.05$; Figure 4, A and B).

As a second test, we sought to assess the impact of usp38 depletion on visual function in bbs4-depleted models. We adapted the method described by Scott et al. to monitor startle activity of 5 dpf larvae under light stimulus (55). Consistent with their IHC, while bbs4 CRISPR larvae had minimally recordable response to light stimulus compared with controls ($P < 0.001$; Figure 4C), codepletion of usp38 and bbs4 improved visual function, as indicated by the ability to respond to light stimulation ($P < 0.05$; Figure 4C). This result suggests that ablation of usp38 can ameliorate the visual defects of bbs4 CRISPR larvae. Taken together, our results demonstrate the potential of usp38 suppression to prevent mislocalization of rhodopsin and to ameliorate visual defects in bbs4 mutants.

Assessing the efficacy of USP35 suppression in other ciliopathies. We next asked whether USP35/USP38 suppression might also exert amelioration effects in other ciliopathy models. Intraflagellar transport 88 (IFT88) is a core protein of anterograde IFT complex, which is responsible for transporting protein cargo from basal body to the tip of cilia (1). Mutations of IFT88 are also associated with renal cysts and retina degeneration (56, 57). Therefore, we suppressed usp38 in an ift88-depleted model and asked whether knockdown of usp38 can ameliorate the phenotypic defects of ift88 morphants; similar to the bbs4-depleted model, suppression of ift88 also results in defects of CE movements (58). While knockdown of ift88 led to 65% of embryos with CE phenotypes (Supplemental Figure 12; $P < 0.0001$ compared with controls), cosuppression of usp38 in ift88 morphant significantly ameliorated the CE defects (Supplemental Figure 12; $P < 0.0001$). We then evaluated the rescue efficacy of usp38 knockdown in the retina of ift88 morphants. We harvested retinas of 5 dpf embryos and performed immunostaining to measure, quantitatively, the abundance of rhodopsin in the inner segment. Similar to ift88 mutants (59), we observe mislocalized rhodopsin in the ONL of ift88 morphants (Figure 5, A and B; $P < 0.0001$). While knockdown of usp38 alone does not cause significant impact regarding rhodopsin localization (Figure 5, A and B), cosuppression of usp38 in ift88 morphant significantly ameliorated the mislocalization of rhodopsin (Figure 5, A and B; $P < 0.01$). Finally, we evaluated the impact of usp38 depletion on visual function in ift88 morphants. Consistent with the results of rhodopsin immunostaining, ift88 morphant exhibits a reducing number of responses to light stimulation (Figure 5C; $P < 0.0001$). This defect was ameliorated by the suppression of usp38 (Figure 5C; $P < 0.0001$). Together, these results indicate that suppression of usp38 can ameliorate the phenotypic defects caused by loss of ift88, suggesting that the therapeutic potential of usp35/usp38 is not limited to BBS4.

Discussion

While the advancement of sequencing technologies has significantly improved the diagnostic rate of ciliopathy patients, the lack of available treatment options for managing disease progression remains challenging. To identify therapeutic targets, we and others have been motivated to understand the pathomechanism of disease, allowing for the elucidation of targets that can restore the dysfunction caused by the loss of ciliary genes (2, 20). Here, we capitalized on our previous findings that deficient ciliary function results in hyperactivation of Wnt/β-caten signaling and asked which genes, when suppressed, can ameliorate the aberrant Wnt/β-caten hyperactivation. By performing genome-wide siRNA screening, we identified 10 genes that, when suppressed, can ameliorate the defects caused by loss of ciliary gene function. From a therapeutic standpoint, loss-of-function mutations in some of these loci have been associated with cellular or organismal pathology that renders them poor targets. For example, loss-of-function mutations in DTX1 cause craniosynostosis (60), while suppression of PTMA, a caspase 9 regulator, renders cells sensitive to UV-mediated apoptosis (61). From a mechanistic, signaling perspective, however, the discovered suppressors potentially link BBS4 to both existing and new links of ciliary biology. The suppressor DTX1 encodes an E3 ubiquitin ligase, which is known to regulate Notch signaling through both ubiquitination-dependent and -independent mechanisms (62–64). In contrast, Engase is an N-acetylglucosaminidase, supporting the recent observation that regulation of this posttranslational modification might be relevant to ciliary transport and function (65), whereas PITPNM2 is relevant to the function of the retinal degeneration B locus in Drosophila (66). We were surprised with the identification of DRD5 as a potential ameliorator, although the fact that DRD5 alone disrupts early development reduces its potential suitability as a therapeutic target (Supplemental Figure 4). Furthermore, we speculate that the ability of DRD5 and BBS4 suppression to correct early development might intimate that they have opposite roles.
Given our prior observations regarding the roles of proteasomal regulation in BBS (20, 23), we focused on USP35, whose function is to remove ubiquitin chains from targeted proteins, preventing their degradation by the proteasome (30, 33). UPS has been reported to regulate the biosynthesis of primary cilia (29), warranting the questions of (a) whether USP35 may play a role in ciliogenesis and (b) whether restoration of the functional mechanism of USP35 is cilium dependent. However, these questions do not exclude the possibility that USP35 may modulate signaling pathways through a cilium-independent mechanism because a low percentage of ciliated hTert-RPE1 (~10%) can be observed under normal culture condition (with 10% FBS in F12/DMEM). To date, downstream targets of USP35 remain elusive. Park et al. reported that USP35 regulates cell cycle progression by interacting with and deubiquitinating Aurora B, preventing its degradation. Suppression of USP35 significantly reduces the number of cells expressing phospho–histone H3, suggesting an inhibition of cell proliferation (31). aberrant cell cycle progression has been linked as a mechanism of renal cyst formation (67–69); this, coupled to the reported USP35-mediated mitotic progression, may explain why USP35 suppression is able to ameliorate the renal defects observed in bbs4 morphants. However, the observed rescue of gastrulation movements and rhodopsin trafficking, as well as the USP35-mediated degradation of β-cat, suggests that other USP35 targets likely drive the observed rescue. Similarly, in addition to Wnt/β-cat signaling, other cilium-mediated pathways (such as Hh and Notch signaling; ref. 20, 70, 71) may be affected by USP35 suppression, as well. Although we have also observed that USP35 suppression affects...
Notch and HH signaling pathways, further proteomic analyses to identify targets of USP35/USP38 will likely be required to inform the biochemical mechanism of rescue.

Finally, we note that USP35 was not the only USP to rescue BBS4-dependent signaling defects. USP44 also significantly rescued these defects (Supplemental Table 2); it is a protein shown to regulate the ubiquitination of CDC20 (72), which in turn regulates ciliary length and disassembly (73). It will be important to understand what subset of deubiquitinases are relevant, directly or indirectly, to ciliary biogenesis, homeostasis, and function and what their role might be in conferring protection from the consequences of mutations that affect this organelle.

In summary, we have developed a functional screening platform to identify potential therapeutic targets for ciliopathy patients. In combination with previously established zebrafish models, we observed that suppression of the USP35 ortholog in zebrafish can restore the renal morphology and visual ability, 2 common features of ciliopathy patients. Further applying these discoveries, we speculate that inhibition of USP35 or other related molecules might be of therapeutic value. Importantly, suppression of USP35 or other similar treatments did not induce by themselves overt pathology in the zebrafish embryo, suggesting that treatment paradigms based on this molecule might be tolerated in humans.

Methods

Generation of cell lines and reporter plasmids. hTert-RPE1 (ATCC) cells were grown in DMEM and Ham’s F-12 Nutrient 1:1 mixture (F12/DMEM, Invitrogen) with 10% FBS and 2 mM L-glutamine. To generate the Wnt/β-cat reporter, the TCF/LEF binding sites were excised from the SuperTOPFLASH construct (74) using KpnI and HindIII and cloned into pGL4.18 [Luc2P/neo] vector (Promega). The hTert-RPE1_WntRep cell line was generated by FuGen6 transfection (Promega) with a Wnt reporter followed by selection with Geneticin (500 μg/mL; Invitrogen). The short hairpin targeting BBS4 (5′-GGCACACAGACCATGGCAAAAA-3′) was cloned into the plKO vector (Addgene, 10878) and transduced into hTERT-RPE1_WntRep cells, followed by selection with puromycin (MilliporeSigma). Wnt3a conditioned media was obtained by collecting the cultured media from L-Wnt3a cells.

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Genome-wide suppressor screen. Reverse transfection of siRNA (15 nM) was performed with RNAiMax reagent (Invitrogen). hTERT-RPE1_WntRep_shRNA-BBS4 cells (4 × 10³ cells/well) were seeded into 384-well plates containing siRNA and transfection reagents. At 72 hours after transfection, cells were stimulated with Wnt3α media and incubated for 4 hours. Cells were lysed with Passive Lysis Buffer (25 μL/well) (Promega). Luciferase and LDH activity of lysates were measured using the Luciferase Reporter Assay System (Promega) and LDH plus (Roche) on the FLUOSTar Omega microplate reader (BMG Labtech), and they were analyzed with MARS Data Analysis Software (BMG Labtech). The luciferase results of each well were divided by the LDH results to account for cell viability for each knockdown condition. Since knockdown of BBS1 has been shown to activate Wnt/β-cat signaling (23), BBS1 siRNA was utilized as a control. For quality control of the assay, we included 12 wells/plate of siRNA-control and BBS1 siRNA (5′-TTGCCCTTGTGTCTATGTAAA-3′) to be able to calculate Z′ (1 – 3 [SD BBS1 + SD cont]/ [M BBS1 – M cont]; where SD indicates standard deviation and M indicates mean). The assay was redone for the plates with Z′ less than 0.2. These controls are included to ensure that assay performance complies with the established assay validation data package, which vigorously examines interplate, intraplate, and interas- say variability per NIH-recommended large-scale screening guidelines (75).

qPCR analyses. Total RNA was isolated following the standard TRIzol (Invitrogen) protocol. cDNA was synthesized from 1 μg of total RNA using the QuantiTect kit (Qiagen). qPCR was performed with Power SYBR Green PCR Master Mix (Applied Biosystems) on a 7900HT (Applied Biosystems). Real-time data were collected and analyzed with a Sequence Detection System software package version 2.3 (Applied Biosystems). Primer sequences are listed in the Supplemental Table 3.

Zebrafish embryo manipulation and phenotyping. To determine the effect of bbs4 or usp38 suppression in zebrafish, we obtained previously (76) described MOs from Gene Tools (Gene Tools); bbs4-MO: 5′-CCGTTCCTCATAAGCTTCGGCCA-3′; usp38-MO: 5′-CAACACAGGTATTTACTGACATGGAA-3′; zic1-MO (77): 5′-ACTTGTGCTGTCGGTCAAGACAGCAT-3′; ptma-MO: 5′-CAGAAGTGTATCTGATTTACCCTTTGCCG3′; enzase-MO: 5′-CTCATAAAGGCCAAGTTACCTGAC-3′; dtx1-MO (78): 5′-TTACGACCATAGCCTACAGGCCG-3′; tex36-MO: 5′-TTAAATGCGGTATTATCCTACCCAGT-3′; tdrl2-MO (79): 5′-TGATTTCCACATCTCATAATTTCT-3′; pitpmm2-MO: 5′-GTTGTTGCATACGTGACCGTGGC-3′; c1orf166-MO: 5′-TCACTTCAGGCAAAATCTTACCTTT-3′; enp6-MO: 5′-AATGTAACATAC-
CATTTGGCTCCA-3′; and enpp7-MO: 5′-TGCTGTGTTCCCTTCTACCTACAA-3′. We used the standard control MO purchased from Gene Tools as our negative control (5′-CCT TCT ACC TCA GTT ACA ATT TAT A-3′). This MO is also used to adjust the total amount of MO in the coinjection experiments. For example, in the experiment of Figure 2A, the injections were done as (a) control MO (1 ng), (b) bbs4-MO (0.5 ng) + control MO (0.5 ng), (c) bbs4-MO (0.5 ng) + usp38-MO (0.5 ng), and (d) control MO (0.5 ng) + usp38-MO (0.5 ng). The MO was injected into WT (EK x AB) zebrafish embryos at the 1- to 4-cell stage. CRISPR target sequences (bbs4: 5′-AGCTCCTGAGCTTCCCATCC-3′ [60 pg], usp38: 5′-ACCCTGGAGAAATGGCCGG-GG-3′ [7.5 pg]) were identified by crispr.mit.edu or CHOPCHOP (http://chopchop.cbu.uib.no) and in vitro synthesized with the GeneArt Precision gRNA synthesis kit (Invitrogen) following the manufacturer’s manual. An injection solution of gRNA plus 100 pg Cas9 protein (PNA Bio) was injected into 1-cell stage WT zebrafish embryos. For CE phenotyping, embryos were initially scored as described previously (34) at the 8- to 10-somite stage, and images were captured using an AZ100 microscope and NIS Elements software (Nikon). The CE phenotypes were then quantitatively examined by measuring the anterior-posterior gap angle. Class I was defined by the angle larger than the mean angle of control embryos plus 2SD (Mcontrol+ 2SD), and Class II was defined by the angle larger than Mcontrol+ 4SD. To assess renal phenotypes, immunostaining with Na/K ATPase antibody (1:20; DSHB) was performed in 4 dpf larvae as described (36). Stained larvae were imaged in glycerol using an AZ100 microscope (Nikon). Pairwise comparisons of bbs4 morphants or bbs4 F0 mutant embryos compared with cosuppression conditions consisting of bbs4 plus usp38 reagents for rescue efficacy were conducted using a χ² test (GraphPad).

Immunoprecipitation and immunoblotting. HEK293 cells were cultured in DMEM containing 10% HI-FBS and transfected with plasmids indicated in the figures. To assess the ubiquitination of β-cat, cells were treated with MG132 (Calbiochem) for 5 hours to prevent the degradation of ubiquitinated β-cat and then harvested with Subcellular Protein Fractionation Kit (Thermo Fisher Scientific). The lysates were incubated with β-cat (Santa Cruz Biotechnology Inc.; sc-7199) antibody at 4°C overnight, followed by incubation with the Protein G–coupled agarose beads (Santa Cruz Biotechnology Inc.) at 4°C for 2 hours. The beads were collected and washed with RIPA buffer (50 mM sodium chloride, 50 mM Tris–HCl, pH 7.5, 1% NP-40, 0.5% sodium deoxycholate, and 0.1% SDS) (created in-house) with 1× proteasome inhibitor (Roche). Protein lysates were run on a 4%–15% SDS-PAGE gel (Bio-Rad) and immunoblotted with β-cat (1:3,000; Santa Cruz Biotechnology Inc., sc-7199) or ubiquitin (1:1,000; Abcam, ab8134) antibody. To assess the stability of NICD, transfected cells and tissue were lysed in RIPA buffer with 1× proteasome inhibitor (Roche) and centrifuged at 4°C for 15 minutes. Protein concentration was measured by Pierce BCA Protein assay Kit (Thermo Fisher Scientific) on the FLUOstar Omega microplate reader (BMG Labtech) and analyzed with MARS Data Analysis Software (BMG Labtech). Total protein lysates were separated by 4%–15% SDS-PAGE (Bio-Rad) with Spectra Multicolor Broad Range Protein Ladder (Fermentas) and transferred to Immuno-Blot PVDF Membrane (Bio-Rad). The membrane was blocked with 5% nonfat milk and probed with commercial primary antibodies: anti-GAPDH (1:3,000 Santa Cruz Biotechnology Inc., sc-32233) and anti-NICD (1:2,000; Abcam, ab8925). Densitometric analysis was carried out with QuantityOne software (Bio-Rad).

Rhodopsin mislocalization assay. Zebrafish at 5 dpf were fixed in 4% paraformaldehyde in PBS solution overnight at 4°C. They were then submerged in 30% sucrose-1 × PBS for at least 24 hours at 4°C prior to embedding in OCT (Tissue-Tek) for transverse sectioning. Embryos were sectioned (7 μM–thick sections) along the transverse plane to attain retina sections at or near the optic nerve, which were then adhered onto slides for immunostaining.

Sections on slides were stored at −20°C prior to staining. For staining, sections were initially washed with IF (immunofluorescence) buffer (1% BSA, 1 × PBST) for 10 minutes, followed by 30 minutes of incubation in blocking solution (1 × PBS, 1% BSA, 10% sheep serum) (Sigma-Aldrich). Sections were stained overnight at room temperature with rhodopsin antibody (1:1,000; EMD Millipore; 4D2) in blocking solution, followed incubation with a secondary antibody solution (Alexa 488 goat anti-mouse; Thermo Fisher Scientific, A32723) for 2 hours at room temperature. A final wash in IF buffer was performed prior to staining with DAPI (1:5,000; Roche) and mounted in Vectashield anti-fade medium (Vector Laboratories Inc.).

Fluorescent signals were visualized using Nikon 90i fluorescent microscope. In a normal retina, rhodopsin is localized to the outer segment and DAPI-positive cells outline the ONL vs. inner nuclear layer (INL) in the retina. To quantify the amount of rhodopsin mislocalization to the INL, we measured...
the total fluorescence of the rhodopsin signal in the DAPI-positive INL region of the retina (Image J).
A background fluorescence value was taken from the ONL tissue, which was subtracted from the total rhodopsin fluorescence value of the INL to attain a corrected measure of rhodopsin mislocalization within the INL. Groups of 5–7 zebrafish were compared statistically by 1-way ANOVA with no post-hoc correction (GraphPad).

Visual startle response (VSR). Automated VSR experiments were adapted from the protocol described in Scott et al. (55). Prior to the assay, 5 dpf larvae were transferred to 96-well plate and placed in the DanioVision (Noldus). The larvae went through an acclimation period (30 minutes, light) and a 2.5-minute testing period (5 cycles of 1 second dark followed by 29 seconds light). Ethovision software tracked and recorded the movement of zebrafish in 1-second increments for the entire duration of the experiment (32.5 minutes). The activity metrics were exported to excel file format. Using excel software, the activity results of the testing period were filtered out (Microsoft) and the number of VSR were determined at the threshold > 0.01.

Statistics. GraphPad Prism for Windows (GraphPad Software) was used for statistical analyses. The quantification data are presented as the box-and-whiskers plot (Tukey’s method). All data were analyzed using a 1-way ANOVA (retina staining and VSR), a 2-tailed Student’s t test (qPCR and Western blot quantification) or the \( \chi^2 \) test (CE and renal morphology). A \( P \) value less than 0.05 was considered statistically significant.

Study approval. The zebrafish experiments were approved by the IRB (Duke University IACUC, Durham, North Carolina, USA). All animal work was performed in accordance with protocols approved by the Duke University IACUC.

Author contributions
NK and ICT designed the study, and ICT, KAA, JAT, OS, and PLT performed the experiments. NK and ICT wrote the main manuscript text, and ICT and KA prepared the figures. All authors approved and commented on the manuscript.

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