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A transposase-derived gene required for human brain development

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1 **Abstract:** DNA transposable elements and transposase-derived genes are present in most living
2 organisms, including vertebrates, but their function is largely unknown. PiggyBac Transposable
3 Element Derived 5 (PGBD5) is an evolutionarily conserved vertebrate DNA transposase-derived
4 gene with retained nuclease activity in human cells. Vertebrate brain development is known to be
5 associated with prominent neuronal cell death and DNA breaks, but their causes and functions are
6 not well understood. Here, we show that PGBD5 contributes to normal brain development in mice
7 and humans, where its deficiency causes disorder of intellectual disability, movement, and
8 seizures. In mice, Pgbd5 is required for the developmental induction of post-mitotic DNA breaks
9 and recurrent somatic genome rearrangements. In the brain cortex, loss of Pgbd5 leads to aberrant
10 differentiation and gene expression of distinct neuronal populations, including specific types of
11 glutamatergic neurons, which explains the features of PGBD5 deficiency in humans. Thus,
12 PGBD5 might be a transposase-derived enzyme required for brain development in mammals.

13

14 **One-Sentence Summary:** PiggyBac Transposable Element Derived 5 (PGBD5) is required for
15 brain development in humans and mice through genetic and epigenetic mechanisms.

1 Vertebrate brain development requires neuronal cell diversification and self-organization
2 into signaling networks (1). While cell diversification is required for the development of many
3 tissues, the development of nervous and immune systems is also uniquely dependent on DNA
4 break repair and developmental apoptosis (2-9). For example, several human DNA damage repair
5 deficiency syndromes, such as ataxia telangiectasia (AT) and Seckel syndromes, exhibit both
6 abnormal brain neuron development and immune lymphocyte deficiencies. Likewise, mice
7 deficient for the evolutionarily conserved DNA repair factors, such as *Xrcc5/Ku80*, are also
8 characterized by abnormal neuron and lymphocyte development. In developing immune
9 lymphocytes, efficient end-joining DNA repair is required to ligate DNA breaks induced by the
10 domesticated DNA transposase RAG1/2 during somatic diversification of immunoglobulin
11 receptor genes. Somatic genetic neuronal diversification of cell adhesion receptors was originally
12 proposed more than 50 years ago to provide a mechanism for the complex organization of
13 vertebrate brains (10). Initially considered for clustered protocadherins based on their structural
14 similarity to the immunoglobulin receptor genes (11, 12), somatic DNA breaks have now been
15 detected in a diverse set of neuronal genes (13, 14). Indeed, recent single-cell sequencing studies
16 have found extensive somatic genetic mosaicism in human neurons (13, 15-17), as bolstered by
17 numerous prior studies in mice (13, 18, 19). While somatic DNA rearrangements and
18 developmental apoptosis are known to be essential for the evolution and function of vertebrate
19 adaptive immunity, the mechanisms of somatic DNA breaks and neuronal apoptosis during brain
20 development remain obscure.

21 Recently, we found that PiggyBac Transposable Element Derived 5 (PGBD5), the most
22 evolutionarily conserved domesticated DNA transposase-derived gene in vertebrates, is expressed
23 in most childhood solid tumors where it mediates sequence-specific oncogenic DNA
24 rearrangements dependent on its putative nuclease activity and cellular end-joining DNA repair
25 (20-22). PGBD5-induced DNA rearrangements in human cells have been validated by multiple
26 laboratories (20, 23), and recently also confirmed independently by Bigot et al (24). Since most
27 PGBD5-expressing childhood solid tumors share a common neuroectodermal developmental
28 origin (21, 24, 25), we hypothesized that PGBD5 may be required for normal nervous system
29 development, at least in part by mediating somatic DNA rearrangements in developing neurons.
30 Indeed, PGBD5 is expressed predominantly in nervous system tissues, and the brain in particular
31 (Fig. 1A-B & S1A-B), with the highest expression in glutamatergic neurons followed by
32 GABAergic neurons, both in humans (Fig. S2A&C) and mice (Fig. S2B&D).

33 To investigate the function of PGBD5 in human brain development, we identified five
34 unrelated consanguineous families with *PGBD5* mutations using GeneMatcher (26). Exome
35 sequencing analysis demonstrated distinct homozygous *PGBD5* mutations segregating with
36 affected family members. We confirmed the observed *PGBD5* mutations using genomic PCR and
37 Sanger sequencing (Figure S1C, Table S1). *PGBD5* mutations in affected individuals consisted of
38 predicted nonsense and frameshift variants, most of which occurred upstream of the evolutionarily
39 conserved aspartate triad thought to be required for the biochemical activity of the *PGBD5*
40 transposase-homology domain in cells (Fig. 1C). Expression of cDNAs encoding the observed
41 *PGBD5* c.49G>T (E17*) and c.509del (F170Sfs*5) mutations led to substantial reduction of
42 PGBD5 protein in HEK293T cells (Fig. S1D-E). While additional studies will be needed to
43 establish the effects of observed mutations on endogenous loci in PGBD5-expressing cells, at least
44 some of the phenotypes of the affected individuals can be attributed to the loss of PGBD5 protein.

45

1 Importantly, affected children with inherited PGBD5 mutations shared conserved clinical
2 phenotypes across neurodevelopmental and motor domains (Fig. 1D-J; Supplemental Clinical
3 Summaries; Table S2). While quantification of brain MRI volumes did not identify quantitatively
4 significant changes (Fig. 1D), visual analysis identified thin corpus callosum (6/7) and reduced
5 cerebellar size associated with widening of the vermis folia (7/7) which became more apparent in
6 patients older than 6 years or on follow-up imaging (Fig. 1E-I). Neurodevelopmental features
7 include intellectual disability and developmental delay (ID/DD; 10/10), epilepsy (9/9), limited or
8 no speech (9/9), autism spectrum disorder or social delay (ASD; 4/6). Prominent motor features
9 included axial hypotonia (9/9), increased peripheral tone (7/9) or decreased peripheral tone (2/9),
10 increased tendon reflexes (5/9) or decreased tendon reflexes (4/9). Less frequently, we observed
11 spasticity mainly affecting the legs (5/9), intermittent dystonia (3/10), and ataxia (7/10). Some
12 patients were of short stature (5/9), although height and head circumference were generally normal.
13 We noted some dysmorphic features, including telecanthus (6/7), fleshy earlobes (8/8), deep
14 philtrum (7/8), downturned mouth corners (6/7), and short chin (6/8; Fig. 1J; Data S1 and Table
15 S2). While additional patients will be needed to define the full spectrum of human PGBD5
16 deficiency syndrome, these findings indicate that PGBD5 mutations are associated with
17 developmental delay, intellectual disability, ataxia-dystonia, and epilepsy.

18 To investigate the physiologic functions of PGBD5 in nervous system development, we
19 used a dual recombinase-mediated cassette exchange to engineer *Pgbd5^{fl/fl}* mice, in which *Pgbd5*
20 exon 4 is flanked by *loxP* sites (27). We bred *Pgbd5^{fl/fl}* mice with *Ella-Cre* mice to generate *Pgbd5^{-/-}*
21 mice (Fig. S3A), as confirmed by genomic PCR (Fig. S3C) and Sanger sequencing. *In situ*
22 hybridization microscopy analysis of the hippocampus, which has some of the highest density of
23 *Pgbd5*-expressing neurons (Figs. S1A-B, S2A-D, S3B), revealed no measurable *Pgbd5* exon 4
24 transcript expression in *Pgbd5^{-/-}* mice (Fig. S3B), though RNA sequencing analysis revealed
25 residual *Pgbd5* transcripts lacking exon 4, consistent with potential retention of truncated alleles
26 lacking the transposase domain (Fig. S3D). We also engineered *Pgbd5^{3xFLAG-HA-P2A-eGFP}* knockin
27 mice which permit specific detection of endogenous *Pgbd5* expression in cells (Fig. S4A) and
28 confirmed that *Pgbd5* is expressed in neurons but not astrocytes or microglia, as established by
29 specific co-staining with NeuN, GFAP, and TMEM119, respectively (Fig. S4B-D).

30 We found that both *Pgbd5^{-/-}* and their *Pgbd5^{wt/-}* littermate mice were born at the expected
31 Mendelian ratios (Fig. S5A-B), but *Pgbd5^{-/-}* mice were runted and had significantly smaller brains,
32 as compared to their wild-type littermates (t-test $p = 3.4E-3$ and $1.6E-2$, for females and males,
33 respectively; Fig. S5C-H). Given the neurodevelopmental deficits associated with PGBD5
34 deficiency in humans, we used specific behavioral tests correlating with features of human PGBD5
35 deficiency to examine *Pgbd5^{-/-}* mice (Fig. S6A-C). Automated video tracking locomotor test
36 analysis revealed significantly increased locomotor activity of *Pgbd5^{-/-}* and *Pgbd5^{wt/-}* mice, as
37 compared to their wild-type littermates (ANOVA $p = 5.4E-7$ and $5.5E-7$, for females and males,
38 respectively; Fig. 2A-B). We assessed anxiety using the elevated plus maze test (EPM; Fig. 2C).
39 Both female and male *Pgbd5^{-/-}* mice traveled longer distances in the open maze arms (normalized
40 to total distance traveled) as compared to their wild-type littermates, indicating reduced avoidance
41 of the anxiogenic open arm of the EPM, consistent with reduced anxiety-like behavior (ANOVA
42 $p = 2.7E-6$; Fig. 2D). Reduced avoidance of female and male *Pgbd5^{-/-}* mice was also reflected by
43 their increased entry and time spent in the open arms (Fig. S6A-B). *Pgbd5^{wt/-}* females and males
44 exhibited an intermediate phenotype in open arm time and entries indicating that a partial deficit
45 in *Pgbd5* expression is sufficient to elicit the EPM phenotype.

1 Prompted by the motor deficits of *PGBD5*-deficient humans, we assayed *Pgbd5*-deficient
2 mice using the Rotarod performance test (Figs. 2E-F & S6D-J). Despite having no significant
3 differences in grip strength ($p = 0.08$; Fig. S6H), *Pgbd5*^{-/-} mice exhibited significantly reduced
4 rotarod fall latency, consistent with impaired motor learning in males (One-way ANOVA $p = 9.2E$ -
5 3, post-hoc Tukey's test $p = 0.5E$ -3; Fig. 2E-F). Both male and female *Pgbd5*^{-/-} mice also exhibited
6 thermal hypersensitivity (Fig. S6K), without any apparent gait effects (Fig. S6I-J). Lastly, we
7 assayed *Pgbd5*-deficient mice for susceptibility to seizures. We found that most *Pgbd5*^{-/-} mice
8 developed partial motor and generalized tonic-clonic seizures in response to stressful handling as
9 compared to their wild-type littermates (χ^2 -test $p = 5.8E$ -7; Fig. 2G). To investigate the anatomic
10 basis of this complex behavioral syndrome, we used high-resolution manganese-enhanced MRI
11 (MEMRI) to analyze brain architecture in *Pgbd5*-deficient mice. This revealed significant
12 reductions in the cortical volumes in *Pgbd5*^{-/-} male and female mice, as assayed using quantitative
13 volumetric mouse brain atlas analysis (ANOVA Bonferroni-adjusted $p = 1.9E$ -2 and $9E$ -4,
14 respectively; Fig. 2H-I, Fig. S7B-C). Overall, *Pgbd5*-deficient mice display complex behavioral
15 deficits, including seizures, behavioral and motor deficits, and structural brain abnormalities that
16 resemble the human *PGBD5* deficiency syndrome.

17 PiggyBac-type enzymes utilize conserved aspartate residues to catalyze DNA hydrolysis
18 and rearrangements, with analogous residues required for the cellular DNA remodeling activities
19 of *PGBD5* (21, 28), though whether *PGBD5* functions enzymatically as a transposase,
20 recombinase, or a different type of nuclease needs to be determined (24). To test whether mouse
21 brain development requires *Pgbd5* nuclease activity, we used CRISPR engineering to generate
22 *Pgbd5*^{D236A/D236A} knock-in mice (*Pgbd5*^{ki/ki}; Fig. 2J & S8A), in which one of the evolutionarily
23 conserved aspartate residues required for cellular DNA activity was mutated to inactive alanine
24 (20). We confirmed that the analogous mutation in human *PGBD5* does not impair cellular protein
25 stability by Western immunoblotting or its ability to associate with chromatin by ChIP-seq (20,
26 21). We verified *Pgbd5*^{D236A} mutation in two independent founder strains using genomic PCR and
27 Sanger sequencing (Fig. S8A), germ-line transmission by restriction enzyme mapping (Fig. S8B),
28 and lack of off-target gene mutations by whole-genome sequencing (Fig. 2L; Table S3).
29 Homozygous *Pgbd5*^{ki/ki} mice exhibited physiologic and unaltered expression of endogenous *Pgbd5*
30 mRNA as compared to their *Pgbd5*^{wt/wt} littermates, as assessed using in situ hybridization with
31 *Pgbd5*-specific probes (Fig. 2K). *Pgbd5*^{ki/ki} mice showed no difference in body weights as
32 compared to their wild-type littermates (Fig. 2M-N) but exhibited tonic-clonic seizures similar to
33 *Pgbd5*-deficient mice (χ^2 -test $p = 7.4E$ -05; Fig. 2O). Thus, brain functions of *Pgbd5* at least in part
34 require specific aspartate activity of its transposase-homology domain.

35 Mammalian neurogenesis occurs largely during embryonic development, with mouse
36 cortex development peaking in the mid-to-late embryos (29). Given the well-defined layered
37 organization of the mouse motor cortex, we analyzed its architecture in 14.5-day old (E14.5)
38 embryos. Prior studies of this developmental period have also documented that post-mitotic
39 neurons accumulate extensive DNA breaks and activate end-joining DNA repair as they migrate
40 to the mantle layer upon differentiation of progenitor neuroblasts in the ventricular zone (2, 3, 7).
41 Thus, we used a neuron-specific tubulin isoform Tuj1 as a specific marker of post-mitotic neurons
42 (30), and immunofluorescence microscopy to examine post-mitotic neurons in the brain cortices
43 of 14.5-day old embryonal (E14.5) *Pgbd5*^{-/-} mice (Fig. 3A-C & S9-S13).

44 Using γ H2AX as a specific surrogate of neuronal DNA break repair (31), we observed a
45 significant reduction in the number of neurons with γ H2AX foci specifically among post-mitotic

1 (Tuj1-positive), as compared to proliferating (Tuj1-negative) neuronal precursor in *Pgbd5*^{-/-} mice
2 as compared to their wild-type littermates (t-test $p = 0.029$; Fig. 3D-E & S14A-B). We confirmed
3 the specificity of this effect by analyzing the fraction of Tuj1-negative neurons in brain cortical
4 neurons, which showed no significant differences between *Pgbd5*-deficient and wild-type
5 littermate brains (Fig. 3D-E & S15A). The observed *Pgbd5*-dependent neuronal γ H2AX foci were
6 specifically induced during cortical neuronal development in E14.5 embryos, as analysis of E12.5
7 brain cortices which contain only a single mantle layer revealed no significant differences (Fig.
8 S16). Importantly, *Pgbd5*^{ki/ki} mice also exhibited significant reduction of γ H2AX foci as compared
9 to wild-type littermate controls (t-test $p = 3.8E-3$ and $2.9E-3$ for Tuj1-positive and negative
10 neurons, respectively; Fig. 3F-G) Thus, *Pgbd5* and enzymatic activity of transposase-homology
11 domain are specifically required for the developmental induction of DNA breaks and/or their
12 resolution during cortical brain development.

13 While *Pgbd5* contains an evolutionarily conserved and transposase-derived gene with
14 nuclease cellular activity (20, 21), it is possible that the observed DNA breaks in neurons occur
15 independently of its DNA breakage activity. To determine whether *Pgbd5*-dependent neuronal
16 DNA breaks require DNA double-strand break repair, we analyzed genetic interaction between
17 *Pgbd5* and *Xrcc5/Ku80*, the key factor in non-homologous end-joining (NHEJ) DNA repair (Fig.
18 4E). NHEJ DNA repair is required for the ligation of double-strand DNA breaks induced by many
19 'cut-and-paste' DNA transposase enzymes and their domesticated derivatives like PGBD5 and
20 RAG1/2 (32). Similar to human DNA damage repair deficiency syndromes, such as AT and Seckel
21 syndromes, *Xrcc5*^{-/-} mice have neurodevelopmental defects, associated with unrepaired DNA
22 breaks and extensive neuronal apoptosis during cortical development, as well as severe combined
23 immunodeficiency due to the failure to repair RAG1/2-induced DNA breaks and rearrangements
24 in developing lymphocytes (33).

25 First, we confirmed that *Xrcc5*^{-/-} mice failed to produce normal T- and B-lymphocytes, as
26 assayed by fluorescence-activated cell scanning (FACS) using CD4/CD8 and B220/IgM-specific
27 antibodies, respectively, as compared to their wild-type or *Pgbd5*^{-/-} littermates (Figs. S21I-J &
28 S22). In agreement with prior studies, *Xrcc5*^{-/-} mice showed a significant increase in the number
29 of neurons with γ H2AX breaks as compared to their wild-type littermates in post-mitotic neurons
30 (t-test $p = 4.1E-2$; Fig. 4C) and proliferative progenitors (t-test $p = 2.4E-2$; Fig. 4D). Remarkably,
31 we found that *Pgbd5*^{-/-};*Xrcc5*^{-/-} mice had significantly reduced DNA damage as compared to their
32 *Pgbd5*^{wt/wt};*Xrcc5*^{-/-} littermates (t-test $p = 4.1E-2$ and $2.4E-2$ for Tuj1-negative and positive neurons,
33 respectively; Figs. 4C-D, S14C-D, and S17-20). Thus, *Pgbd5*-induced neuronal DNA damage
34 repair requires *Xrcc5* (Fig. 4E). Commensurate with the physiologic function of developmental
35 neuronal DNA break repair, we found that *Pgbd5*^{-/-};*Xrcc5*^{-/-} mice were similarly runted and failed
36 to thrive as compared to their *Pgbd5*^{wt/wt};*Xrcc5*^{-/-} littermates (Fig. S21A-H & S22), which was
37 associated with increased neuronal cell death as measured by terminal deoxynucleotidyl
38 transferase dUTP nick end labeling (TUNEL) specifically in E14.5 but not E12.5 brains (t-test p
39 $= 1.5E-2$ and $p = 0.89$, respectively; Fig. S23). In all, these findings indicate that *Pgbd5* is required
40 for the developmental induction of DNA breaks and cortical brain development.

41 To determine whether *Pgbd5* induces somatic DNA rearrangements during brain
42 development, we used PCR-free paired-end Illumina whole-genome sequencing (WGS) of diverse
43 anatomically dissected brain regions from multiple individual *Pgbd5*-deficient and wild-type
44 littermate mice. Current single-cell DNA sequencing methods enable accurate detection of single
45 nucleotide variation, but their requirements for DNA amplification prevent the detection of larger

1 rearrangements, such as those expected from DNA nucleases (34). While bulk PCR-free DNA
2 sequencing is not sufficiently sensitive to detect DNA rearrangements occurring in single neurons,
3 we reasoned that if *Pgbd5* functions as a somatic neuronal DNA nuclease, its developmental
4 activity would yield recurrent somatic signals in multiple diverse wild-type but not *Pgbd5*^{-/-} litter
5 mate brains via involvement of shared loci and/or sequences in bulk cell sequencing.

6 We tested this conjecture by analyzing somatic DNA rearrangements observed using PCR-
7 free paired-end Illumina WGS analysis of peripheral blood mononuclear cells (PBMC) isolated
8 from 30-day old mice (mean genome coverage 90-fold, Fig. 5A). First, we validated that our
9 analysis was not biased by sequencing coverage (Fig. S24A-B) and produced accurate detection
10 of somatic DNA variants based on the allele frequencies in matched tissues (Fig. S24C-F). We
11 analyzed the resultant sequencing data using recently developed methods optimized for the
12 accurate detection of somatic genome variation (35-37).

13 Consistent with the known somatic V(D)J DNA recombination activity of RAG1/2 in
14 blood lymphocytes, we observed somatic deletions of the *Igkj1* and *Igkj2* loci (among other
15 immunoglobulin receptor genes) with common breakpoints in multiple sequencing reads in PBMC
16 as compared to matched brain tissue (mean variant fraction = 0.015; Fig. S25A). Lack of apparent
17 somatic deletions of *Igkj1* and *Igkj2* or related immunoglobulin gene loci in fetal spleens of 14.5-
18 day old mouse embryos as compared to their matched brain tissue confirmed the specificity of this
19 approach (Fig. S25A), consistent with the known absence of RAG1/2 activity in fetal
20 hematopoietic cells in mouse spleen (38). In contrast, we observed clonal deletions of *Pgbd5* exon
21 4 in both adult PBMCs and fetal spleens of *Pgbd5*^{-/-} mice but not in their *Pgbd5*^{wt/wt} littermates
22 (Fig. S25B).

23 Using this comparative approach to detect developmental somatic DNA rearrangements by
24 the domesticated RAG1/2 DNA recombinase in blood cells, we examined somatic genomic
25 variation of brain tissues dissected from *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} littermate mice. We performed
26 independent analyses to quantify somatic single nucleotide variants (SNVs) and DNA
27 rearrangements such as deletions, and then tested for their recurrence by comparing genomic
28 locations of somatic variants in individual mice or their anatomic brain regions, as explained in
29 detail in the methods section. We observed no significant differences in somatic SNVs in the brain
30 tissues of both 30-day old adult and 14.5-day old embryonal *Pgbd5*^{wt/wt} as compared to their *Pgbd5*^{-/-}
31 litter mate mice, consistent with their equal chronological and biological age (median allele
32 fraction = 0.096 and 0.094 for adult *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} mice, respectively; Fig. S23A-B).

33 In agreement with the stochastic nature of somatic nucleotide substitutions, most of which
34 are due to DNA replication errors in proliferating tissues (39), we also found no genomic regions
35 that recurrently accumulated somatic SNVs across different brain regions or different individual
36 mice, which have an apparently random distribution across the mouse genome (Fig. S26A-B;
37 Table S4). We then focused on the analysis of somatic deletions, insertions, and duplications in
38 adult and embryonal *Pgbd5*^{wt/wt} brains, as compared to their *Pgbd5*^{-/-} litter mate controls (Fig.
39 S27A-F). While we observed some differences in the various types of structural DNA
40 rearrangements, there were no statistically significant differences in the total numbers of somatic
41 DNA rearrangements between *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} brains, both in adults and embryos (Fig.
42 S27A-F).

43 In contrast, individual adult *Pgbd5*^{wt/wt} mice showed significantly more recurrent somatic
44 DNA rearrangements both among different individual mice and their cerebella, hippocampi, and
45 olfactory bulbs, as compared to their *Pgbd5*^{-/-} litter mates. This was detected using both recurrence

1 of somatic structural rearrangement breakpoints and their complete overlaps (24 versus 12, and 10
2 versus 2, respectively; χ^2 -test $p = 1.3\text{E-}9$ and $1.6\text{E-}17$, respectively; Figs. 5A-D & S26C-G).
3 Importantly, there were no significant differences in the recurrence of somatic DNA
4 rearrangements in 14.5-day old embryonal brain tissues isolated from *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} litter
5 mate embryos (Fig. 5D & S26G), consistent with the onset of *Pgbd5/Xrcc5*-dependent DNA break
6 repair during this developmental period.

7 Finally, recurrent somatic DNA rearrangements shared among different individual mice
8 and brain regions showed distinct genomic distributions (Figs. 5E & S26H; Table S4). Manual
9 inspection of sequencing reads of a subset of DNA rearrangements was consistent with their
10 somatic induction in brain tissues in *Pgbd5*^{wt/wt} but not *Pgbd5*^{-/-} littermate mice (Fig. S28A-C;
11 Table S4). While the definition of physiologic *Pgbd5* genomic targets and their rearranged
12 sequences will require the development of improved single-cell genomic sequencing methods, we
13 propose that the somatically rearranged genomic elements identified here represent signals of
14 developmental physiologic *Pgbd5* activity in normal brain development.

15 To elucidate the specific neuronal populations that may require *Pgbd5* activity during brain
16 development, we performed single-nucleus RNA-sequencing (snRNA-seq) combined with assay
17 for transposase-accessible chromatin-sequencing (snATAC-seq) of nuclei isolated from the brain
18 motor cortex of three 21-day old *Pgbd5*^{wt/wt} and three *Pgbd5*^{-/-} littermate mice (Fig. 6A, Table S5).
19 Upon mapping the observed gene expression onto the developmental ontogeny of normal mouse
20 cortex using two recently established brain atlases (40, 41), we clustered the gene expression states
21 of detected nuclei. This identified specific *Pgbd5*-expressing neuronal populations, as compared
22 to astrocytes, oligodendrocytes and immune cells, most of which lack *Pgbd5* expression (Figs. 6B
23 & S29A-C; Table S6). First, we confirmed that the *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} brain cortices had
24 relatively equal cellular sampling, consistent with their preserved overall morphologic
25 organization (Fig. S4). We found no significant differences in the apparent proportions of
26 annotated cell types between *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} brain cortices (Fig. S30A-B).

27 In contrast, there were significant differences in gene expression of specific populations of
28 neurons with both relatively high and low *Pgbd5* expression between *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-}
29 brains (Fig. 6C). This included the large population of high *Pgbd5*-expressing intratelencephalic
30 (IT) glutamatergic pyramidal neurons of layers 2/3, 4/5, and 6 that project to other cortical areas
31 and the striatum (42), as well as the smaller population of low *Pgbd5*-expressing *Meis2*
32 GABAergic interneurons that are present in the cortical white matter and likely represent
33 projection neuron precursors (43, 44) (Fig. 6C). Interestingly, pyramidal tract (PT) neurons, which
34 are the other major cortical pyramidal neurons that project to subcortical structures, as well as
35 cortical GABAergic *Pvalb*, *Sst*, *Vip* interneurons, had relatively few differentially expressed
36 genes, consistent with the distinct function of *Pgbd5* in specific neuronal populations (Fig. 6C).
37 Thus, loss of *Pgbd5* induces distinct changes in the organization and gene expression of cortical
38 neurons.

39 We next assessed changes in the chromatin accessibility of promoter regions of
40 differentially expressed genes between *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} cells. Significantly affected cortical
41 neuronal populations included glutamatergic cluster 5 layers 2/3 and 4/5 IT and cluster 9
42 GABAergic *Meis2* neurons (Figs. 6F-G & S32A-D). We also observed substantial correlations
43 between differential gene expression and chromatin accessibility of distinct sets of genes (Figs.

1 6D & 6F). The concordance between *Pgbd5*-dependent gene expression and chromatin
2 accessibility suggests that *Pgbd5* deficiency leads to the dysregulation of specific gene expression
3 within neuronal populations. Gene ontology pathway analysis of differentially expressed genes
4 from the cortical neuronal populations revealed multiple sets of genes involved in the regulation
5 of neuronal membrane potentials, synapse organization, ion channel signaling, and neuronal and
6 axonal projection regeneration, among other neuronal functions (Figs. 6E-G & S31A-B). At least
7 in part, this may explain the phenotype of human PGBD5 deficiency, including developmental
8 delay, intellectual disability, ataxia-dystonia, and in particular epilepsy, given its known imbalance
9 of excitatory and inhibitory neuronal activity (45). In all, these results indicate that *Pgbd5* is
10 required for the function of specific excitatory and inhibitory cortical neurons.

11 Although somatic genetic mosaicism has been documented extensively in diverse tissues,
12 and somatic genetic diversification during neuronal development was originally proposed more
13 than 50 years ago (10), the existence of physiologic somatic DNA rearrangements in vertebrate
14 brain development has not been proven so far. Here, we demonstrate that an evolutionarily
15 conserved domesticated DNA transposase-derived PGBD5 is an unanticipated cause of double
16 strand DNA breaks in normal neuronal and mammalian brain development. We provide evidence
17 that PGBD5 is required for normal brain development in humans and mice, where its genetic
18 inactivation constitutes the PGBD5 deficiency syndrome, characterized by developmental delay,
19 intellectual disability, language and motor impairments, seizures, and reductions in corpus
20 callosum and cerebellar size. This function likely requires the nuclease activity of PGBD5, as
21 evident from studies of mice engineered to express an enzymatically impaired *Pgbd5* nuclease
22 mutant.

23 We observe that *Pgbd5* is responsible for recurrent somatic DNA breaks in mouse brains,
24 which explains the long-standing observations of the requirement of NHEJ DNA repair for
25 mammalian brain development. Similar to RAG1/2-dependent somatic genetic diversification
26 during normal lymphocyte development, mammalian neuronal development also requires the
27 evolutionarily conserved NHEJ DNA repair factor XRCC5/Ku80, which we now show to be
28 associated with PGBD5-dependent neuronal DNA breakage. While we cannot exclude the formal
29 possibility that PGBD5 induces DNA breaks to promote cortical neuronal death occurring during
30 the same developmental period, we provide evidence that *Pgbd5*-induced somatic DNA
31 rearrangements affect recurrent neuronal chromosomal loci. In all, this study establishes the human
32 PGBD5 deficiency syndrome and identifies distinct neuronal populations and *Pgbd5*-dependent
33 gene expression programs required for normal mammalian brain development and function. These
34 findings and diverse engineered mouse models set a foundation for the identification of molecular
35 mechanisms of PGBD5 and its substrates for neuronal genetic diversification and self-organization
36 in brain development.

37 PGBD5-mediated somatic neuronal DNA rearrangements may offer a genetic mechanism
38 for neuronal group selection and developmental apoptosis, which are known to affect a large subset
39 of cells produced during mammalian neuronal development (46-48). Many studies have implicated
40 DNA replication as a cause of somatic genetic brain mosaicism. However, this mechanism does
41 not explain how DNA breaks and repair occur in post-mitotic neurons. The data presented here
42 offer a plausible mechanism by which physiologic somatic DNA rearrangements induced by
43 PGBD5 may contribute to somatic neuronal diversification and cellular selection as progenitor

1 neuroblasts differentiate and exit the cell cycle and migrate from the ventricular zone to the mantle
2 layer, where post-mitotic neurons exhibit NHEJ-dependent DNA damage and apoptosis (2, 3, 7).
3 Indeed, independent concurrent study by Gustincich and Sanges and colleagues has also identified
4 *Pgbd5* as a cause of developmental neuronal DNA breaks in mice, with *Pgbd5* being required for
5 normal brain cortical neuronal migration and differentiation (49). Since *RAG1/2* targets distinct
6 genomic loci in developing B- and T-lymphocytes, *PGBD5* targets may also depend on neuronal
7 differentiation and function, and in the case of the brain cortex, the specific neuronal populations
8 identified in this study (Figs. 6D-G and S31-32). Future studies will be needed to define *PGBD5*
9 functions in various brain regions including the hippocampus and medial temporal regions, given
10 the prominent seizure phenotype of *PGBD5* deficiency.

11 While we favor the conclusion that *PGBD5* acts directly on DNA (20, 21, 24), additional
12 biochemical and structural studies will be needed to define the exact enzymatic mechanisms of
13 *PGBD5* cellular activities and their developmental regulatory factors, including the possibility that
14 *PGBD5* promotes somatic DNA rearrangements through recruitment of other nucleases and
15 chromatin remodeling factors. It is also possible that *PGBD5* has additional nuclease-independent
16 functions in nervous system development, such as those mediated by interactions with chromatin
17 and other cellular factors. Finally, we cannot exclude non-central nervous system contributions to
18 the developmental defects observed in *PGBD5*-deficient mice and humans, as *PGBD5* is likely
19 expressed in other neuronal tissues such as neuroendocrine and peripheral nervous system.

20 We must emphasize that *PGBD5*-dependent DNA rearrangements are not solely
21 responsible for the physiologic requirement for DNA damage repair in nervous system function.
22 For example, post-mitotic neurons also require *XRCC1*-dependent base excision/single-strand
23 break repair due to single-strand DNA breaks induced by developmental cytosine demethylation
24 (46). Recent studies have also shown that brain aging may involve additional somatic genetic
25 processes (47, 48). While we used amplification-free DNA sequencing, specificity and sensitivity
26 of bulk Illumina sequencing have intrinsic limitations, and further studies using amplification-free
27 single-cell analyses will be needed to establish specific somatic neuronal DNA rearrangements
28 and their functions, as recently shown by mapping recurrent mosaic copy number variation in
29 human neurons (17).

30 Developmentally controlled DNA rearrangements have been discovered in diverse
31 biological processes. For example, in addition to the function of the domesticated DNA
32 transposase *RAG1/2* in immunoglobulin receptor gene diversification in vertebrate lymphocytes
33 (50), the *Spo11* DNA recombinase initiates recombination in eukaryotic meiosis (51), the *Kat1*
34 DNA transposase controls the yeast mating switching (52), and the *PiggyMac* DNA transposase
35 mediates somatic DNA elimination during macronucleus development in ciliates (53). *PGBD5*-
36 dependent mammalian neuronal genome rearrangements suggest that other evolutionarily
37 conserved DNA transposases may be domesticated as developmental somatic nucleases. This
38 would provide molecular mechanisms for genetic diversification during physiologic somatic tissue
39 and organ development. In turn, dysregulation of these processes can cause deleterious somatic
40 mutations, leading to disease. In the case of *RAG1/2* and *PGBD5*, their dysregulation causes
41 somatic oncogenic DNA rearrangements in blood cancers and solid tumors affecting children and
42 young adults (54). Thus, dysregulation of *PGBD5* functions during brain development may also
43 contribute to the somatic DNA rearrangements in specific neurodevelopmental disorders.

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30 Supervision: AK, LJ

31 Writing – original draft: AK, LJZ, MT, RLG, MY, HM

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37 **Data and materials availability:** All data are openly available via Zenodo
38 (10.5281/zenodo.13291236), with sequencing data available from the NCBI Sequence Read

1 Archive (PRJNA876210) as well as single-nucleus RNA/ATAC-seq (GSE272642).
2 Genetically engineered mouse strains are available from the Jackson Laboratory (*Pgbd5^{fl/fl}*,
3 *Pgbd5^{D236A}*, and *Pgbd5^{3xFlag-HA-P2A-eGFP}* stock numbers 037535, 038881, and 039713,
4 respectively).

5 **Supplementary Materials**

6 Materials and Methods

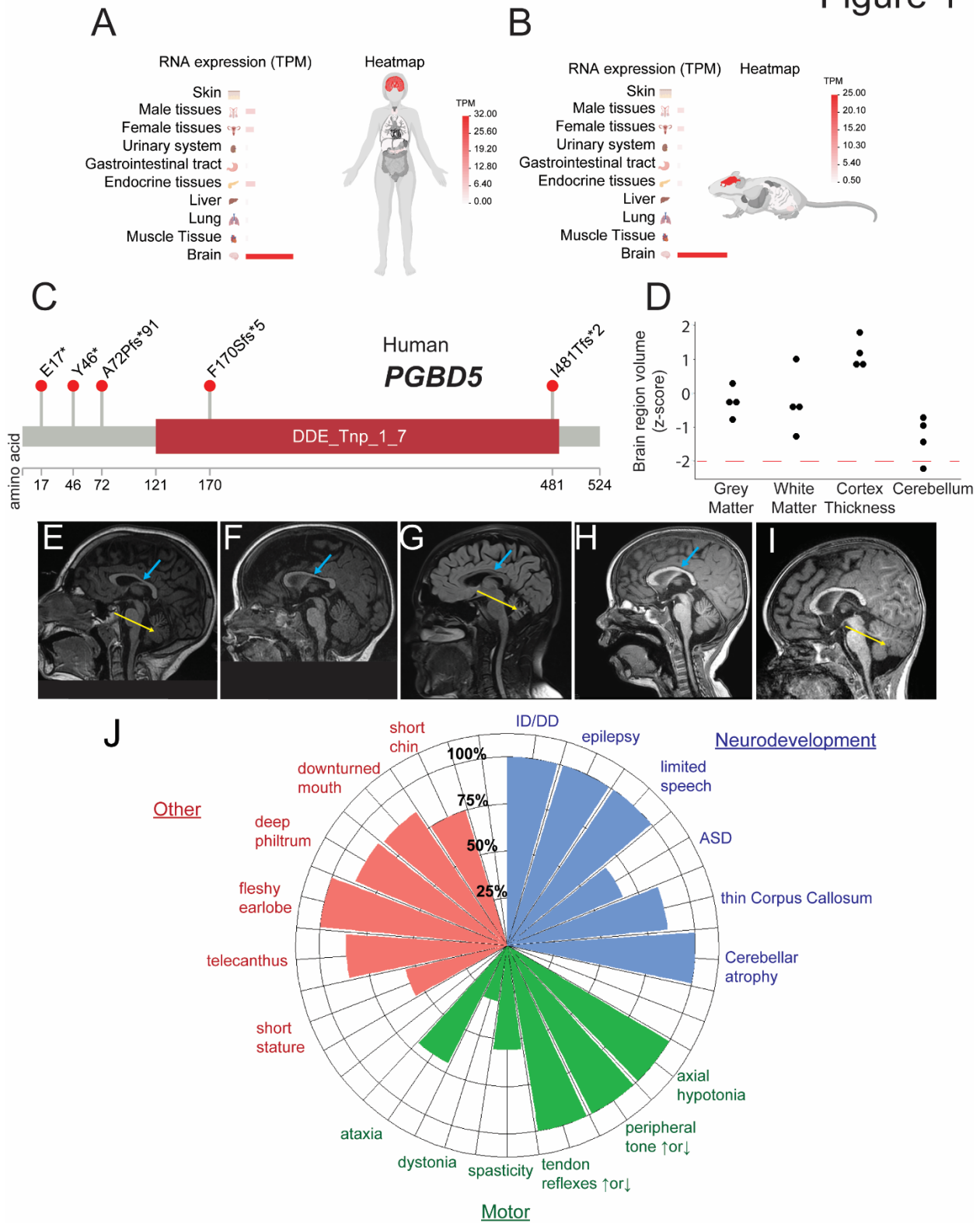
7 Supplementary Text

8 Figs. S1 to S32

9 Tables S1 to S9

10 References (01–80)

Figure 1

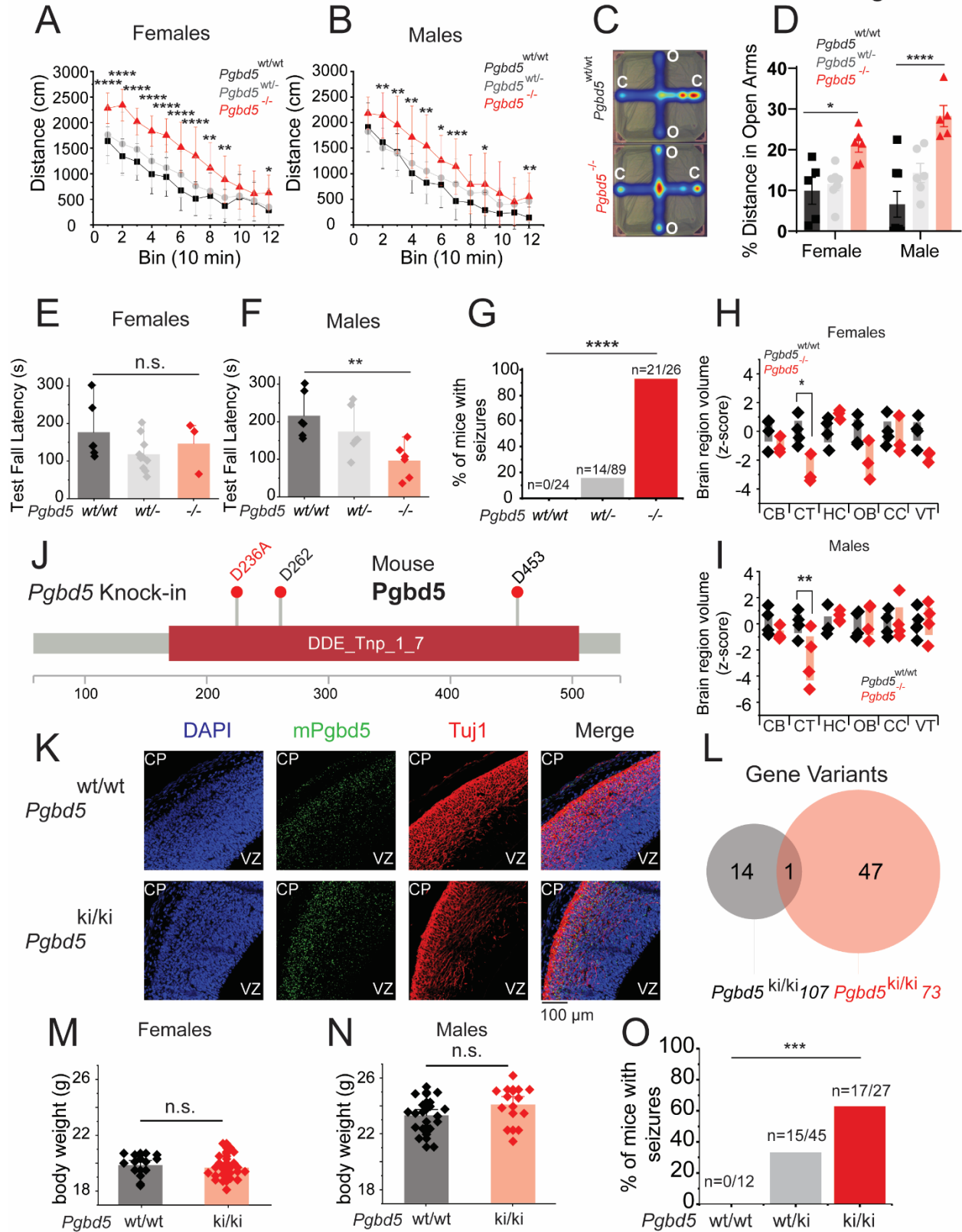


1

2

1 **Fig. 1. *PGBD5* is specifically expressed in neuronal tissues and its deficiency in humans is**
2 **associated with abnormal brain development. (A-B)** Bar graphs showing specific neuronal
3 tissue expression of *PGBD5* in human (A) and mouse (B) tissues. Color gradient from red to white
4 indicates gene expression in transcripts per million reads (TPM). (C) Schematic of the primary
5 structure of *PGBD5* with observed genetic variants, most of which appear to be loss-of-function
6 upstream of the evolutionarily conserved DDE_Tnp_1_7 transposase domain (red box). **D,**
7 Comparison of volumes of different brain structures between 4 *PGBD5* patients and age/sex
8 matched controls. Dashed red line indicates 2 standard deviations from controls. **E-I,** Sagittal MRI
9 brain images demonstrating thin corpus callosum (thick blue arrow) in patients 2 years and older
10 and decreased cerebellar size (thin yellow arrow) in patients 6 years and older. **E,** Patient 1.1 (10
11 years) with progressive cerebellar atrophy determined after repeat imaging as compared to 4 years
12 of age, **F,** Patient 1.2 (2 years) with CC thinning present, **G,** Patient 2.1 (15 years) with marked
13 cerebellar atrophy, **H,** Patient 5.1 (3 years) with some thinning of CC, **I,** Patient 5.2 (21 months)
14 with cerebellar atrophy. **J,** Phenogram summarizing frequency of conserved features in
15 neurodevelopmental, motor, and congenital anomaly domains. Frequency calculated using patients
16 with data provided, excluding N/A from denominator. ID/DD=intellectual
17 disability/developmental delay, ASD=autism spectrum disorder.
18

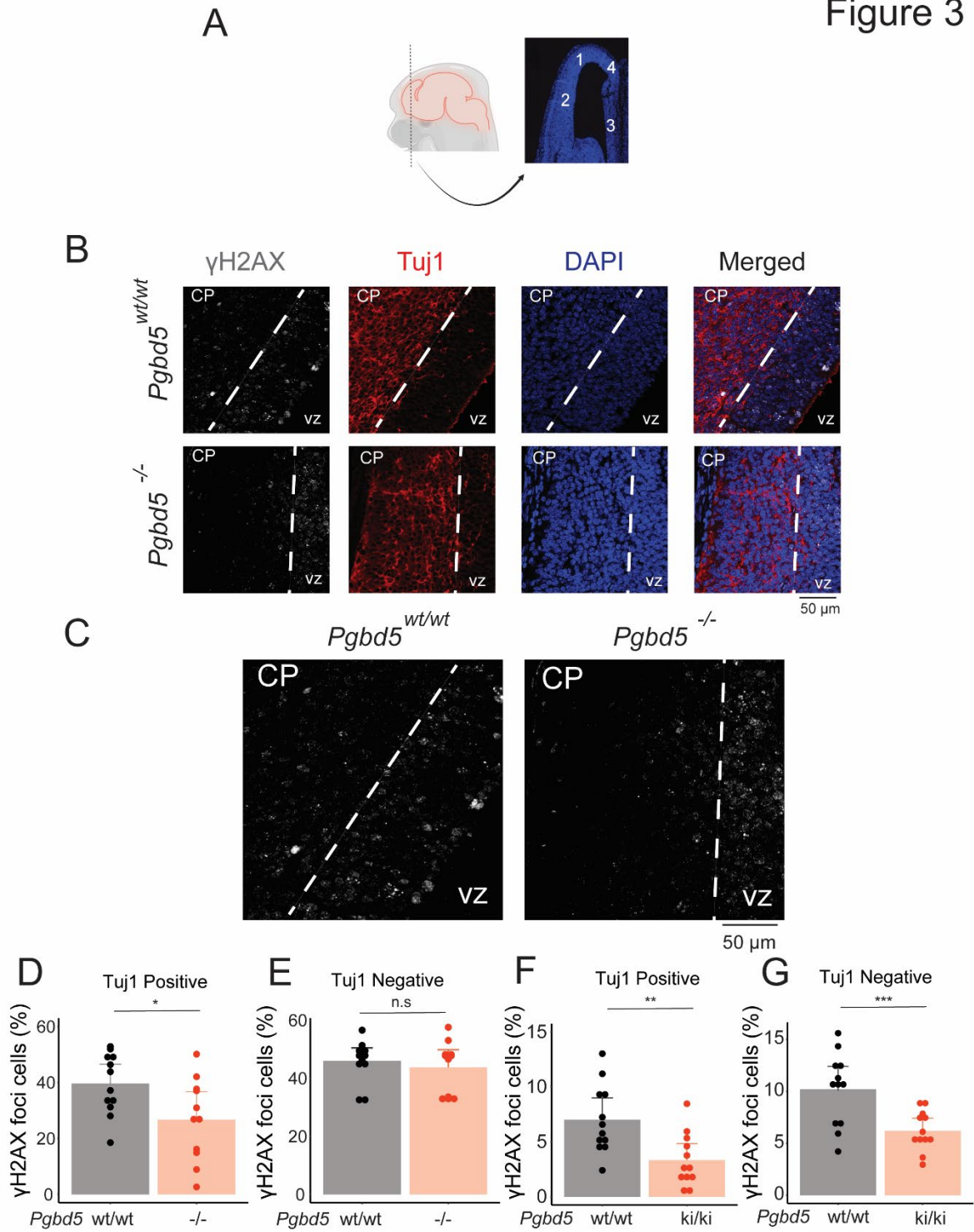
Figure 2



1 **Fig. 2. *Pgbd5* knock-out and knock-in mice reproduce behavioral and brain developmental**
2 **deficits associated with human *PGBD5* mutation. A-B,** Whisker plot analysis of the distance
3 traveled in locomotor assays of 12-week old female (A) and male (B) *Pgbd5*^{wt/wt} (black), *Pgbd5*^{wt/-}
4 (grey), and *Pgbd5*^{-/-} (red) mice, demonstrating significantly increased activity of *Pgbd5*-deficient
5 mice (Female and male $n=12$ and two-way ANOVA $p = 5.41E-7$ and $n=12$ and $p = 5.47E-5$,
6 respectively; post-hoc Tukey test * $p<0.05$, ** $p<0.01$, *** $p<0.001$, **** $p<0.0001$). C,
7 Representative heatmaps of elevated plus maze assay (color index from dark blue (low) to red
8 (high) indicates time spent in the area), with D, bar plot of the percentage of the distance traveled
9 in the open arm by 12-weeks old *Pgbd5*^{wt/wt} (black), *Pgbd5*^{wt/-} (grey), and *Pgbd5*^{-/-} (red) mice.
10 *Pgbd5*-deficient mice exhibit a significantly increased propensity to explore the open arms (Two-
11 way ANOVA $p = 2.6E-6$ for genotype and $p = 0.3$ for sex; * Tukey test $p = 0.019$ and **** $p =$
12 $2.67E-7$). E-F, Bar plots of probe day Rotarod fall latency in females (E) and males (F), showing
13 significant reduction by *Pgbd5*^{-/-} (red) as compared to *Pgbd5*^{wt/wt} in male mice (** = One-way
14 ANOVA $p = 9.2E-3$, Tukey's test $p = 7.5E-3$ in males; n.s. = One-way ANOVA $p = 0.2$, Tukey's
15 test $p = 0.76$ ** ANOVA. G, Bar plot of seizure activity of *Pgbd5*^{-/-} versus *Pgbd5*^{wt/wt} litter mate
16 mice (χ^2 -test $p = 5.8E-7$). n indicates number of mice with seizures over the total number of mice
17 assayed. H-I, Box plots of z-scores of brain MRI volumetric measurements of 60-day old *Pgbd5*^{-/-}
18 as compared to *Pgbd5*^{wt/wt} mice, showing significant reduction in cortex and ventricle size brain
19 regions in *Pgbd5*-deficient female (* = Two-way ANOVA $p = 9E-4$, Cortex Bonferroni-adjusted
20 $p = 5.7E-3$) (H) and male (** = Two-way ANOVA $p = 0.28$, Cortex Bonferroni-adjusted $p = 1.9E-2$)
21 (I) mice. J, *Pgbd5* primary protein sequence schematic indicating the location of conserved
22 aspartate triad and in red, the exon 2 D236A (ki) substitution. ENSMUST00000140012.8 *Pgbd5*
23 transposase domain highlighted in red. K, Representative fluorescence *in situ* hybridization
24 micrographs of coronal sections of heads of 14.5-day old *Pgbd5*^{ki/ki} as compared to *Pgbd5*^{wt/wt} litter
25 mate embryos, showing similar expression of *Pgbd5* transcripts between *Pgbd5*^{wt/wt} and *Pgbd5*^{ki/ki}
26 litter mates. Green staining indicates mouse *Pgbd5* RNA, red indicates Tuj1 staining of postmitotic
27 neurons and blue denotes nuclei stained with DAPI. Scale bar = 100 μ m. L, Venn diagram of gene
28 variants detected in the whole-genome sequencing of *Pgbd5*^{ki/ki} 107 and *Pgbd5*^{ki/ki} 73 founder lines.
29 Only the *Pgbd5* gene variant was found to be shared between founder lines. M-N, Total body
30 weight of 60-day old *Pgbd5*^{wt/wt} (black), and *Pgbd5*^{ki/ki} (red) mice, shows no difference of total
31 weights in females (n.s. $p = 0.3$) (M) and males (n.s. $p = 0.6$) (N) mice. O, Bar plot of seizure
32 activity *Pgbd5*^{-/-} versus *Pgbd5*^{ki/ki} litter mate mice (χ^2 -test $p = 7.41E-05$). n indicates number of
33 mice with seizures over total number of mice assayed; O = open arm, C = closed arm, CB =
34 cerebellum, CT = cortex, HC = hippocampus, OB = olfactory bulb, CC = corpus callosum, VT =
35 ventricles.

36

Figure 3

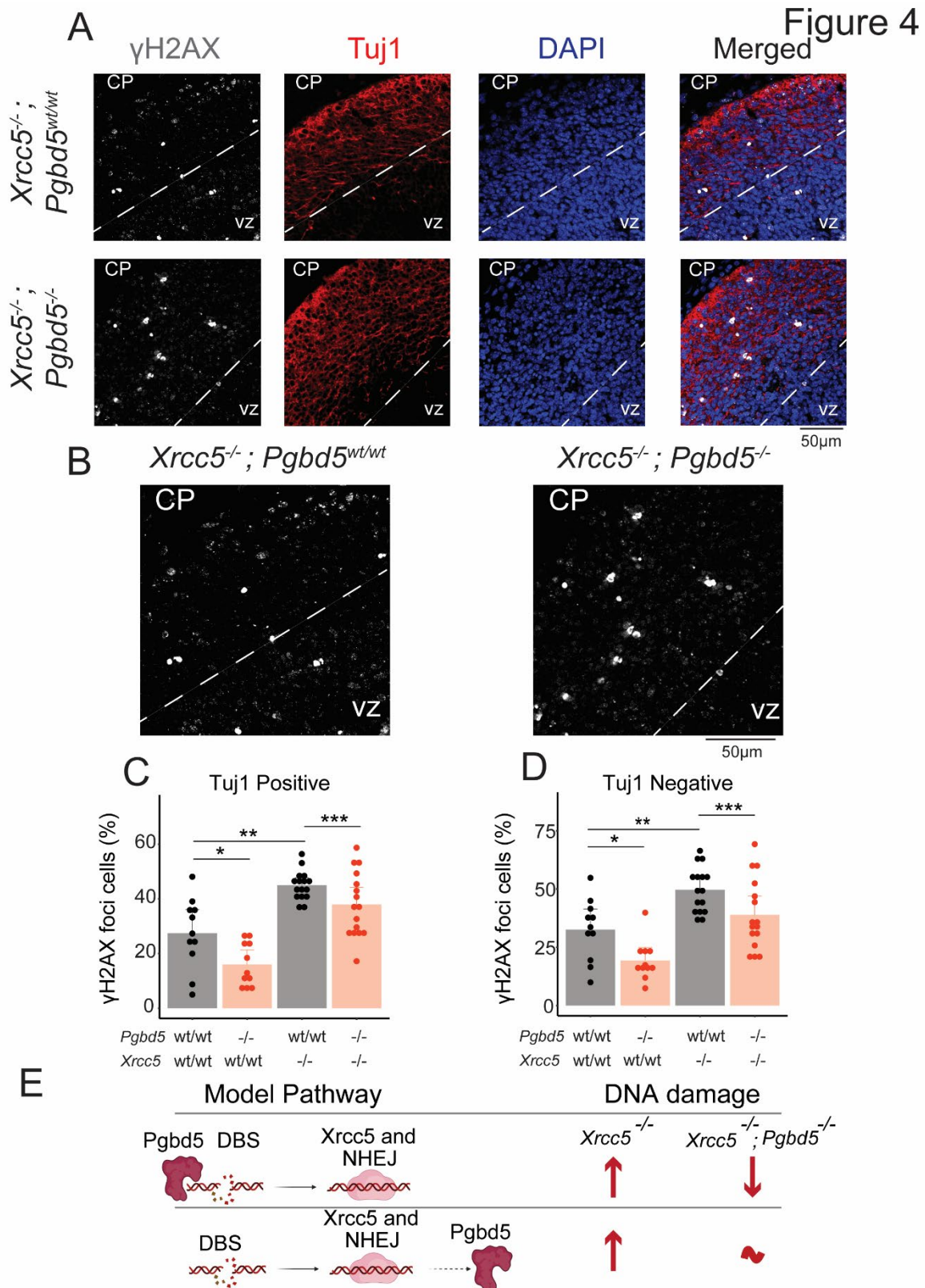


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1 **Fig. 3. *Pgbd5* is required for developmental induction of DNA breaks in postmitotic cortical**
2 **neurons. A,** Schematic showing representative coronal section of a 14.5-days old embryo mouse
3 forebrain and the regions selected for further quantification. **B,** Representative
4 immunofluorescence micrographs of *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} 14.5-day old litter mate embryos.
5 DAPI shown in blue stains nuclei, γ H2AX in white indicates sites of double-strand DNA break
6 repair, and Tuj1 in red marks differentiated postmitotic neurons; CP = cortical plate, VZ =
7 ventricular zone. **C,** Enlarged representative γ H2AX immunofluorescence micrographs from panel
8 A of *Pgbd5*^{wt/wt} (left) and *Pgbd5*^{-/-} (right) 14.5-day old litter mate embryos stained for γ H2AX in
9 white. **D-G,** Quantification of γ H2AX in postmitotic (Tuj1 positive) and proliferating neurons
10 (Tuj1 negative) in the *Pgbd5*^{wt/wt} and *Pgbd5*^{ki/ki} mice. **D-E,** Bar plots showing the percentages of
11 cells with punctate γ H2AX staining in Tuj1-positive (**D**) and Tuj1-negative neurons (**E**) in
12 *Pgbd5*^{wt/wt} versus *Pgbd5*^{-/-} mice (t-test * $p = 0.029$ and n.s. $p = 0.6$ for % of positive cells). **F-G,**
13 Bar plots showing the percentages of cells with punctate γ H2AX staining in Tuj1-positive (**F**) and
14 Tuj1-negative neurons (**G**) in *Pgbd5*^{wt/wt} versus *Pgbd5*^{ki/ki} mice (t-test ** $p = 3.8E-3$ and *** $p =$
15 $2.9E-3$ for Tuj1 positive and negative cells, respectively).
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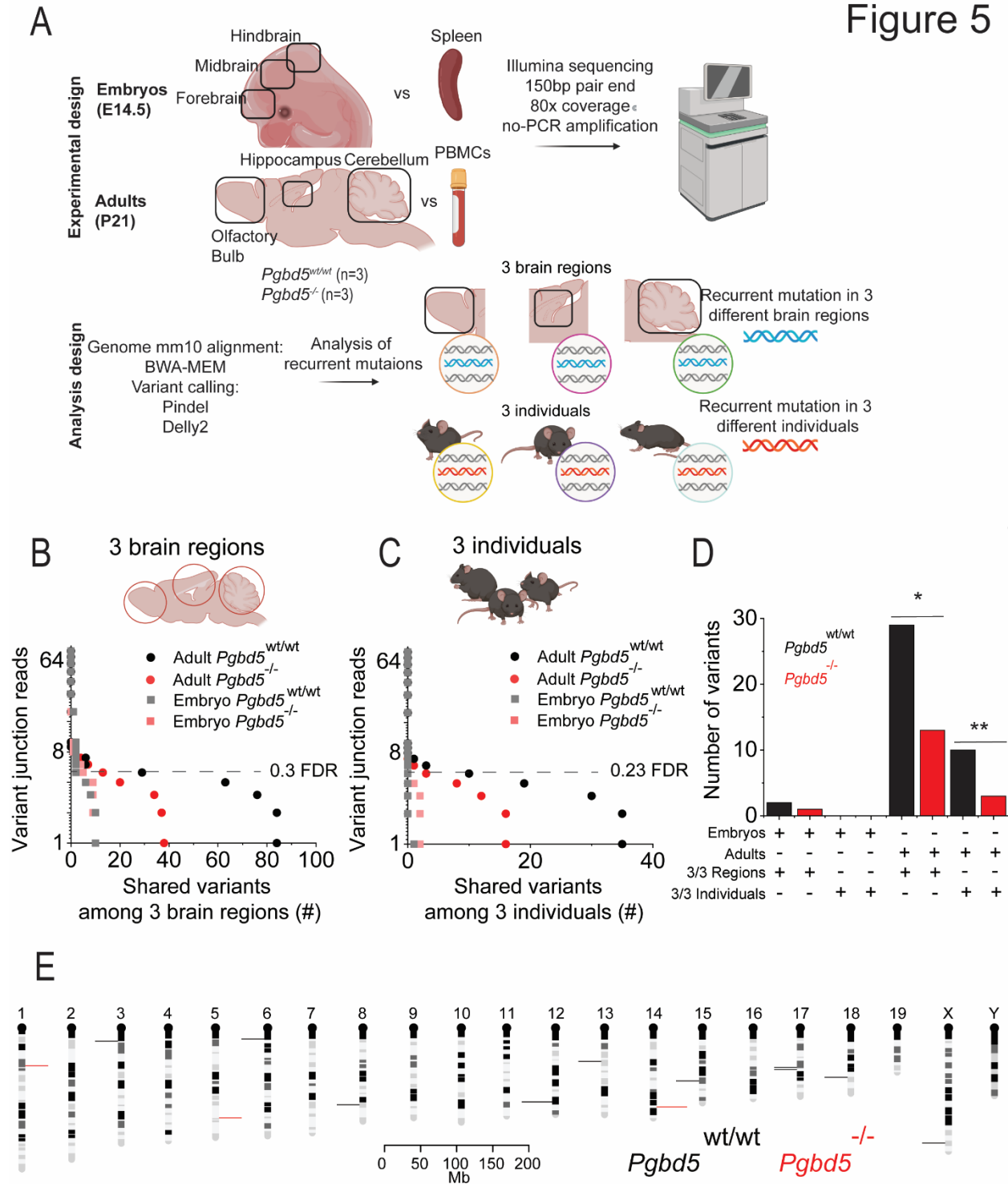
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1 **Fig. 4. *Xrcc5* is required for *Pgbd5*-induced double-strand DNA break repair. A,**
2 Representative immunofluorescence micrographs of *Xrcc5*^{-/-};*Pgbd5*^{wt/wt} (top) and *Xrcc5*^{-/-};*Pgbd5*^{-/-}
3 (bottom) 14.5-day old litter mate embryos stained for γ H2AX. DAPI nuclear staining is shown
4 in blue; γ H2AX indicates sites of double-strand break repair (white), and Tuj1 marks postmitotic
5 neurons (red); CP = cortical plate, VZ = ventricular zone. **B,** Enlarged representative
6 immunofluorescence micrographs of *Xrcc5*^{-/-};*Pgbd5*^{wt/wt} and *Xrcc5*^{-/-};*Pgbd5*^{-/-} 14.5-day old litter
7 mate embryos from panel A. **C-D,** Quantification of nuclear γ H2AX in postmitotic neurons (Tuj1
8 positive) and proliferating neurons (Tuj1 negative). Bar plots showing percentages of cells with
9 punctate γ H2AX staining in Tuj1-positive (**C**; t-test **p* = 2.3E-2, ***p* = 1E-3, and ****p* = 4.1E-2)
10 and Tuj1-negative neurons (**D**; t-test **p* = 0.012 and ***p* = 1.8E-3, ****p* = 0.024 for postmitotic
11 and proliferating neurons, respectively). **E,** Schematic showing potential genetic interaction
12 models between *Pgbd5* and *Xrcc5* in cortical neuronal developmental DNA break repair. Arrows
13 denote relative levels of DNA damage.
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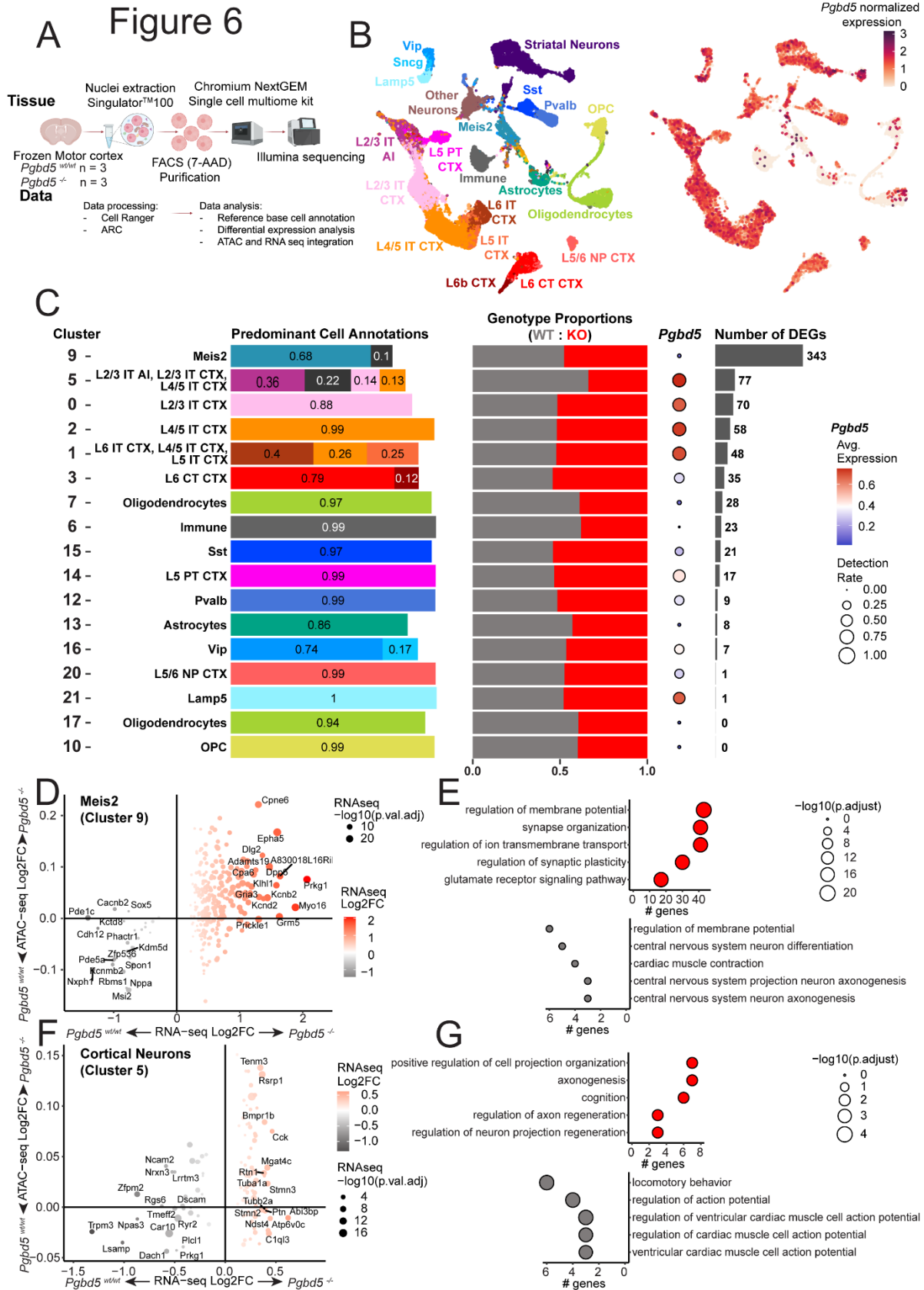
Figure 5



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1 **Fig. 5. *Pgbd5* is required for recurrent somatic DNA rearrangements in developing mouse**
2 **brain. A,** Schematics for somatic whole-genome sequencing analysis of neuronal and non-
3 neuronal tissues from three *Pgbd5*^{wt/wt} and three *Pgbd5*^{-/-} adult and embryonal littermate mice. **B-**
4 **D,** Dot plots showing numbers of somatic structural variants at different variant junction read
5 thresholds shared across cerebellum, hippocampus, and olfactory bulb brain regions (**B**) and three
6 individuals (**C**) in adult and embryonal *Pgbd5*^{wt/wt} (black circles and grey squares, respectively)
7 and *Pgbd5*^{-/-} (red circles and light-red squares, respectively). The overlap among structural variants
8 was calculated using the breakpoint analysis (Fig. S26D): 5' and 3' DNA breakpoint \pm 350bp
9 requiring an overlap of at least 1%. There are significantly more recurrent somatic structural
10 variants in *Pgbd5*^{wt/wt} with support of at least 5 variant junction reads in the recurrent events shared
11 among three individuals and three brain regions (* χ^2 -test $p = 2.2\text{E-}145$ and $2.8\text{E-}133$, respectively).
12 (**D**) Bar plot summarizing the results from **B** and **C** using the support threshold of at least 5 variant
13 junction reads. Significant differences between the number of recurrent somatic DNA
14 rearrangements between adult *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} shared among three individuals and three
15 brain regions (** χ^2 -test $p = 1.6\text{E-}17$ and $1.3\text{E-}9$, respectively). **E,** Mouse chromosome ideograms
16 showing the locations of recurrent somatic DNA rearrangements in three individuals observed in
17 *Pgbd5*^{wt/wt} (black) and *Pgbd5*^{-/-} (red) brains; bin = 1 million bases.
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1 **Fig. 6. *Pgbd5* deficiency alters gene expression in distinct cortical neurons.** **A**, Schematic of
2 experimental procedures for analysis of combined single-nucleus RNA and ATAC sequencing of
3 brain motor cortices from three *Pgbd5*^{wt/wt} and three *Pgbd5*^{-/-} littermate mice. **B**, Uniform manifold
4 approximation and projection (UMAP) plots of single nuclei gene expression from brain motor
5 cortices of *Pgbd5*^{wt/wt} and *Pgbd5*^{-/-} littermates, colored by their classification with respect to the
6 reference atlas of normal mouse brain cortex (left; $n = 18,107$ and $14,359$, respectively). Right
7 UMAP is colored by *Pgbd5* expression (normalized white to dark red). **C**, Cell clusters with greater
8 than 200 nuclei corresponding to cell populations of cortical origin in *Pgbd5*^{wt/wt} (grey) and *Pgbd5*^{-/-}
9 (red) mice, excluding ‘Striatal Neurons’ and ‘Other Neurons’. From left to right: proportions of
10 predominant cell type annotations per cluster; proportion of each genotype per cluster; expression
11 (dot color) and detection rate (dot size) of *Pgbd5* expression in wildtype cells of each cluster;
12 number of differentially expressed genes (DEG; $\log_2FC > 0.25$, adjusted $p < 0.05$) between the
13 genotypes per cluster. **D-G**, Differential expression and promoter accessibility analysis in clusters
14 corresponding to Meis2 cluster 9 (**D-E**) and cortical cluster 5 neurons (**F-G**). Bubble plots showing
15 changes in gene expression correlated with changes in chromatin accessibility at the corresponding
16 gene promoter regions (+/- 2.5kb from TSS). Only genes with significant changes in expression
17 (adjusted $p < 0.05$) are plotted in Meis2 cluster 9 (**D**) and cortical intratelencephalic (IT) neurons
18 (**F**). Top GO pathways ranked by the number of genes showing adjusted p -values in bubble size
19 for DEGs upregulated in knockout (top) and wildtype (bottom) cells of the corresponding cluster
20 in Meis2 cluster 9 (**E**) and cortical IT cluster 5 neurons (**G**).
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