

An Evolutionarily Conserved piRNA-producing Locus Required for Male Mouse Fertility

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SUMMARY (≤150 words; now 150)

Pachytene piRNAs, which comprise >80% of all small RNAs in the adult mouse testis, have been proposed to bind and regulate target RNAs like miRNAs, to cleave targets like siRNAs, or to lack biological function altogether. Although mutants lacking proteins that make pachytene piRNAs are male sterile, no biological function has been identified for any mammalian piRNA-producing locus. Here, we report that loss of piRNA precursor transcription from a conserved pachytene piRNA locus on mouse chromosome 6 (*pi6*) perturbs male fertility. Loss of *pi6* piRNAs has no measurable effect on sperm quantity or transposon repression, yet *pi6*^{-/-} mice produce sperm with defects in motility, egg fertilization, and embryo development, severely reducing pup production even at the peak of male reproduction. Our data establish a direct role for pachytene piRNAs in spermiogenesis and embryo viability and enable new strategies to identify the RNA targets of individual piRNA species.

Keywords: PIWI-interacting RNA; piRNA; MIWI; A-MYB; MYBL1, spermatogenesis; acrosome; zona pellucida; sperm; pachytene piRNA; meiosis

Highlights

- Normal male mouse fertility and spermiogenesis require piRNAs from the *pi6* locus
- Normal sperm motility and binding to zona pellucida require *pi6* piRNAs
- Sperm from *pi6* males fail to support embryo development
- Defects in *pi6* sperm reflect changes in the abundance of specific mRNAs

INTRODUCTION

Only animals produce PIWI-interacting RNAs (piRNAs), 21–35-nt small RNAs that form the most abundant class of small RNA in the germline. In most animals, piRNAs protect the germline genome from transposons and repetitive sequences, and, in many arthropods, piRNAs fight viruses and transposons in somatic tissues (Houwing et al., 2007; Aravin et al., 2008; Batista et al., 2008; Das et al., 2008; Lewis et al., 2018). The mammalian male germline makes three classes of piRNAs: (1) 26–28 nt transposon-silencing piRNAs predominate in the fetal testis (Aravin et al., 2008); (2) shortly after birth 26–27 nt piRNAs derived from mRNA 3' untranslated regions (UTRs) emerge (Robine et al., 2009); and (3) at the pachytene stage of meiosis, ~30 nt, non-repetitive pachytene piRNAs appear. Pachytene piRNAs accumulate to comprise >80% of all small RNAs in the adult mouse testis, and they continue to be made throughout the male mouse reproductive lifespan. These piRNAs contain fewer transposon sequences than the genome as a whole, and most pachytene piRNAs map only to the loci from which they are produced. The diversity of pachytene piRNAs is unparalleled in development, with >1 million distinct species routinely detected in spermatocytes or spermatids. Intriguingly, the sequences of pachytene piRNAs are not themselves conserved, but piRNA-producing loci have been maintained at the syntenic regions across eutherian mammals (Girard et al., 2006; Chirn et al., 2015), suggesting that the vast sequence diversity of pachytene piRNAs is itself biologically meaningful.

In mice, 100 pachytene piRNA-producing loci have been annotated (Girard et al., 2006; Grivna et al., 2006; Lau et al., 2006; Ro et al., 2007; Li et al., 2013). All are coordinately regulated by the transcription factor A-MYB (MYBL1), which also promotes expression of proteins that convert piRNA precursor transcripts into mature piRNAs, as well as proteins required for cell cycle progression and meiosis (Bolcun-Filas et al., 2011). Of the 100 piRNA-producing loci, 15 pairs of pachytene piRNA-producing genes

are divergently transcribed from bidirectional, A-MYB-binding promoters (Li et al., 2013). The contribution of pachytene piRNAs from each piRNA-producing locus is unequal, with just five loci—*pi2*, *pi6*, *pi7*, *pi9*, and *pi17*—contributing to >50% of all pachytene piRNA production at 17 days postpartum (dpp).

Loss of proteins required to make pachytene piRNAs, including the pachytene piRNA-binding protein, MIWI (PIWIL1), invariably arrests spermatogenesis and renders males sterile (Deng and Lin, 2002; Reuter et al., 2011; Zheng and Wang, 2012; Li et al., 2013; Castañeda et al., 2014; Wasik et al., 2015). Yet, loss of the chromosome 17 pachytene piRNA-producing locus, *17-qA3.3-27363(-),26735(+)* (henceforth, *pi17*), has no detectable phenotype or impact on male fertility (Homolka et al., 2015), even though *pi17* produces ~30% of all pachytene piRNAs. Similarly, mice disrupted in expression of a piRNA cluster on chromosome 2 are viable and fertile (P.-H.W., K.C., and PDZ, unpublished; Xu et al., 2008). Consequently, the function of pachytene piRNAs in mice is actively debated. One model proposes that pachytene piRNAs regulate meiotic progression of spermatocytes by cleaving mRNAs during meiosis (Goh et al., 2015; Zhang et al., 2015). Another model posits that pachytene piRNAs direct degradation of specific mRNAs via a miRNA-like mechanism involving mRNA deadenylation (Gou et al., 2014). A third model proposes that MIWI functions without piRNAs, and that piRNAs are byproducts without a critical function (Vourekas et al., 2012). Compelling evidence exists to support each model.

In fact, direct demonstration of piRNA function in any animal has proven elusive. Only two piRNA-producing loci have been directly shown to have a biological function—both are in flies and were identified genetically before the discovery of piRNAs (Livak, 1984; Livak, 1990; Palumbo et al., 1994; Péliesson et al., 1994; Bozzetti et al., 1995; Prud'homme et al., 1995; Robert et al., 2001; Robert et al., 2001; Mével-Ninio et al., 2007). In male flies, piRNAs from *Suppressor of Stellate*, a multi-copy gene on the Y chromosome, silence the selfish gene *Stellate*, and deletion of *Suppressor of Stellate*

leads to Stellate protein crystals in spermatocytes (Aravin et al., 2001; Aravin et al., 2003). In female flies, deletion of the piRNA-producing *flamenco* gene, which is expressed in somatic follicle cells that support oogenesis, leads to *gypsy* family transposon expression and infertility (Brennecke et al., 2007; Saito et al., 2009).

Here, we report that a small promoter deletion in the chromosome 6 pachytene piRNA cluster *6-qF3-28913(-),8009(+)* (henceforth, *pi6*) that eliminates *pi6* piRNA production disrupts male fertility. The *pi6* locus, one of the five most productive piRNA-producing loci in mice, generates 5.8% of pachytene piRNAs in the adult testis and is conserved among eutherian mammals. Mice lacking *pi6*-derived piRNAs produce normal numbers of sperm and continue to repress transposons. However, *pi6* mutant sperm fertilize eggs poorly due to defective sperm motility and zona pellucida penetration. Consistent with these phenotypes, the steady-state abundance of mRNAs encoding proteins crucial for ciliary function, zona pellucida proteolysis, and egg binding was significantly decreased in sperm progenitor cells from *pi6* males. Our findings provide direct evidence for a biological function for pachytene piRNAs in male mouse fertility, and *pi6* promoter deletions provide a new model for the future identification of piRNA targets in vivo.

RESULTS

***pi6* Promoter Deletion Eliminates *pi6* pachytene piRNAs**

To eliminate production of *pi6* pachytene piRNAs while minimizing the impact on adjacent genes, we used a pair of single-guide RNAs to delete 227 bp, including the A-MYB-binding promoter sequences, from *pi6* (Figure 1, S1A, and S1B, and Table S1; Li et al., 2013). For comparison, we created an analogous promoter deletion in *pi17*. We established stable mutant lines (*pi6^{em1}*-1, -2, and -3 in Figure S1B) from three founders whose *pi6* promoter deletion sizes range from 219 to 230 bp and differ at their deletion boundaries, reflecting imprecise DNA repair after Cas9 cleavage. All three deletions

eliminated *pi6* primary transcripts and mature pachytene piRNAs from both arms of the locus (Figure 1). Because these lines were created using the same pair of sgRNA guides, we refer to all as the *pi6^{em1}* allele.

***pi6* is Required for Male Mouse Fertility**

When paired with C57BL/6 females, *pi6^{em1/em1}* males between 2 and 8 months old produced fewer pups compared to their littermates, even at peak reproductive age (Figure 2A and S2A). In six months, C57BL/6 males produced 7 ± 1 ($n = 5$) litters, while *pi6^{em1/em1}* males produced 2 ± 2 ($n = 6$) litters. The significantly smaller number of progeny produced by *pi6^{em1/em1}* males over their reproductive lifetime does not reflect fewer pups produced in each litter: *pi6^{em1/em1}* males sired 5 ± 2 ($n = 4$) pups per litter compared to 6 ± 2 ($n = 27$) pups per litter for C57BL/6 control males (Figure 2A). Moreover, *pi6^{em1/em1}* males regularly produced mating plugs, a sign of mating, in cohabiting females. Instead, the reduced progeny from *pi6^{em1/em1}* males reflects two abnormal aspects of their fertility (Figure 2B). First, 29% of *pi6^{em1/em1}* males never produced pups. Second, the mutants that did sire pups did so less frequently. These defects are specific for the loss of *pi6* piRNAs in males, because *pi6^{+/-em1}* heterozygous males and *pi6^{em1/em1}* homozygous mutant females showed no discernable phenotype. As observed previously for a partial-loss-of-function *pi17* promoter deletion (Homolka et al., 2015), males and females carrying a ~583-bp promoter deletion in *pi17* were fully fertile, despite loss of primary transcripts and mature piRNAs from both arms of the *pi17* locus (Figure 1).

To test that the reduced fertility of *pi6^{em1/em1}* male mice reflects loss of the *pi6* promoter—and not an undetected Cas9-induced off-target mutation elsewhere in the genome—we used Cas9 and a second pair of sgRNAs to generate a 117 bp *pi6* promoter deletion, *pi6^{em2}* (Figures 1, S1A, and S1C, and Table S1). Like *pi6^{em1/em1}* male mice, *pi6^{em2/em2}* males produced neither primary *pi6* transcripts nor mature *pi6* piRNAs

and showed reduced fertility (Figure S2A). We conclude that *pi6* piRNAs are required for C57BL/6 male fertility in mice.

***pi6^{em1/em1}* Males Produce Fewer Embryos**

pi6 mutant male matings were less likely to produce fully developed embryos. We examined the embryos produced by natural mating of C57BL/6 females housed with C57BL/6, *pi6^{+ /em1}*, or *pi6^{em1/em1}* males at 8.5, 14.5, or 16.5 days after occurrence of a mating plug. At 8.5 days after mating, C57BL/6 females housed with *pi6^{em1/em1}* males carried fewer embryos (2 ± 2 , $n = 3$) compared to the females paired with *pi6^{+ /em1}* (6 ± 5 , $n = 2$) or C57BL/6 control (7 ± 4 , $n = 1$) males (Figure 2C). At 14.5 and 16.5 days post-mating, female mice paired with *pi6^{em1/em1}* males had even fewer embryos. Consistent with the observation that naturally-born pups sired by *pi6^{em1/em1}* males were rare but healthy, the surviving embryos resulting from natural mating showed no obvious abnormalities.

Moreover, *pi6* piRNAs appear to play little if any role in the soma of the developing embryo. *pi6^{+ /em1}* heterozygous males mated to *pi6^{+ /em1}* heterozygous females yielded progeny at the expected Mendelian and sex ratios. Moreover, the weight of *pi6^{em1/em1}* homozygous pups (28.3 ± 0.6 g, $n = 8$) that developed to adulthood was indistinguishable from their C57BL/6 (26.9 ± 0.3 g, $n = 8$) or heterozygous littermates (28.6 ± 0.3 g, $n = 8$) (Figure S2B). We detected no difference in the gross appearance or obvious changes in behavior among these pups.

***pi6^{em1/em1}* Males Produce Mature Spermatozoa**

Two-to-four months after birth, both *pi6^{+ /em1}* and *pi6^{em1/em1}* testes weighed slightly less than C57BL/6 testes (Figure S2B). Nonetheless, *pi6^{em1/em1}* testis gross histology was normal, with all expected germ cell types present in seminiferous tubules and sperm clearly visible in the lumen (Figure 2D). The quantity of caudal epididymal sperm

produced by *pi6^{em1/em1}* mice (19 ± 10 million sperm per ml; $n = 6$) was also comparable to that of their *pi6^{+/em1}* (23 ± 7 million sperm/ml; $n = 4$) or C57BL/6 (20 ± 10 million sperm per ml; $n = 13$) littermates (Figure 2E).

Although *pi6^{em1/em1}* mice produce normal numbers of sperm, the sperm showed signs of agglutination compared to C57BL/6 sperm after 90 min of incubation in vitro, and ~10% of *pi6^{em1/em1}* caudal epididymal sperm had abnormal head morphology (Figure S2C). Defects in germ cell chromosomal synapsis, triggering errors in gene expression, have been linked to abnormal sperm head shape (Wong et al., 2008; de Boer et al., 2015). In fact, 22 ± 7 percent of *pi6^{em1/em1}* pachytene spermatocytes had unsynapsed sex chromosomes or incompletely synapsed autosomal chromosomes, compared to 7 ± 3 percent for C57BL/6 ($n = 4$) (Figure S2E).

***pi6^{em1/em1}* Sperm Fail to Fertilize**

pi6 mutant males produce ordinary numbers of normally shaped sperm (~90%), yet are ineffectual at siring offspring. We used in vitro fertilization (IVF) to distinguish between defects in mating behavior and sperm function, incubating sperm from C57BL/6, *pi6^{+/em1}*, or *pi6^{em1/em1}* males with wild-type oocytes and scoring for the presence of both male and female pronuclei and the subsequent development of the resulting bi-pronuclear zygotes into two-cell embryos 24 h later (Figure 3A). The majority of oocytes incubated with C57BL/6 ($91 \pm 5\%$; $n = 5$) or *pi6^{+/em1}* ($60 \pm 35\%$; $n = 3$) sperm developed into two-cell embryos. By contrast, only $7 \pm 5\%$ ($n = 7$) of oocytes incubated with *pi6^{em1/em1}* sperm reached the two-cell stage. The majority of these oocytes remained one-cell embryos, and few contained a male pronucleus, suggesting that *pi6^{em1/em1}* sperm are defective in fertilization.

***pi6^{em1/em1}* Sperm Nuclei Support Fertilization**

The best studied piRNA function is transposon silencing, and mouse *pi2* has been proposed to be involved in LINE1 element silencing, although *pi2* mutant males are fertile (Xu et al., 2008). Moreover, LINE1 transcript abundance increases in mice bearing inactivating mutations in the catalytic site of MIWI (Reuter et al., 2011). Transposon activation can produce DNA damage, and genomic integrity is critical for fertilization (Ahmadi and Ng, 1999; Morris et al., 2002; Bourc'his and Bestor, 2004; Lewis and Aitken, 2005). However, pachytene piRNAs are depleted of repetitive sequences in contrast to other types of piRNA-producing genomic loci (Figure S3A; Aravin et al., 2006; Girard et al., 2006; Gainetdinov et al., 2018).

We asked whether the defect in fertilization by *pi6^{em1/em1}* might reflect DNA damage or epigenetic dysregulation of the *pi6^{em1/em1}* sperm genome. *pi6^{+/em1}* or *pi6^{em1/em1}* sperm heads were individually injected into the cytoplasm of wild-type oocytes (intracytoplasmic sperm injection, or ICSI) (Figure 3B), bypassing the requirement for sperm motility, acrosome reaction, egg binding, or sperm-egg membrane fusion (Kuretake et al., 1996). *pi6^{em1/em1}* sperm heads delivered by ICSI fertilized the oocyte at a rate similar to that of *pi6^{+/em1}* sperm: 66% of oocytes injected with homozygous mutant *pi6^{em1/em1}* sperm heads reached the two-cell stage, compared to 79% for *pi6^{+/em1}*. Thus, most *pi6^{em1/em1}* nuclei are capable of fertilization.

The steady-state abundance of transposon RNA in *pi6^{em1/em1}* testicular germ cells further supports the view that the fertilization defect caused by loss of *pi6* piRNAs does not reflect a failure to silence transposons. We used RNA-seq to measure the abundance of RNA from 1,007 transposons in four distinct germ cell types, purified by fluorescence-activated cell sorting: pachytene spermatocytes (4C), diplotene spermatocytes (4C), secondary spermatocytes (2C), and spermatids (1C). *pi6* piRNAs are plentiful in pachytene spermatocytes onwards (Figure S3B), yet when *pi6* piRNAs

were eliminated, we found no significant changes in steady-state RNA abundance (i.e., an increase or decrease ≥ 2 -fold and $\text{FDR} \leq 0.05$) for any transposon family compared to C57BL/6 cells (Figure S3C). We also note that, similar to C57BL/6 testis, γH2AX expression is confined to meiotic spermatocytes in *pi6^{em1/em1}* testis, indicating absence of DNA damage (data not shown). Together with the rescue of the fertilization defects of *pi6^{em1/em1}* sperm by ICSI, these data suggest that transposon silencing is unlikely to be the biological function of *pi6* piRNAs.

Impaired Motility in *pi6* Mutant Sperm

To assess whether abnormal sperm motility might contribute to *pi6^{em1/em1}* male subfertility, we observed freshly extracted caudal epididymal sperm from *pi6^{em1/em1}* or C57BL/6 mice for 5 h. Ten minutes after sperm extraction, most *pi6^{em1/em1}* sperm moved more slowly than C57BL/6 control sperm (Movies S1 and S2). With time, *pi6^{em1/em1}* sperm motility declined more rapidly than C57BL/6 sperm (Movies S3–S10). At 4 and 5 h, most *pi6^{em1/em1}* sperm only moved in place and showed signs of agglutination (Movies S8 and S10).

To quantify the differences between *pi6* mutant and control sperm, we used computer-assisted sperm analysis (CASA) to measure *pi6^{em2/em2}* sperm motility 10 min after isolation (Mortimer, 2000). While control sperm swam at a path velocity comparable to previously reported ($110 \pm 50 \mu\text{m/sec}$ for 221 ± 75 cells measured; $n = 3$; Ren et al., 2001), *pi6^{em2/em2}* sperm moved at a lower average path velocity ($80 \pm 60 \mu\text{m/sec}$ for 232 ± 57 cells measured; $n = 3$) (Table 1). Similarly, The *pi6^{em2/em2}* sperm also showed less forward, progressive movement (progressive velocity = $50 \pm 60 \mu\text{m/sec}$ for 232 ± 57 cells measured; $n = 3$) compared to control sperm (progressive velocity = $70 \pm 50 \mu\text{m/sec}$ for 221 ± 75 cells measured; $n = 3$). For comparison, knockout of *CatSper1* leads to ~65% reduction in path velocity and ~62% reduction in progressive velocity (Ren et al., 2001). As a population, the speed and

progressivity of *pi6* mutant sperm motility patterns varied more widely than control sperm (Movies S1–S10 and Table 1). Lower average path and progressive velocity in sperm populations is linked to worse outcomes in fertilization and pregnancy in IVF (Donnelly et al., 1998). Thus, the slower and less progressive movement in *pi6^{em1/em1}* sperm likely contributes to the subfertility of *pi6^{em1/em1}* males.

***pi6* Mutant Sperm Struggle to Penetrate the Zona Pellucida**

Mammalian spermatozoa stored in the epididymis are dormant. Sperm “capacitate,” i.e., resume maturation, only upon entering the female reproductive tract (de Lamirande et al., 1997). Upon capacitation, sperm become capable of undergoing the acrosome reaction, which is required to bind and penetrate the outer oocyte glycoprotein layer, the zona pellucida (Florman and Storey, 1982; de Lamirande et al., 1997; Jin et al., 2011). To test whether the defect in fertilization by *pi6* mutant sperm was due to impaired binding to or penetration of zona pellucida, we compared IVF using wild-type oocytes with their zona pellucida either intact or removed (Figure 4A). As before, $10 \pm 6\%$ ($n = 3$) of intact oocytes incubated with *pi6^{em1/em1}* sperm reached the two-cell stage, compared to $94 \pm 5\%$ ($n = 3$) for C57BL/6 sperm (Figure 4B). Strikingly, removing the zona pellucida from the wild-type oocytes fully rescued the fertilization rate of *pi6* mutant sperm: $92 \pm 7\%$ ($n = 3$) of zona pellucida-free oocytes incubated with *pi6^{em1/em1}* sperm reached the two-cell stage, compared to those with intact zona pellucida ($10 \pm 6\%$; $n = 3$)

Ex vivo, the acrosome reaction occurs spontaneously in some sperm and can be further triggered by inducing Ca^{2+} influx using the ionophore A23187 (Talbot et al., 1976), which results in an acrosome reaction visually indistinguishable from that triggered by natural ligands such as progesterone (Osman et al., 1989) or ZP3 (Arnoult et al., 1996), while bypassing signaling pathways essential for acrosome reaction in vivo (Tateno et al., 2013) (Figure 4C and 4D). The spontaneous acrosome reaction rates for

C57BL/6 ($19 \pm 3\%$; $n = 3$) and *pi6* mutant sperm were similar ($17 \pm 8\%$; $n = 3$).

Acrosome reaction triggered by ionophore-induced Ca^{2+} influx differed between the two genotypes: $45 \pm 14\%$ of *pi6* mutant sperm ($n = 3$) underwent partial or complete reaction, compared to $66 \pm 6\%$ ($n = 3$) for C57BL/6 (Figure 4C). Our data suggest that *pi6* mutant sperm less effectively undergo an acrosome reaction triggered by ionophore-induced Ca^{2+} influx, a defect expected to impair binding and penetrating the zona pellucida.

Potential Role of Paternal *pi6* piRNAs in Embryo Development

Even when *pi6* sperm successfully fertilize the oocyte, the resulting heterozygous embryos are less likely to complete gestation. Two-cell embryos generated by IVF using heterozygous or homozygous *pi6* mutant or C57BL/6 control sperm were transferred to C57BL/6 surrogate mothers (Figure 5A). At least half of embryos from *pi6*^{+/em1} ($50 \pm 10\%$; $n = 3$) or C57BL6 control ($70 \pm 10\%$; $n = 3$) sperm developed to term (Figure 5B), a rate typical for the C57BL/6 background (González-Jara et al., 2017).

The low number of fertilized two-cell embryos produced in IVF using *pi6*^{em1/em1} sperm precluded transferring the standard number of embryos to surrogate mothers. For example, in two IVF experiments using *pi6*^{em1/em1} sperm, only 5 or 7 embryos could be transferred; the surrogate females failed to become pregnant (Figure 5B and S4A, Trials 1 and 2). In theory, this result might suggest a paternal role for *pi6*. A more mundane explanation is that the low number of embryos transferred reduced the yield of live fetuses, as reported previously (McLaren, 1955; Johnson et al., 1996; González-Jara et al., 2017). We conducted additional experiments to distinguish between these two possibilities. Oocytes were again fertilized by IVF with *pi6*^{em1/em1} or C57BL/6 control sperm, and two-cell embryos transferred to surrogate females, but matching the number of embryos transferred to each surrogate for the two sperm genotypes. We used two strategies. First, similar numbers of embryos derived from *pi6*^{em1/em1} sperm and filler

embryos derived from control sperm were transferred to separate oviducts (Figure 5B, Trials 3 and 4). Again, fewer embryos developed to term for *pi6^{em1/em1}* (17%) compared to control sperm (37%). Second, embryos were mixed before transfer and then equal numbers of embryos, selected randomly, were implanted in each oviduct (Figure 5B, Trial 5). Pups isolated by cesarean section 18.5 days after transfer were genotyped by PCR. In this experiment, only 40% of embryos derived from *pi6^{em1/em1}* sperm developed to term, compared to 80% of filler embryos. Finally, in one experiment (Trial 6) where we obtained sufficient numbers of embryos derived from *pi6^{em1/em1}* sperm, 10 *pi6^{em1/em1}*-derived two-cell embryos were transferred to each oviduct of the surrogate female. Nevertheless, only 15% of the *pi6^{em1/em1}*-derived embryos developed to term, compared to 85% of the control.

We also monitored pre-implantation development ex vivo for up to 96 h, a period during which the one-cell embryo develops into a blastocyst. Of all the oocytes incubated with *pi6^{em1/em1}* sperm, 40% remained one cell without evidence of a male pronucleus, presumably because they were not fertilized by *pi6^{em1/em1}* mutant sperm. Among the remaining 60% oocytes that progressed to at least two-cell stage, which indicated successfully fertilization by *pi6^{em1/em1}* sperm, 82% showed delayed development, requiring 48 h to reach the two-cell stage. None of these developed further. Only 3% of fertilized oocytes progressed to the blastocyst stage by 96 h, compared to 98% of oocytes fertilized by C57BL/6 sperm (Figure 5C).

Further support for this idea comes from transfer of embryos generated by ICSI (Figure 5D). ICSI with *pi6^{em1/em1}* or *pi6^{+/em1}* sperm yielded comparable normal numbers of fertilized oocytes (Figure 3B), so no filler embryos were used; all embryos were transferred into a single oviduct of the surrogate female. In two independent experiments in which embryos generated by ICSI were transferred to surrogate mothers, only 19% of two-cell embryos derived from *pi6^{em1/em1}* sperm heads developed to term, compared to 34% for embryos fertilized with *pi6^{+/em1}* (Figure 5C). Only four of

seven (57%) surrogate mothers carrying embryos derived from *pi6^{em1/em1}* sperm became pregnant. All three surrogate mothers receiving embryos derived from *pi6^{+/em1}* sperm became pregnant (Figure S4B).

We note that the live fetuses generated using *pi6^{em1/em1}* sperm in IVF or sperm heads in ICSI, like those produced by natural mating using *pi6^{em1/em1}* males, showed no obvious morphological abnormalities and grew to adulthood normally when fostered by host mothers. This suggests a direct or indirect requirement for paternal *pi6* piRNAs in early embryogenesis.

Changes in Spermatocyte mRNA Abundance Accompany Loss of *pi6* piRNAs

To characterize the molecular phenotypes of *pi6* and *pi17* mutants, we used RNA-seq to measure steady-state RNA abundance in pachytene spermatocytes, diplotene spermatocytes, secondary spermatocytes, and spermatids purified from *pi6^{em1/em1}*, *pi17^{-/-}*, and C57BL/6 adult testis (Figure 6A). *pi6* and *pi17* precursor transcripts are abundant in meiotic pachytene spermatocytes (tetraploid), decrease in diplotene spermatocytes, and fall to low levels in post-meiotic spermatids (haploid) (Figure S5B). Compared with C57BL/6 controls, *pi6^{em1/em1}* mutants had widespread changes in mRNA abundance in pachytene spermatocytes—481 mRNAs more than doubled, while 394 fell by more than half (FDR ≤ 0.05 ; Figure 6B and S5A, and Table S2)—but caused little alteration in mRNA abundance in diplotene spermatocytes, secondary spermatocytes, or spermatids. In contrast, *pi17^{-/-}* mutants showed significant changes in mRNA abundance in diplotene (10 mRNAs increased, 267 decreased) and secondary spermatocytes (103 mRNA increased, 400 decreased) but not in pachytene spermatocytes or spermatids (Figure S5A). Among the mRNAs that changed in the diplotene spermatocytes of *pi17^{-/-}* mutants, 56% remained different from controls in secondary spermatocytes in these mutants. These data suggest that, despite similar temporal expression, *pi6* piRNAs function primarily in pachytene spermatocytes, while

pi17 piRNAs may be more important at a later stage of spermatogenesis. Furthermore, 734 (84%) of mRNAs with altered abundance in *pi6^{em1/em1}* pachytene spermatocytes were unchanged in any *pi17^{-/-}* sorted germ cell type we examined, suggesting that distinct sets of genes are dysregulated in *pi6^{em1/em1}* and *pi17^{-/-}* mutants.

The abundance of piRNAs from the other four major pachytene piRNA clusters, including *pi17*, was unaffected by loss of *pi6* piRNAs, and loss of neither *pi6* nor *pi17* piRNAs had any significant effect on the abundance of mRNAs encoding piRNA pathway proteins (Table S3), suggesting that the changes in mRNA abundance in *pi6^{em1/em1}* or *pi17^{-/-}* cells reflect direct regulation of target genes by *pi6* or *pi17* piRNAs or the downstream regulation through the direct targets of these piRNAs.

Gene Ontology (GO) analysis of the 481 up-genes found over 354 significantly enriched GO biological processes ($FDR \leq 0.01$ and enrichment ≥ 2). Curiously, 106 of these GO terms correspond to developmental processes that do not normally occur in testis, suggesting a failure to suppress inappropriate programs without *pi6* piRNAs. Similarly, *pi6^{em1/em1}* mutants show increased mRNA abundance for 20 transcription factors that normally act in undifferentiated spermatogonia or spermatogonial stem cells or the stem cells of other tissues (Table S4).

The mRNA abundance of several miRNA pathway genes also increased in *pi6^{em1/em1}* pachytene spermatocytes, including *Lin28a* (5.6-fold), *Zc3h7b* (5-fold), and *Ajuba* (5.3-fold; Figure S5C) (Dresios et al., 2005; James et al., 2010; Pilotte et al., 2011; Piskounova et al., 2011). LIN28A inhibits *let-7* biogenesis by binding to the loop of pre-*let-7*, blocking its processing by DICER (Piskounova et al., 2008; Hagan et al., 2009; Heo et al., 2009), and *let-7* promotes *Lin28a* degradation by binding two conserved sites in the *Lin28a* 3' untranslated region (Reinhart et al., 2000; Agarwal et al., 2015) predicting that *let-7* levels should fall and *let-7* targets should rise in *pi6^{em1/em1}*. Indeed, in *pi6^{em1/em1}* adult testis, the aggregate abundance of *let-7a*, *let-7b*, *let-7c*, *let-7e*, *let-7f*, *let-7g*, and *let-7i*, the seven most abundant *let-7* family members (≥ 10 ppm in

wild-type testis) fell to less than half of wild-type, suggesting *pi6* regulation of downstream target genes via *let-7*. Moreover, 48 predicted *let-7* targets (Agarwal et al., 2015) increased in the absence of *pi6^{em1/em1}*, including *Lin28a* and the mRNAs encoding three transcription factors: *Sall4* (increased 8.7-fold), *Elf4* (increased 7-fold), and *Pbx2* (increased 6.7-fold). SALL4 is normally expressed in undifferentiated spermatogonia where it represses genes that specify somatic gene expression programs (Gassei and Orwig, 2013; Yamaguchi et al., 2015; Chan et al., 2017). ELF4 has been implicated in regulation of quiescence in hematopoietic stem cells (Lacorazza et al., 2006). Our data suggest that piRNAs, miRNAs, and transcription factors collaborate to ensure precise regulation of gene expression in spermatogenesis.

Genes that Function in the Cilium Assembly, Cilium Motility, and Fertilization Pathways Decrease in mRNA Abundance upon Loss of *pi6* piRNAs

GO analysis of the 394 down-genes revealed only 36 significantly enriched GO biological processes ($\text{FDR} \leq 0.01$ and fold enrichment ≥ 2), of which 34 are related to the production and function of sperm and can be organized into four sets (Table S5). One set encompasses broad spermatogenesis terms (e.g., *male gamete generation*, 4.6-fold enriched, $\text{FDR} = 5.8 \times 10^{-11}$; *sperm capacitation*, 12-fold enriched, $\text{FDR} = 7.4 \times 10^{-3}$) while three sets are highly specific and match the in vivo phenotypes of *pi6* mutant males. The first specific set includes *cilium assembly* (6.2-fold enriched, $\text{FDR} = 4.1 \times 10^{-9}$) and *axonemal dynein complex assembly* (18-fold enriched, $\text{FDR} = 1.1 \times 10^{-5}$). The second set contains *sperm motility* (13-fold enriched, $\text{FDR} = 6.0 \times 10^{-10}$) and *cilium movement involved in cell motility* (27-fold enriched, $\text{FDR} = 2.0 \times 10^{-3}$). The third set involves *fertilization* (6.2-fold enriched, $\text{FDR} = 1.7 \times 10^{-5}$) and *binding of sperm to zona pellucida* (12-fold enriched, $\text{FDR} = 2.3 \times 10^{-3}$). None of these three sets of GO terms is enriched in the 481 genes whose mRNA levels increased in *pi6^{em1/em1}* pachytene spermatocytes. The three sets of specific GO terms contain 28, 36, and 22 genes

whose mRNAs decreased (63 total and 23 shared between sets; Figure 6C and Table S6). The last two general GO terms—*microtubule-based process* (GO:0007017; with 27 genes whose mRNA abundance declined) and *organelle assembly* (GO:0070925; with 28 genes whose mRNA abundance decreased)—likely gained their enrichment from the large number of genes they share with Cilium assembly and Sperm motility processes (23 and 25 genes for the two GO terms, respectively).

Master Regulators of Cilium Assembly and Sperm Motility

The 63 Cilium Assembly, Sperm Motility, or Fertility genes with reduced mRNA abundance in *pi6* mutants include two transcription factors, *Rfx2* and *Foxj1*, that act as master regulators of ciliogenesis (Figure 6C). Like *pi6* itself, *Rfx2* transcription is activated by A-MYB, and RFX2 also binds its own promoter (Horvath et al., 2009). Of the genes with decreased mRNA abundance in *pi6^{em1/em1}* pachytene spermatocytes, 31 both bind RFX2 and have reduced mRNA abundance in *Rfx2^{-/-}* testis, suggesting they are direct targets of RFX2 (Figure 6C and Table S7) (Kistler et al., 2015). Intriguingly, 23 of these 31 RFX2-regulated genes also bind A-MYB (Table S7). *A-Myb* mRNA levels are normal in *pi6^{em1/em1}*, which may account for the relatively modest decreases in the mRNA abundance of these 23 genes. Unlike RFX2, the role of FOXJ1 in sperm flagellar assembly has not been extensively studied but its role in general ciliogenesis is well established: *FoxJ1^{-/-}* mouse died at or soon after birth due to absence of cilia in multiple organs (Chen et al., 1998; Blatt et al., 1999; Brody et al., 2000; Yu et al., 2008). Six genes—*Tekt4*, *Spa17*, *Drc1*, *Rsph1*, *Meig1*, and *Tsnaxip1*—out of the 394 genes with reduced mRNA abundance in *pi6^{em1/em1}* pachytene spermatocytes are regulated by FOXJ1 in ciliogenesis in other tissues (Yu et al., 2008; Stauber et al., 2017). Fourteen genes whose mRNA abundances decrease in *pi6^{em1/em1}* are uniquely annotated with the GO term Fertilization (Figure 6C and Table S6). Several are required for sperm to bind the zona pellucida or for acrosome function, including *Acrosin* (halved in *pi6^{em1/em1}*

pachytene spermatocytes), *Adam3* (decreased 2.5-fold), *Zbp2* (decreased 3.3-fold), and the FOXJ1-regulated gene *Spa17* (decreased 5-fold). Among the genes with decreased or increased mRNA abundance in *pi6^{em1/em1}* cells, 28 have been reported to disrupt mouse or human male fertility or to play a role in spermatogenesis, spermiogenesis, or sperm function (Table S8).

DISCUSSION

Deletion of the mouse pachytene piRNA *pi6* locus results in specific, quantifiable defects in male fertility. These include impaired sperm mobility and failure in sperm to bind and penetrate the zona pellucida. The male fertility defects accompanying loss of *pi6* piRNAs are specific to this locus, as deletion of the promoter of *pi17*, which eliminates *pi17* piRNAs, had no detectable effect on male or female fertility or viability, as reported previously (Homolka et al., 2015). The phenotypic defects of *pi6* mutants reflect the molecular changes—decreased steady-state abundance of mRNAs encoding proteins that function in ciliary motility and fertilization. Mutations in four of these genes also cause infertility in men. The molecular changes were detected only in pachytene spermatocytes but not in diplotene spermatocytes, secondary spermatocytes, or spermatids. By contrast, RNA-seq for 17.5 dpp or adult *pi6^{em1/em1}* testes revealed no changes in mRNA abundance compared to controls. These results underscore the power of analyzing sorted germ cells.

Pachytene piRNAs have been proposed to act collectively in meiotic spermatocytes or post-meiotic spermatids to target mRNAs for destruction (Gou et al., 2014; Goh et al., 2015), but the extent to which piRNAs from different pachytene piRNA loci regulate overlapping sets of targets is unknown. Transcriptome analysis of sorted germ cells from *pi6^{em1/em1}* and *pi17^{-/-}* mutant mice revealed distinct changes in mRNA abundance, suggesting that, despite the coordinate temporal expression of pachytene piRNAs, individual pachytene piRNA loci regulate distinct sets of genes. Given that *pi6*

produces 95,677 distinct piRNA sequences, the phenotypic specificity of the *pi6* mutant is extraordinary. For both miRNAs and siRNAs, the seed sequence plays a central role in determining a small RNA's regulatory target. Assuming that pachytene piRNAs find their target RNAs by a similar mechanism, the sequence diversity of the small RNAs produced by individual loci is enormous: *pi6* piRNAs encompass 9,880 distinct seed (g2–g8 or 7mer-m8; Bartel, 2009) and 17,304 distinct extended seed sequences (g2–g9) in adult mouse testis, while *pi17* generates 134,358 distinct piRNA sequences, encompassing 11,324 distinct g2–g8 seed and 21,972 distinct g2–g9 seed sequences. Yet, the g2–g9 seed sequences of the 100 most abundant *pi6* piRNAs are not found among the 100 most abundant *pi17* piRNAs. Furthermore, 97 of these *pi6* g2–g9 seed sequences are not found among any of the 100 most-abundant piRNAs produced by *pi2*, *pi7*, *pi9*, or *pi17*. Together with *pi6*, these loci produce more than half of all pachytene piRNAs. The unique seed sequences of the most abundant *pi6* piRNAs are consistent with the lack of compensation of loss of *pi6* piRNAs by other piRNA-producing loci.

We envision that piRNAs from distinct loci target overlapping sets of genes, ensuring robust control of mRNA abundance across spermatogenesis. Our data show that *pi6* piRNAs regulate—directly or by regulating upstream factors—a specific set of mRNAs whose protein products must be eliminated for successful spermiogenesis. In this view, *pi6* piRNAs target mRNAs whose expression must decline at the onset of the pachynema in order to allow new sets of mRNAs to accumulate, such as the RFX2-regulated genes required for ciliogenesis. While we cannot exclude a direct role for piRNAs in activating gene expression or increasing mRNA stability, we note that the overwhelming majority of siRNAs and miRNAs in plants and animals act as repressors not activators.

The phenotypic and molecular specificity of *pi6* may reflect a lower degree of redundancy with other piRNA clusters. Nonetheless other piRNA clusters may partially

rescue the *pi6* phenotype, accounting for the incomplete penetrance of the *pi6* sterility phenotype. Conversely, the lack of a phenotype for other pachytene piRNA clusters may simply reflect greater redundancy with their piRNA-producing peers. Loss of regulation of the targets of *pi17* piRNAs may be compensated by piRNAs from other loci. Testing this hypothesis is clearly a prerequisite for explaining why loss of *pi6* and not *pi17* piRNAs has a measurable biological consequence.

Beyond the requirement for *pi6* piRNAs to produce fully functional sperm, *pi6* piRNAs appear to play an additional role in embryo development. Our data suggest that the arrested development and reduced viability of embryos derived from *pi6* mutant sperm reflects a paternal defect and not the embryonic genotype. Damaged sperm DNA, abnormal sperm chromatin structure, and failure to form a male pronucleus in fertilized embryos have been reported to be linked to retarded embryo development (Sakkas et al., 1998; Borini et al., 2006). Our analysis of transposon RNA abundance in *pi6* mutant germ cells argues against a role for *pi6* piRNAs in transposon silencing during spermatogenesis, but we cannot currently exclude a direct or indirect role for *pi6* piRNAs in silencing transposons in the early embryo (Peaston et al., 2004). Of course, DNA damage might reflect incomplete repair of the double-stranded DNA breaks required for recombination, rather than transposition or transposon-induced illegitimate recombination.

How piRNAs identify their targets remains poorly understood, in part because suitable biochemical or genetic model systems are not available. The availability of a mouse mutant missing a specific set of piRNAs whose absence causes a readily detectable phenotype should provide an additional tool for understanding the base-pairing rules that govern the binding of piRNAs to their RNA targets and for unraveling the regulatory network created by pachytene piRNAs.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Extended Experimental Procedures, Figures S1–5, Tables S1–S7, and Movies S1–S10.

AUTHOR CONTRIBUTIONS

P.H.W., K.C., Y.F., Z.W., and P.D.Z. conceived and designed the experiments. P.H.W. and K.C. performed the experiments. Y.F. analyzed the sequencing data. D.M.Ö generated A-MYB ChIP-seq datasets. P.H.W., Y.F., and P.D.Z. wrote the manuscript.

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FIGURE LEGENDS

Figure 1. *pi6^{em1/em1}*, *pi6^{em2/em2}*, and *pi17^{-/-}* promoter deletion in mice

Scissors indicate sites targeted by sgRNAs used to guide the Cas9-catalyzed promoter deletions. RNA-seq was used to measure the steady-state abundance of piRNA primary transcripts, and sequencing of NaIO₄ oxidation-resistant small RNA was used to measure the abundance of mature piRNAs in 17.5 dpp testes.

See also Figure S1 and Table S1.

Figure 2. Reduced fertility in *pi6^{em1/em1}* males by natural mating

(A) Number of litters and pups per litter produced by male mice between 2–8 months of age. (B) Frequency and periodicity of litter production. Each bar represents a litter. (C) Number of embryos produced by males mated with C57BL/6 females. (D) Testis morphology analyzed by hematoxylin and eosin staining. (E) Concentration of sperm from the caudal epididymis.

See also Figure S2.

Figure 3. Fertilization defects of *pi6^{em1/em1}* sperm revealed by IVF and ICSI

(A) Sperm function analyzed by in vitro fertilization (IVF). (B) Sperm function analyzed by intracytoplasmic sperm injection (ICSI).

Thick lines denote the median, and whiskers report the 75th and 25th percentiles.

See also Figure S3

Figure 4. Impaired motility and zona pellucida-binding in *pi6^{em1/em1}* sperm

(A) Strategy for zona-free IVF. **(B)** Comparison of sperm function in standard and zona-free IVF. **(C)** Acrosome reaction triggered with the Ca^{2+} ionophore A23187 in vitro. The results using *pi6^{em1/em1}* and *pi6^{em2/em2}* sperm are combined and indicated. **(D)** Representative caudal epididymal spermatozoa with distinct acrosome reaction status. Green, peanut agglutinin to detect the acrosome; blue, DAPI to detect DNA.

See also Movies S1–S10.

Figure 5. Embryos derived from *pi6^{em1/em1}* sperm fail to develop

(A) Strategy for surgical transfer of fertilized two-cell embryos to surrogate mothers. **(B)** Rates of IVF-derived two-cell embryos that developed to term. Each uterine cartoon represents one surrogate mother, and the colored circles represent embryos. The number of embryos transferred to each side of the oviduct is also indicated. **(C)** Development of IVF-derived embryos. Red, the number of embryos that developed to the stage expected for the time after fertilization. **(D)** Rates of ICSI-derived two-cell embryos that developed to term.

See also Figure S4

Figure 6. The abundance of mRNAs encoding proteins required for sperm motility and zona pellucida-binding is decreased in *pi6^{em1/em1}* germ cells

(A) Strategy for purifying specific male germ cell types. **(B)** Volcano plots of steady-state transcript abundance in sorted testicular germ cells. Control cells were sorted from C57BL/6 testis. Each dot represents the mean abundance of an mRNA measured using three biologically independent samples. Differentially expressed transcripts (≥ 2 fold-change and ≤ 0.05 FDR) are indicated. **(C)** Major GO categories containing enriched

GO terms associated with genes with decreased expression in *pi6^{em1/em1}* pachytene spermatocytes (FDR ≤ 0.01 and fold enrichment ≥ 2). Genes annotated for a single category that are discussed in the main text are listed in respective categories. **(D)** RFX2 and A-MYB target genes with significantly decreased mRNA abundance in *pi6^{em1/em1}* pachytene spermatocytes and established functions in sperm motility and zona pellucida-binding. ChIP-seq peaks around respective transcription start sites (TSS) are shown. . RFX-2 or A-MYB occupancy is reported as fold enrichment of ChIP-seq reads relative to input.

See also Table S7 for the complete list of genes regulated by *pi6*, RFX2, and A-MYB.

Table 1. Sperm motility measured by computer-assisted sperm analysis (CASA)

	C57BL/6		<i>pi6^{+/em2}</i>	Mean \pm SD	<i>pi6^{em2/em2}</i>			Mean \pm SD
	Exp. 1	Exp. 2	Exp. 1		Exp.1	Exp. 2	Exp. 3	
Cells counted	271	135	257	n/a	273	167	257	n/a
Motile cells	256	106	227	n/a	247	111	208	n/a
Progressive cells	217	87	187	n/a	146	81	166	n/a
Percent motile	94	79	83	87 \pm 8	90	66	81	80 \pm 10
Percent progressive	80	64	73	70 \pm 8	53	49	65	56 \pm 8
Path Velocity ($\mu\text{m/s}$)	110 \pm 50	110 \pm 60	110 \pm 50	110 \pm 50	70 \pm 80	80 \pm 40	90 \pm 60	80 \pm 60
Progressive Velocity ($\mu\text{m/s}$)	60 \pm 50	50 \pm 60	70 \pm 40	70 \pm 50	50 \pm 70	40 \pm 30	50 \pm 60	50 \pm 60
Track speed ($\mu\text{m/s}$)	210 \pm 90	220 \pm 80	200 \pm 100	210 \pm 90	200 \pm 100	210 \pm 100	210 \pm 100	200 \pm 100
Lateral Amplitude (μm)	13 \pm 8	13 \pm 7	13 \pm 8	13 \pm 8	12 \pm 8	13 \pm 7	13 \pm 7	13 \pm 7
Beat Frequency (%)	30 \pm 10	30 \pm 20	30 \pm 20	30 \pm 20	30 \pm 20	40 \pm 20	30 \pm 20	40 \pm 10
Straightness (%)	60 \pm 30	50 \pm 30	60 \pm 30	60 \pm 30	60 \pm 20	50 \pm 20	50 \pm 30	50 \pm 20

Linearity (%)	30 ± 20	30 ± 20	40 ± 20	30 ± 20	30 ± 20	20 ± 10	20 ± 20	20 ± 20
Elongation	40 ± 20	40 ± 10	40 ± 10	40 ± 10	40 ± 20	40 ± 20	40 ± 10	40 ± 20
Area (μm²)	90 ± 80	80 ± 50	80 ± 60	80 ± 70	60 ± 40	80 ± 60	80 ± 60	70 ± 50
Rapid cells (> 50 μm/s)	217	87	187	n/a	146	81	166	n/a
Medium cells (25–50 μm/s)	4	1	3	n/a	9	0	3	n/a
Slow cells (< 25 μm/s)	35	18	37	n/a	92	30	39	n/a
Static cells (< 10 μm/s)	15	29	30	n/a	26	56	49	n/a
Percent rapid cells	80	64	73	74 ± 8	53	49	65	57 ± 8
Percent medium cells	1	1	1	1 ± 0	3	0	1	2 ± 2
Percent slow cells	13	13	14	13.4 ± 0.6	34	18	15	20 ± 10
Percent static cells	6	21	12	13 ± 8	10	34	19	20 ± 10

STAR METHODS

Mouse mutants

Mice were maintained and sacrificed according to guidelines approved by the Institutional Animal Care and Use Committee of the University of Massachusetts Medical School (A-2222-17).

Small guide RNAs (sgRNAs) flanking piRNA promoters were designed using CRISPR design tools (crispr.mit.edu/). DNA oligos containing guide sequences were cloned into pX330 vectors (Cong et al., 2013), and their cleavage activity tested in NIH3T3 cells by co-transfecting pX330 constructs containing sgRNA sequences and puromycin-resistant plasmid (pPUR) using TransIT-X2 (Mirus Bio, Madison, WI). Puromycin (3 µg/µl) was added 24 h after transfection and DNA extracted 48 h afterwards. Promoter deletions were detected by PCR using primers flanking the predicted Cas9 cleavage sites.

For mice, sgRNAs were generated by in vitro transcription and purified by electrophoresis on 8% (w/v) polyacrylamide gels. To generate the *pi6^{em1/em1}* and *pi17^{-/-}* lines used in this study, in vitro transcribed sgRNAs (10 ng/µl each) targeting *pi6* and *pi17* were mixed with Cas9 mRNA (40 ng/µl) and injected together into the cytoplasm of one-cell C57BL/6 zygotes (RNA only). For some founders, the sgRNA and Cas9 mRNA mixture was combined with pX330 plasmids expressing the same four sgRNAs and Cas9 and injected into both the cytoplasm and pronuclei of one-cell C57BL/6 zygotes (RNA + DNA). For *pi6^{em2/em2}*, in vitro transcribed sgRNAs and Cas9 mRNA were injected into the cytoplasm of one-cell C57BL/6 embryos. Embryos were transferred to pseudopregnant females using standard methods. To screen for mutant founders, DNA was extracted from small pieces of tail clipped from three-week-old pups (Truett et al., 2000). Deletions were detected by PCR, and PCR products purified and cloned into TOPO blunt vectors. Mutant sequences were determined by Sanger sequencing.

Mouse fertility test

Each 2–8 month-old male mouse was housed with one 2–4 month-old C57BL/6 female, who was examined for the presence of a vaginal plug the following morning. When a plug was observed, the female was housed separately. For male mice who did not produce pups after 3 months (~3 cycles), the original female was replaced with a new female and the fertility test continued.

Testis histology, sperm count, and sperm morphology

Mouse testes were fixed in Bouin's solution overnight, washed with 70% ethanol, embedded in paraffin, and sectioned at 5 μ m thickness. Sections were stained with hematoxylin solution, counterstained with eosin solution, and imaged using Leica DMI8 brightfield microscope equipped with an 20 \times 0.4 N.A. objective (HC PL FL L 20 \times /0.40 CORR PH1, Leica Microbiosystems, Buffalo Grove, IL). To quantify sperm abundance, the cauda epididymides were collected from mice and placed in phosphate-buffered saline (PBS) containing 4% (w/v) bovine serum albumin. A few incisions were made in the epididymides with scissors to release the sperm, followed by incubation at 37°C and 5% CO₂ for 20 min. A 20 μ l aliquot of sperm suspension was diluted in 480 μ l of 1% (w/v) paraformaldehyde (PFA), and sperm cells counted at 10 \times by brightfield microscopy. To assess sperm morphology, caudal epididymal sperm were fixed in 1% (w/v) PFA, stained with trypan blue, and a Leica DMI8 brightfield microscope equipped with an 63 \times 1.4 N.A. oil immersion objective (HC PL APO; Leica Microbiosystems, Buffalo Grove, IL). Sperm stained with Alexa 488-conjugated PNA (see below) were also used to assess sperm morphology.

Meiotic chromosome spreads

Meiotic chromosome spreads were prepared as described (Holloway et al., 2014). Mouse testes were incubated in hypotonic buffer (30 mM Tris-Cl, pH 8.2, 50 mM

sucrose, 17 mM sodium citrate, 5 mM EDTA, 0.5 mM DTT) for 30 min on ice, then small fragments of seminiferous tubules were moved to 100 mM sucrose solution and pulled apart with forceps to release germ cells. A drop of sucrose solution containing germ cells was pipetted onto a glass slide with a thin layer of 1× PBS containing 1% PFA and 0.15% (v/v) Triton-X100 (pH 9.2) and spread by swirling. Slides were placed in a humidifying chamber for 2.5 h, air-dried, and washed twice with 1× PBS with 0.4% Photo-Flo 200 (Kodak, Rochester, NY) and once with water with 0.4% Photo-Flo 200, and air-dried. For immunostaining of meiotic chromosomes, slides were sequentially washed with (1) 1× PBS with 0.4% Photo-Flo 200, (2) 1× PBS containing 0.1% (v/v) Triton-X, and (3) blocked with PBS containing 3% (w/v) BSA, 0.05% (v/v) Triton X-100, and 10% (v/v) goat serum in 1× PBS at room temperature. The slides were then incubated with primary antibodies, anti-SCP1 (1:1000 dilution) and anti-SCP3 (1:1000 dilution), in a humidifying chamber overnight at room temperature. Washing and blocking steps were repeated the next day, and the slides were incubated with Alexa 488- or Alexa 594-conjugated secondary antibodies (1:10,000 dilution) for 1 h at room temperature. Slides were washed thrice with 1× PBS containing 0.4% (v/v) Photo-Flo 200, once with water containing 0.4% Photo-Flo 200 mixture, air-dried in the dark, mounted by incubation in ProLong Gold Antifade Mountant with DAPI (4',6'-diamidino-2-phenylindole; Thermo Fisher Scientific, Waltham, MA) overnight in the dark, and imaged using a Leica DMI8 fluorescence microscope equipped with an 63× 1.4 N.A. oil immersion objective (HC PL APO; Leica Microbiosystems, Buffalo Grove, IL).

Cell sorting by FACS

Testicular cell sorting was performed as described (Cole et al., 2014). Testes were collected, decapsulated, and incubated in 0.4 mg/ml collagenase type IV (Worthington LS004188) in 1× Grey's Balanced Salt Solution (GBSS, Sigma, G9779) at 33°C rotating at 150 rpm for 15 min. Separated seminiferous tubules were washed with 1× GBSS and

incubated in 0.5 mg/ml Trypsin and 1 µg/ml DNase I in 1× GBSS at 33°C rotated at 150 rpm for 15 min. Tubules were dissociated on ice by gentle pipetting, and then 7.5% (v/v) fetal bovine serum (f.c.) was added to inactivate trypsin. The cell suspension was filtered through a pre-wetted 70 µm cell strainer, and cells pelleted at 300 × g for 10 min at 4°C. Cells were resuspended in 1× GBSS containing 5% (v/v) FBS, 1 µg/ml DNase I, and 5 µg/ml Hoechst 33342 (Thermo Fisher Scientific, Waltham, MA) and rotated at 150 rpm at 33°C for 45 min. Propidium iodide (0.2 µg/ml, f.c.; Thermo Fisher Scientific, Waltham, MA) was added, and cells strained through a pre-wetted 40 µm cell strainer. Cell sorting was performed on a FACS Aria II (BD Biosciences, Franklin Lakes, NJ). The purity of sorted fractions was assessed by immunostaining. Secondary spermatocyte and spermatid populations were >90% pure, and the pachytene spermatocytes and diplotene spermatocytes were >80% pure.

In vitro fertilization (IVF) and embryo transfer

In vitro fertilization was performed as previously described (Nagy et al., 2003) using spermatozoa from caudal epididymis of either C57BL/6, *pi6^{+/em1}*, or *pi6^{em1/em1}* mice. Spermatozoa were incubated in human tubal fluid (HTF; 101.6 mM NaCl, 4.69 mM KCl, 0.37mM KH₂PO₄, 0.2 mM MgSO₄·7H₂O, 21.4 mM Na-lactate, 0.33 mM Na-pyruvate, 2.78 mM glucose, 25 mM NaHCO₃, 2.04 mM CaCl₂·2H₂O, 0.075 mg/ml Penicillin-G, 0.05 mg/ml streptomycin sulfate, 0.02% (v/v) phenol red, 4 mg/ml BSA) with oocytes (98–146 for control sperm and 120–293 for *pi6^{em1/em1}* sperm) from B6SJLF1/J mice for 3–4 h at 37°C with constant 5% O₂, 90% N₂, and 5% CO₂ concentration. Oocyte viability and the presence of pronuclei were assessed under a Nikon SMZ-2B (Nikon, Tokyo, Japan) dissecting microscope. To observe embryo development, embryos were moved into potassium-supplemented simplex optimized media (KSOM; 95 mM NaCl, 2.5 mM KCl, 0.35 mM KH₂PO₄, 0.2 mM MgSO₄·7H₂O, 10 mM Na-lactate, 0.2 mM Na-pyruvate, 0.2 mM glucose, 25 mM NaHCO₃, 1.71 mM CaCl₂·2H₂O, 1 mM L-glutamine, 0.01 mM

EDTA, 0.075 mg/ml Penicillin-G, 0.05 mg/ml streptomycin sulfate, 0.02% (v/v) phenol red, 1 mg/ml BSA; Millipore Sigma, Burlington, MA) after IVF and assessed every 24 h. To measure birth rates, two-cell embryos were transferred to Swiss Webster pseudopregnant females, and fetuses isolated by cesarean section 18.5 d after embryo transfer.

For zona-free IVF, the zona pellucida of oocytes was removed with acid Tyrode's solution as described (Yanagimachi et al., 1976; Johnson et al., 1991).

Intracytoplasmic sperm injection (ICSI)

Frozen caudal epididymal spermatozoa were thawed, the sperm tails detached (Nagy et al., 2003), and individual *pi6^{+/-em1}* or *pi6^{em1/em1}* sperm heads injected into B6D2F1/J oocytes in Chatot-Ziomek-Bavister media (CZB; 81.62 mM NaCl, 4.83 mM KCl, 1.18 mM KH₂PO₄, 1.18 mM MgSO₄·7H₂O, 25 mM Na₂HCO₃, 1.70 mM CaCl₂·2H₂O, 0.11 mM Na₂-ETDA·2H₂O, 1 mM L-glutamine, 28 mM Na-lactate, 0.27 mM Na-pyruvate, 5.55 mM glucose, Penicillin-G 0.05 mg/ml, 0.07 mg/ml streptomycin sulfate, 4 mg/ml BSA) (Millipore Sigma, Burlington, MA) using the PiezoXpert (Eppendorf, Hamburg, Germany; Cat#5194000024). Surviving oocytes were counted, collected, and cultured in KSOM (Millipore Sigma, Burlington, MA) at 37°C and 5% CO₂ for 24 h. Two-cell embryos were surgically transferred unilaterally into the oviducts of pseudopregnant Swiss Webster females. At 16.5 days after the surgery, live fetus isolated by cesarean section.

Sperm motility

Cauda epididymal sperm were collected from mice and placed in 37°C HTF media in an incubator with 5% CO₂. A drop of sperm was removed from the suspension and pipetted into a sperm counting glass chamber, then assayed by CASA or video acquisition. CASA was conducted using an IVOS II instrument (Hamilton Thorne, Beverly, MA) with the following settings: 100 frames acquired at 60 Hz; minimal

contrast = 50; 4 pixel minimal cell size; minimal static contrast = 5; 0%straightness (STR) threshold; 10 $\mu\text{m/s}$ VAP Cutoff; prog. min VAP, 20 $\mu\text{m/s}$; 10 $\mu\text{m/s}$ VSL Cutoff; 5 pixel cell size; cell intensity = 90; static head size = 0.30–2.69; static head intensity = 0.10–1.75; static elongation = 10–94; slow cells motile = yes; 0.68 magnification; LED illumination intensity = 3000; IDENT illumination intensity = 3603; 37°C. Agglutination of *pi6^{em1/em1}* sperm prevented CASA measurements at later times. A Nikon Diaphot 200 microscope (Nikon, Tokyo, Japan) with darkfield optics equipped with Nikon E Plan 10 \times /0.25 160/- Ph1 DL objective (Nikon, Tokyo, Japan), ZWO ASI 174mm Monochrome CMOS Imaging camera (ZWO, SuZhou, China), and the SharpCap software (<https://docs.sharpcap.co.uk/2.9/>) using darkfield at 10 \times magnification were used to record sperm movement at 37°C.

In vitro acrosome reaction assay

Acrosome reaction was assessed as described (Talbot et al., 1976). Cauda epididymides were collected from mice, placed in HTF media pre-warmed for at least 2 h in a 37°C incubator at 5% CO₂. A few incisions were made in the epididymides with scissors to release the sperm, followed by incubation at 37°C in 5% CO₂ for 90 min. Calcium ionophore A23187 (10 μM f.c. in DMSO) was added, and incubation continued for 30 min. Sperm were fixed at room temperature for 10 min by adding two volumes of 4% (w/v) PFA, pelleting at 1,000 $\times g$ for 5 min, washed with 1 \times PBS, resuspended in fresh 1 \times PBS, spotted on a glass slide, and air-dried. Methanol was pipetted onto the sperm to permeabilize the cells, followed by washing with 1 \times PBS. Slides were incubated overnight in 10 $\mu\text{g/ml}$ Alexa Fluor 488-conjugated peanut agglutinin (PNA) in 1 \times PBS (Mortimer D., 1987), washed with 1 \times PBS, air-dried, and mounted with ProLong Gold Antifade Mountant with DAPI (Thermo Fisher Scientific, Waltham, MA). Sperm were imaged using a Leica DMI8 fluorescence microscope equipped with a 63 \times 1.4 N.A.

oil immersion objective (HC PL APO; Leica Microbiosystems, Buffalo Grove, IL) and analyzed using ImageJ (version 2.0.0-rc-68/1.52e; <https://fiji.sc/>).

Chromatin Immunoprecipitation (ChIP) and sequencing

Frozen testes were cross-linked with 2% (w/v) formaldehyde at room temperature for 30 min using an end-over-end tumbler. Fixed tissues were homogenized in buffer containing 1% (w/v) sodium lauryl sulfate (SDS), 10mM EDTA, and 50mM Tris-HCl (pH 8.1) by 40 strokes in a Dounce tissue grinder with Pestle B (Kimble-Chase, Rockwood, TN). Lysed samples were sonicated using the E220 Covaris ultrasonicator (Covaris, Woburn, MA) to shear the chromatin to 150–200 bp fragments and diluted 1:10 with a buffer containing 0.01% (w/v) SDS, 1.1% (v/v) Triton X-100, 1.2 mM EDTA, 16.7 mM Tris-HCl (pH 8.1), 167 mM NaCl. Immunoprecipitation was performed using 5.5 µg of rabbit anti-A-MYB antibody (Sigma, St. Louis, MO), DNA was extracted with phenol:chloroform:isoamyl alcohol (25:24:1) (pH 8), and ChIP-seq libraries were prepared as previously described (Li et al., 2013). Libraries were sequenced using paired-end reading on NextSeq500 (Illumina, San Diego, CA), and reads were mapped to mouse genome assembly mm10 using Bowtie2 (v2.2.5). ChIP-seq peaks were determined using MACS2 (v2.1.1) and unique mapping reads were reported in this study as fold enrichment over input.

RNA-seq and small RNA-seq

Small RNA-seq and RNA-seq libraries were constructed and sequenced using NextSeq 500 (Illumina, San Diego, CA) as described (Fu et al., 2018). To sequence mature piRNAs, small RNA was oxidized with 25 mM NaIO₄ in 30 mM sodium borate, 30 mM boric acid (pH 8.6; Sigma Aldrich, St. Louis, MO) at 25°C for 30 min. RNA was precipitated with ethanol before adapter ligation. Small RNA-seq and RNA-seq reads were mapped to mouse genome assembly mm10 using piPipes (Han et al., 2015).

Transcript abundance between *pi6*^{+/em1} and C57BL/6 testes were indistinguishable (< 2-fold change and FDR > 0.05). Transcripts with low abundance (< 1 fpkm) in both C57BL/6 and *pi6*^{em1/em1} cells were excluded.

Transposon mapping

RNA-seq reads were intersected using BEDtools (Quinlan and Hall, 2010) with Repeat Masker annotation from UCSC (downloaded from <https://genome.ucsc.edu/cgi-bin/hgTables>). Reads mapping to multiple genomic locations were apportioned. Reads for individual repeats were aggregated to obtain reads counts for repeat families.

Statistics

All statistics were performed using R (<https://www.rstudio.com/>) and graphs were generated using Igor Pro v7.08 (WaveMetrics) or ggplot2 v3.0.0 (<https://ggplot2.tidyverse.org/>). Unless otherwise stated, Mann-Whitney-Wilcoxon test was used to calculate *p* values.

ACCESSION NUMBERS

All sequencing data are available through the NCBI Sequence Read Archive using accession number PRJNA480354.

SUPPLEMENTAL FIGURE, TABLE, AND MOVIES

Supplemental Figure Legends

Figure S1. Confirmation of mutant founder genotypes. Related to Figure 1 and Table S1.

(A) Genotyping of mutant founders by PCR. Genomic sequences of *pi6* promoter region in *pi6^{em1/em1}* (B) and *pi6^{em2/em2}* (C) mouse lines. (D) Genomic sequences of *pi17* promoter region in *pi17^{-/-}* mouse lines. Dashes, genomic sequences deleted by CRISPR; dots, unaltered sequence omitted for clarity.

Figure S2. *pi6^{em1/em1}* adult male phenotype. Related to Figure 2.

(A) Number of litters produced in 6 months by 2–8 month-old males. (B) Body and testis weight of 2–4 month-old *pi6^{em1/em1}* and *pi6^{em2/em2}* males. Each dot represents an individual mouse. The thick lines denote median values, and whiskers indicate the 75th and 25th percentiles. (C) Representative spermatozoon. (D) Representative patterns of meiotic chromosome synapsis in *pi6^{em1/em1}* pachytene spermatocytes. SYCP1, Synaptonemal complex protein 1; SYCP3, Synaptonemal complex protein 3. (E) Quantification of patterns of meiotic chromosome synapsis depicted in (D).

Figure S3. Abundance of transposons in *pi6^{em1/em1}* germ cells. Related to Figure 3.

(A) Proportions of the whole genome or piRNA sequences composed of repetitive sequences. (B) Abundance of repetitive sequences in mouse germ cells. A pseudocount of 1 was added to each value. Each dot represents the mean value of three biologically independent RNA-seq experiments.

Figure S4. Pregnancy rate of surrogate mothers in IVF and ICSI experiments.

Related to Figure 5.

Percent of pregnant surrogate mothers in IVF **(A)** and ICSI **(B)**.

Figure S5. Transcriptome changes in *pi6^{em1/em1}* cells. Related to Figure 6.

(A) Number of altered genes with mRNA abundance altered by ≥ 2 -fold with $FDR \leq 0.05$ in indicated cell types. **(B)** Abundance of pachytene piRNAs and their precursors in C75BL/6 purified germ cells. For piRNA precursor levels, each dot represents the mean value of triplicate datasets and each error bar indicates the standard deviation. For mature piRNAs, each dot represents the mean abundance of unique-mapping reads of two duplicate datasets. **(C)** mRNAs with altered abundance in *pi6^{em1/em1}* cells and encoding protein with functions in meiotic chromosome organization and miRNA-mediated regulation.

Supplemental Table Legends

Table S1. Statistics of CRISPR injection for *pi6* mutant generation. Related to Figure 1 and S1.

Table S2. Differentially expressed genes in *pi6^{em1/em1}* germ cells. Related to Figure 6 and S5.

Mean abundance (fpkm) of significantly altered mRNAs (≥ 2 -fold change \cap FDR 0.05) in C57BL/6 versus *pi6^{em1/em1}* cells of RNA-seq triplicate datasets. A pseudocount of 0.5 was added to each value to calculate the differences. Transcripts with < 1 rpkm in both C57BL/6 and *pi6^{em1/em1}* cells prior to adding pseudocount were excluded.

Table S3. Expression of piRNA pathway genes in *pi6^{em1/em1}* cells. Related to Figure 6 and S5

Mean expression (fpkm) of piRNA genes in C57BL/6 versus *pi6^{em1/em1}* cells of RNA-seq triplicate datasets. A pseudocount of 0.5 was added to each value to calculate the differences. Significant changes were ≥ 2 -fold increase or decrease and FDR ≤ 0.05 .

Table S4. Transcription factors with altered mRNA abundance in *pi6^{em1/em1}* pachytene spermatocytes. Related to Figure 6 and S5.

Table S5. Gene Ontology of genes with decreased expression in *pi6^{em1/em1}* pachytene spermatocytes. Related to Figure 6 and S5.

Table S6. Genes with reduced expression in *pi6^{em1/em1}* pachytene spermatocytes that are mapped to major Gene Ontology categories.

Related to Figure 6 and S5.

Table S7. RFX2 and A-MYB target genes with decreased abundance in *pi6^{em1/em1}* pachytene spermatocytes.

Related to Figure 6 and S5.

Table S8. Published male fertility genes with altered expression in *pi6^{em1/em1}* cells.

Related to Figure 6 and S5.

Legends to Movies

Movies S1-10. *pi6^{em1/em1}* sperm motility.

Movie S1. C57BL/6 sperm motility at 10 minute time point.

Movie S2. *pi6^{em1/em1}* sperm motility at 10 minute time point.

Movie S3. C57BL/6 sperm motility at 90 minute time point.

Movie S4. *pi6^{em1/em1}* sperm motility at 90 minute time point.

Movie S5. C57BL/6 sperm motility at 3 hour time point.

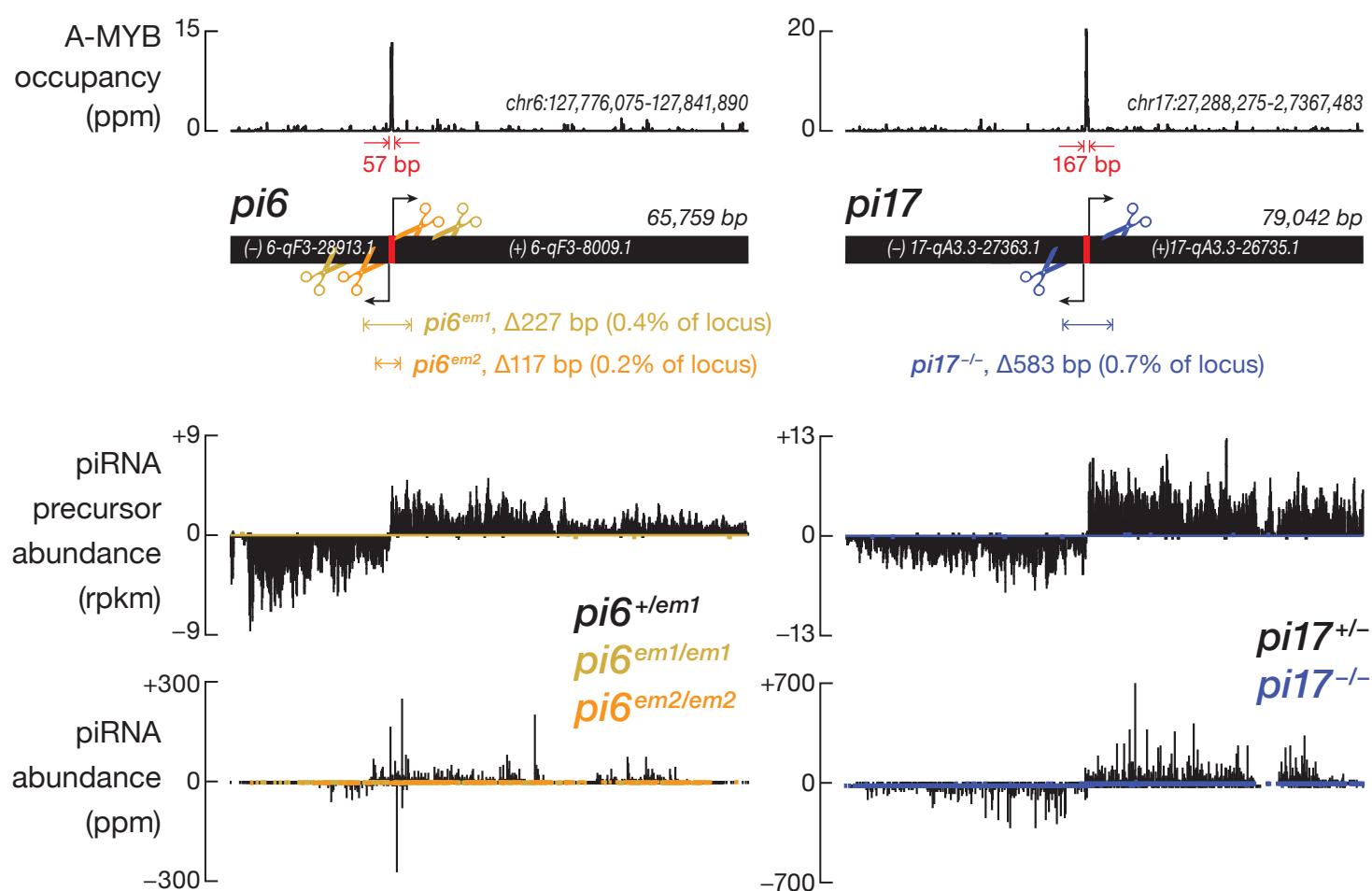
Movie S6. *pi6^{em1/em1}* sperm motility at 3 hour time point

Movie S7. C57BL/6 sperm motility at 4 hour time point.

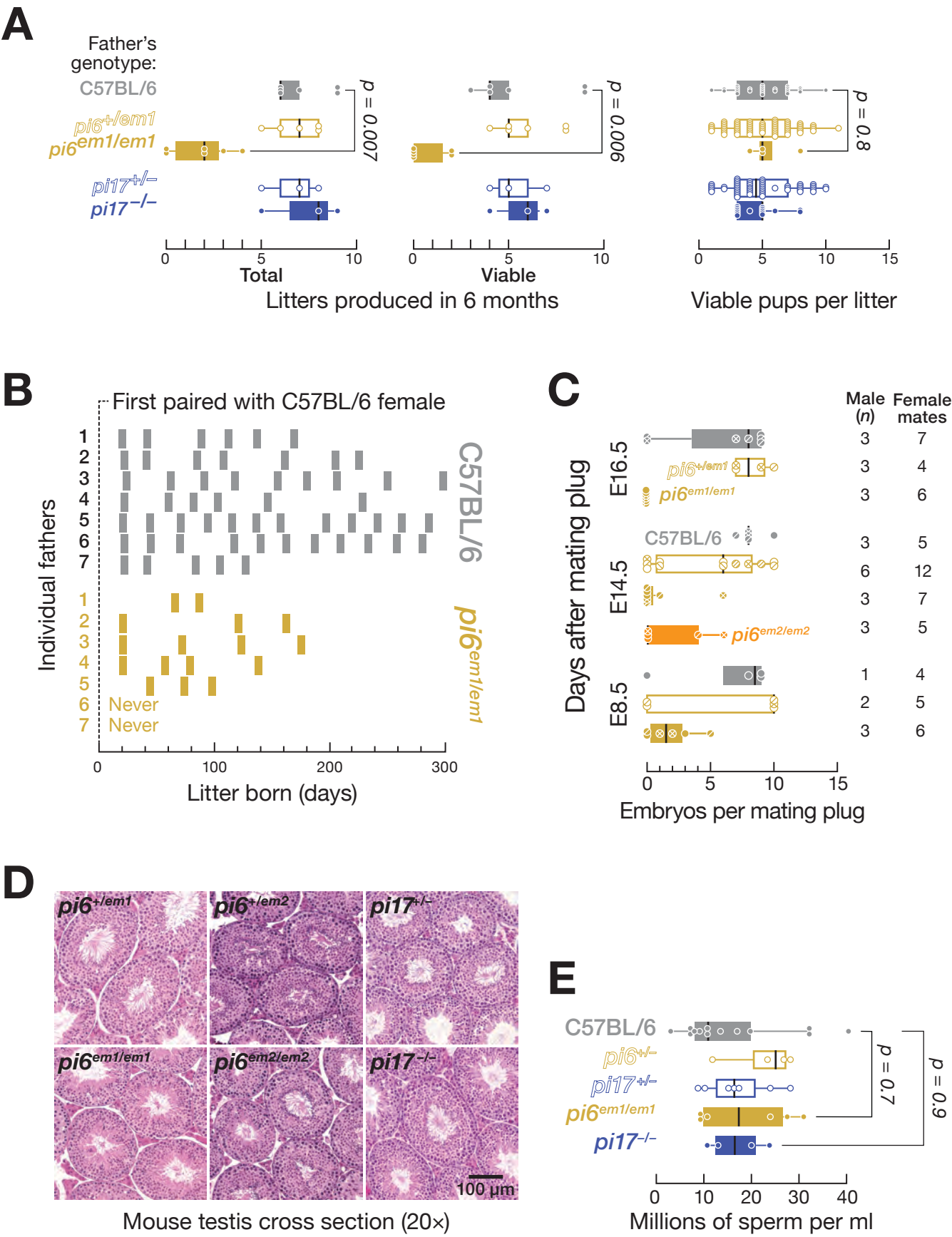
Movie S8. *pi6^{em1/em1}* sperm motility at 4 hour time point.

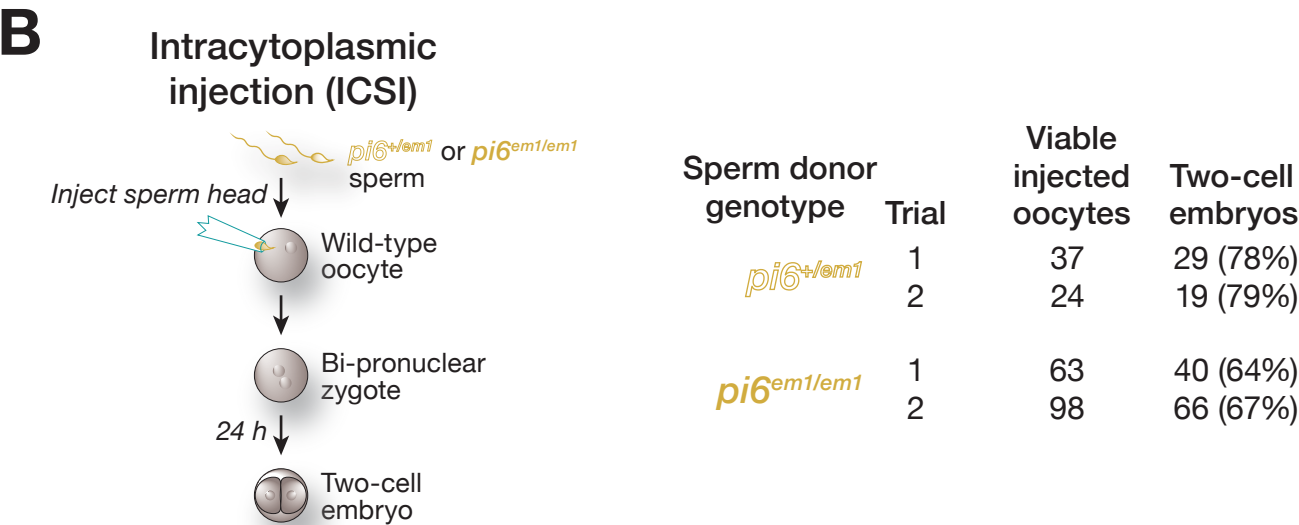
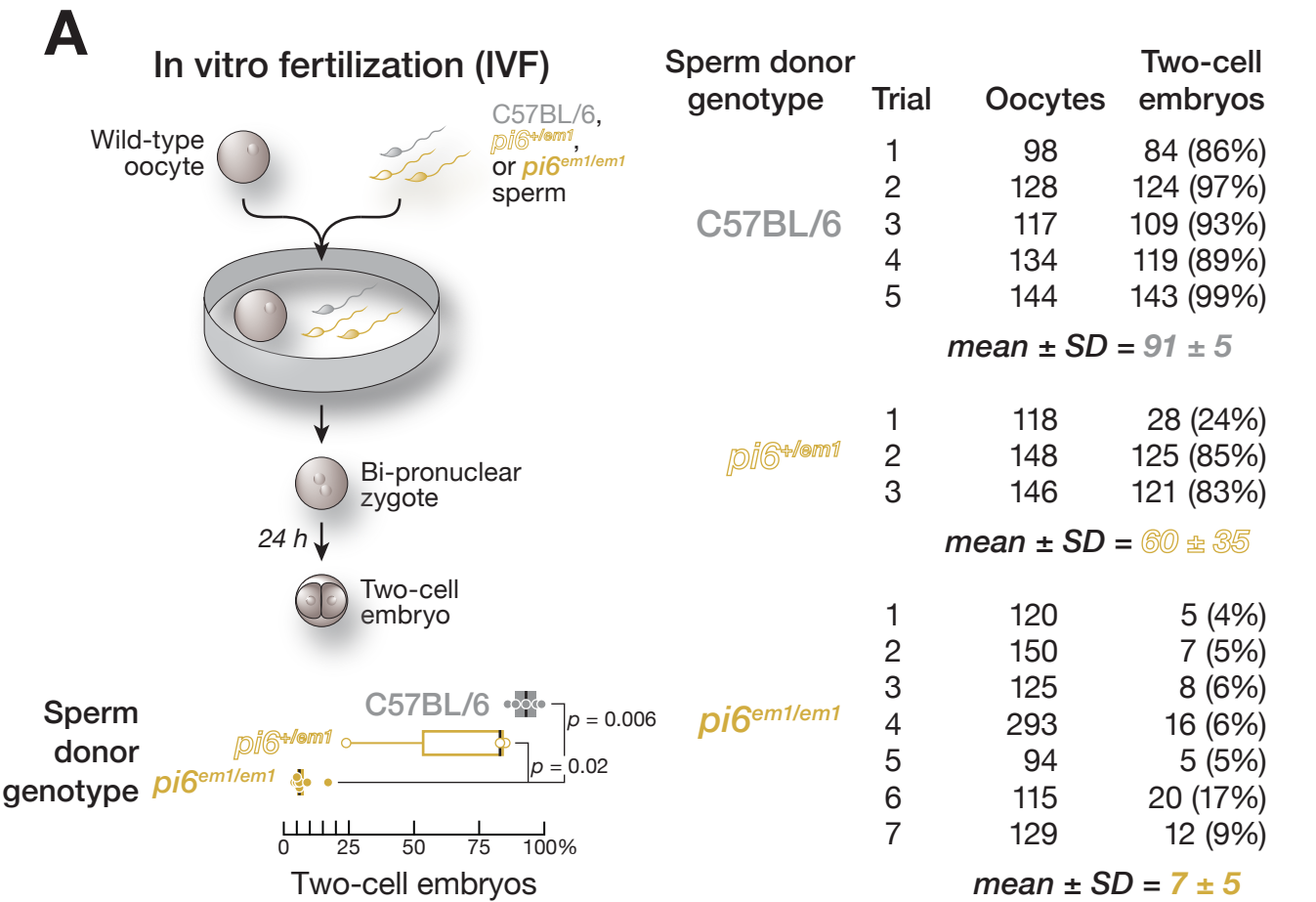
Movie S9. C57BL/6 sperm motility at 5 hour time point.

Movie S10. *pi6^{em1/em1}* sperm motility at 5 hour time point.

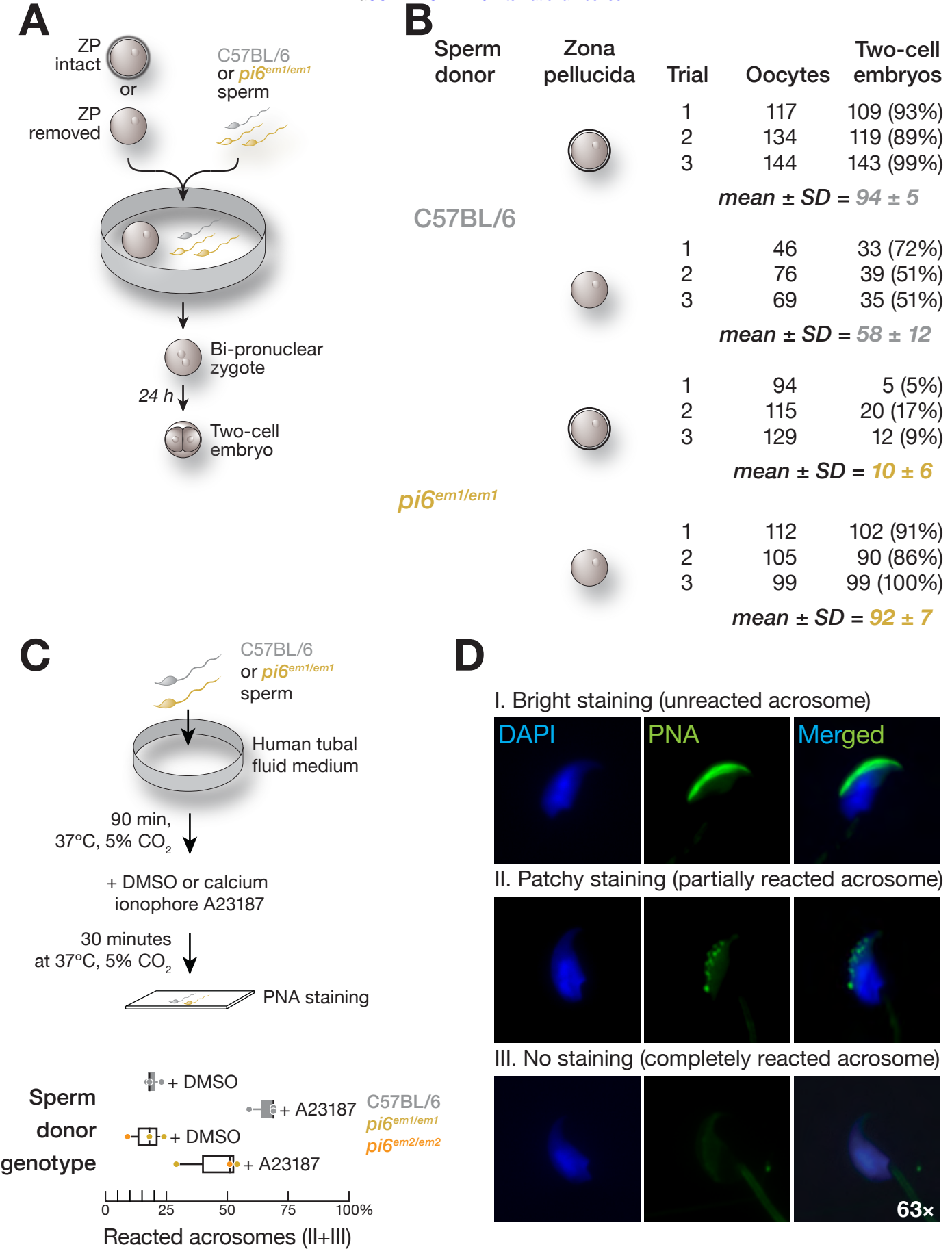


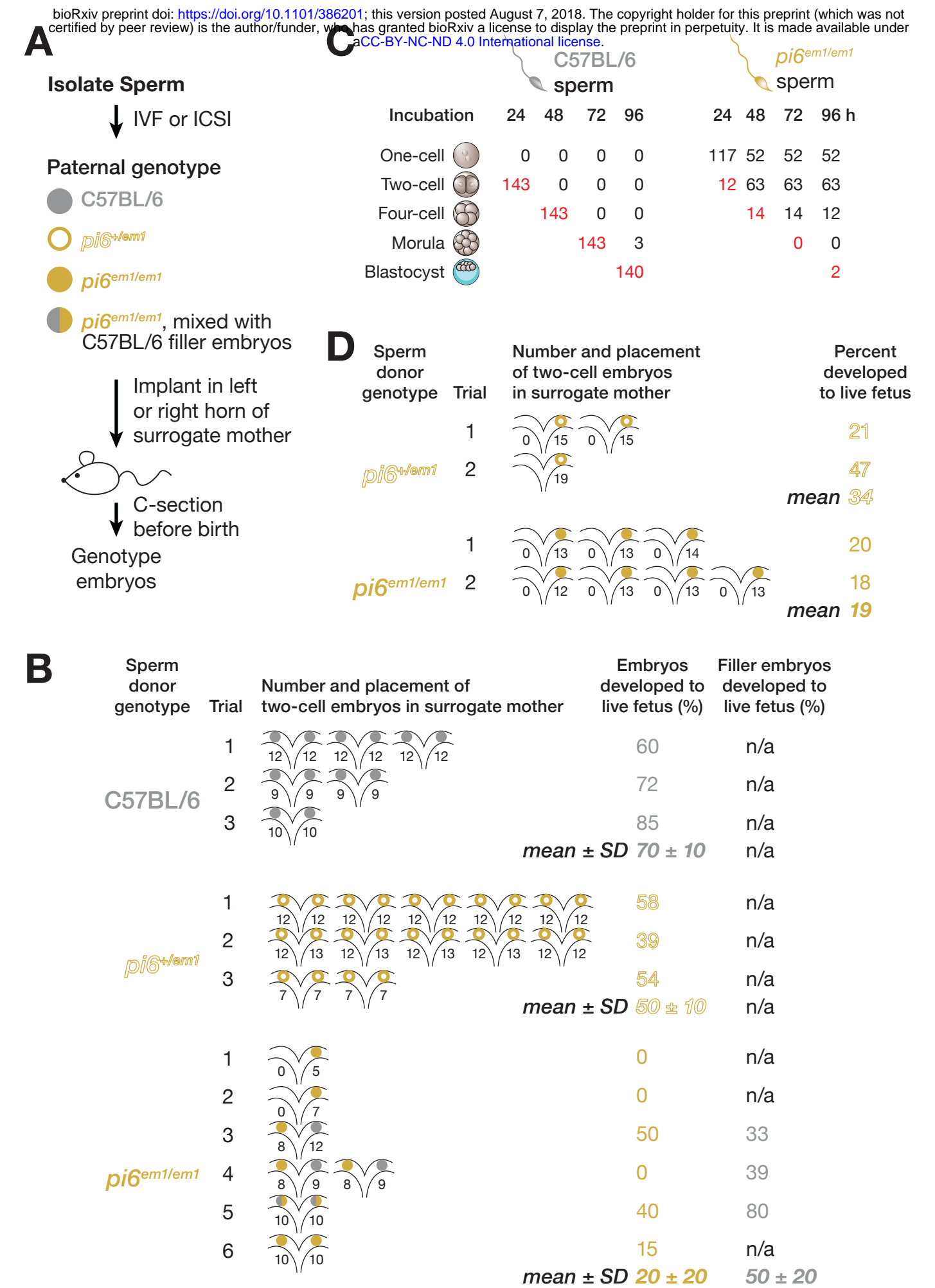
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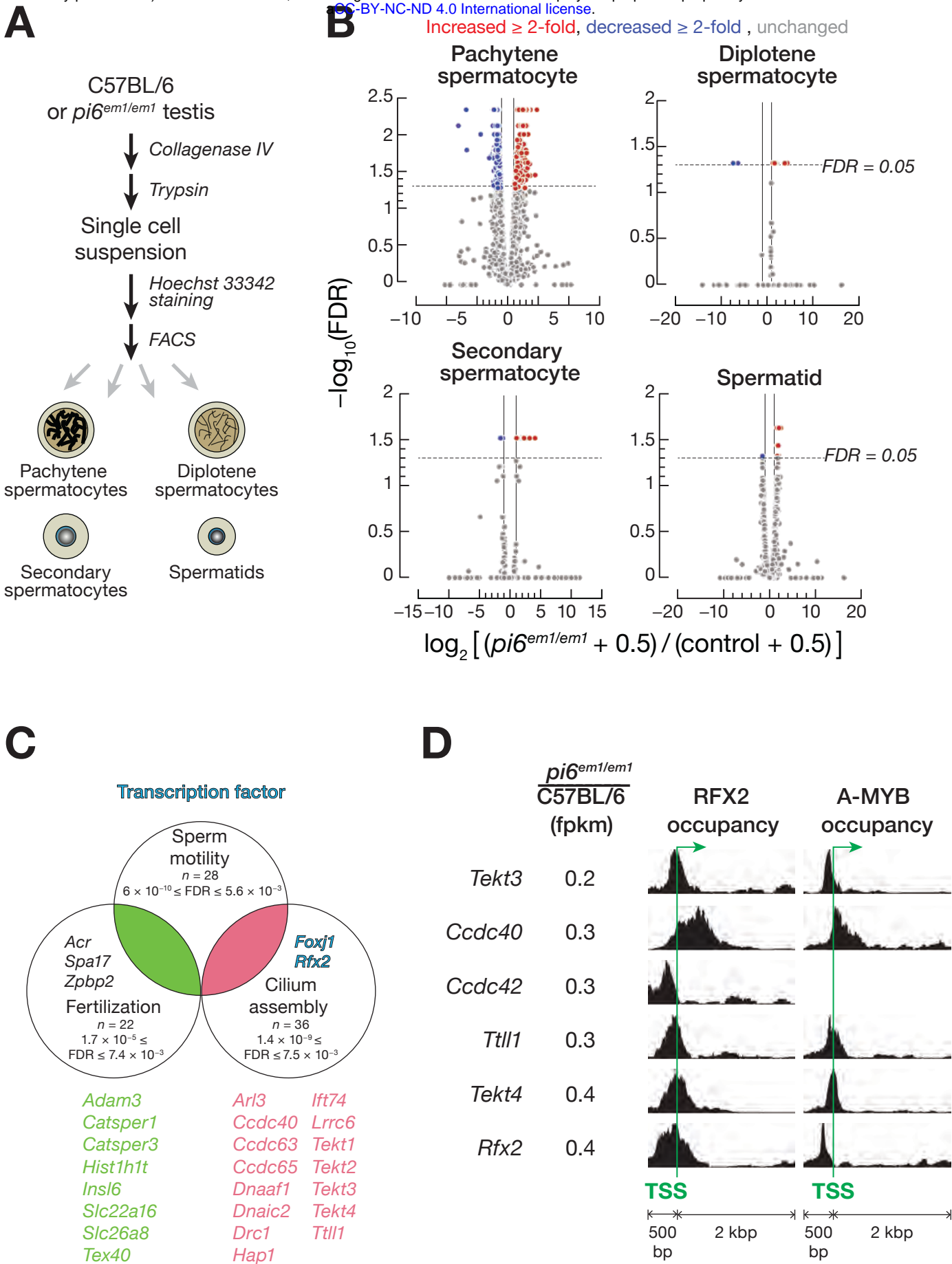


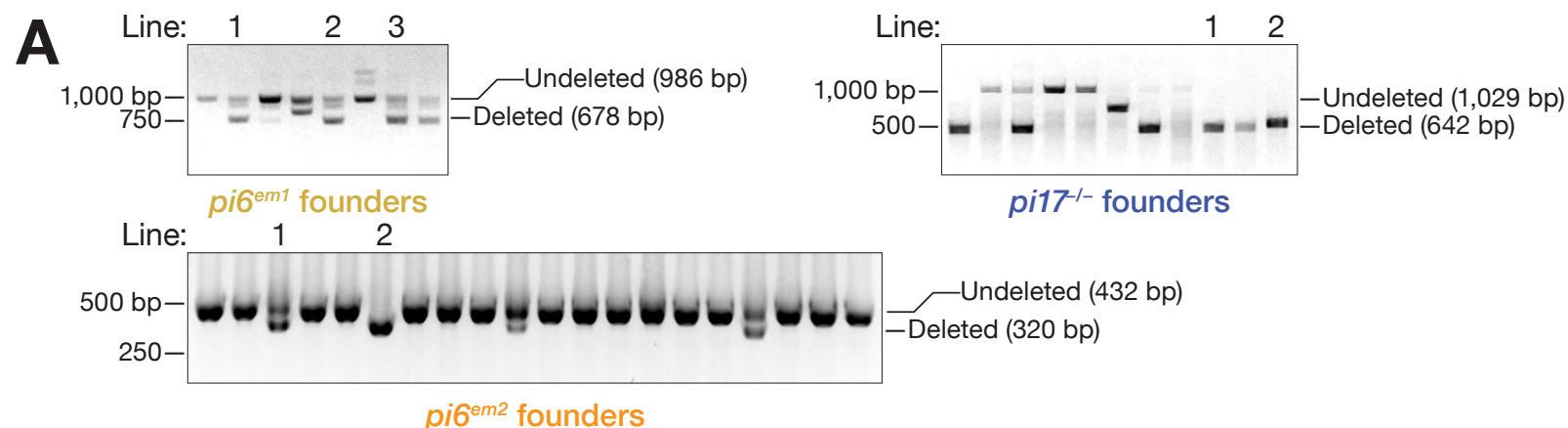
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B

C57BL/6 AGAAGACTGCCTACTCCAAGATAGTGGG.....CACACAAGTGCCCAACGAAATGGAAAACA

sgRNA1 GACTGCCTACTCCAAGATAG sgRNA2 CACACAAGTGCCCAACGAAA

pi6^{em1} 1 AGAAGACTGCCTACTCCAAG-----(Δ 219 bp)-----TGCCCAACGAAATGGAAAACA

pi6^{em1} 2 AGAAGACTGCCTACTCCAAG-----(Δ 230 bp)-----ATGGAAAACA

pi6^{em1} 3 AGAAGACTGCCTACTCCAA-----(Δ 228 bp)-----GAAATGGAAAACA

pi6^{em1} 4 AGAAGACTGCCTACTCCAA-----(Δ 233 bp)-----GGAAAACA

pi6^{em1} 5 AGAAGACTGCCTACTCCAAGA-----(Δ 227 bp)-----AAATGGAAAACA

pi6^{em1} 6 AGAAGACTGCCTACTCCAA-----(Δ 231 bp)-----ATGGAAAACA

C

C57BL/6 ACGGTGGGTTCTATCCAATGAGGTC.....GGGATAGAGTAAGTGAGAAGCTGGCCCTTACATCAT

sgRNA1 ACGGTGGGTTCTATCCAATG sgRNA2 GATAGAGTAAGTGAGAAGC

pi6^{em2} 1 ACGGTGGGTTCTATCCAA-----(Δ 116 bp)-----GCTGGCCCTTACATCAT

pi6^{em2} 2 ACGGTGGG-----(Δ 125 bp)-----AGCTGGCCCTTACATCAT

D

C57BL/6 GGGCTGCTCTGTCTGACAACGGGAC...TCACATCTCTGTGCAG...TCCCTTCACACGGCCGTTTA...CCGTCCCTGATAGTGG

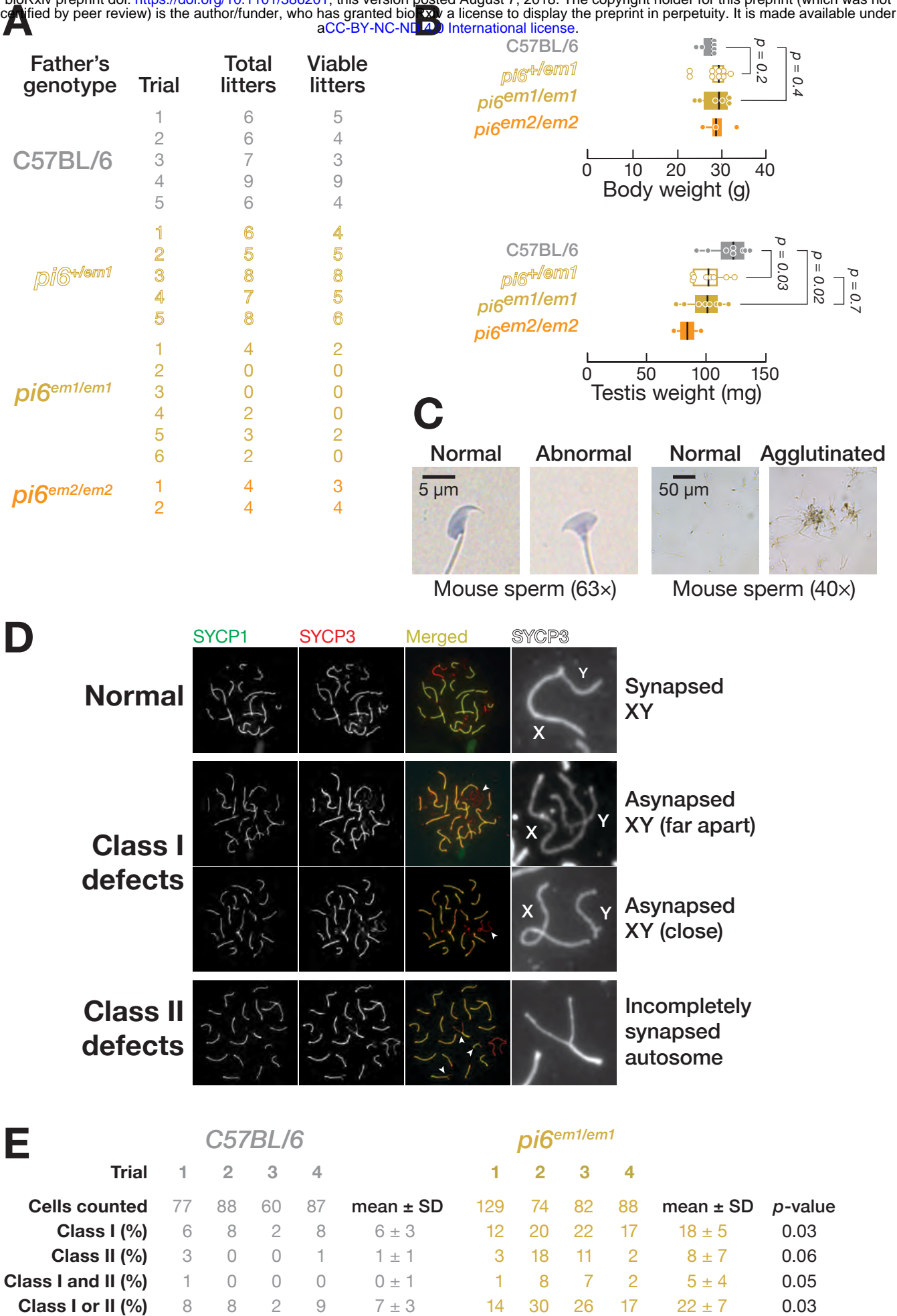
sgRNA2 GCTCTGTCTGACAACGGGAC sgRNA1 TCCCTTCACACGGCCGTTTA

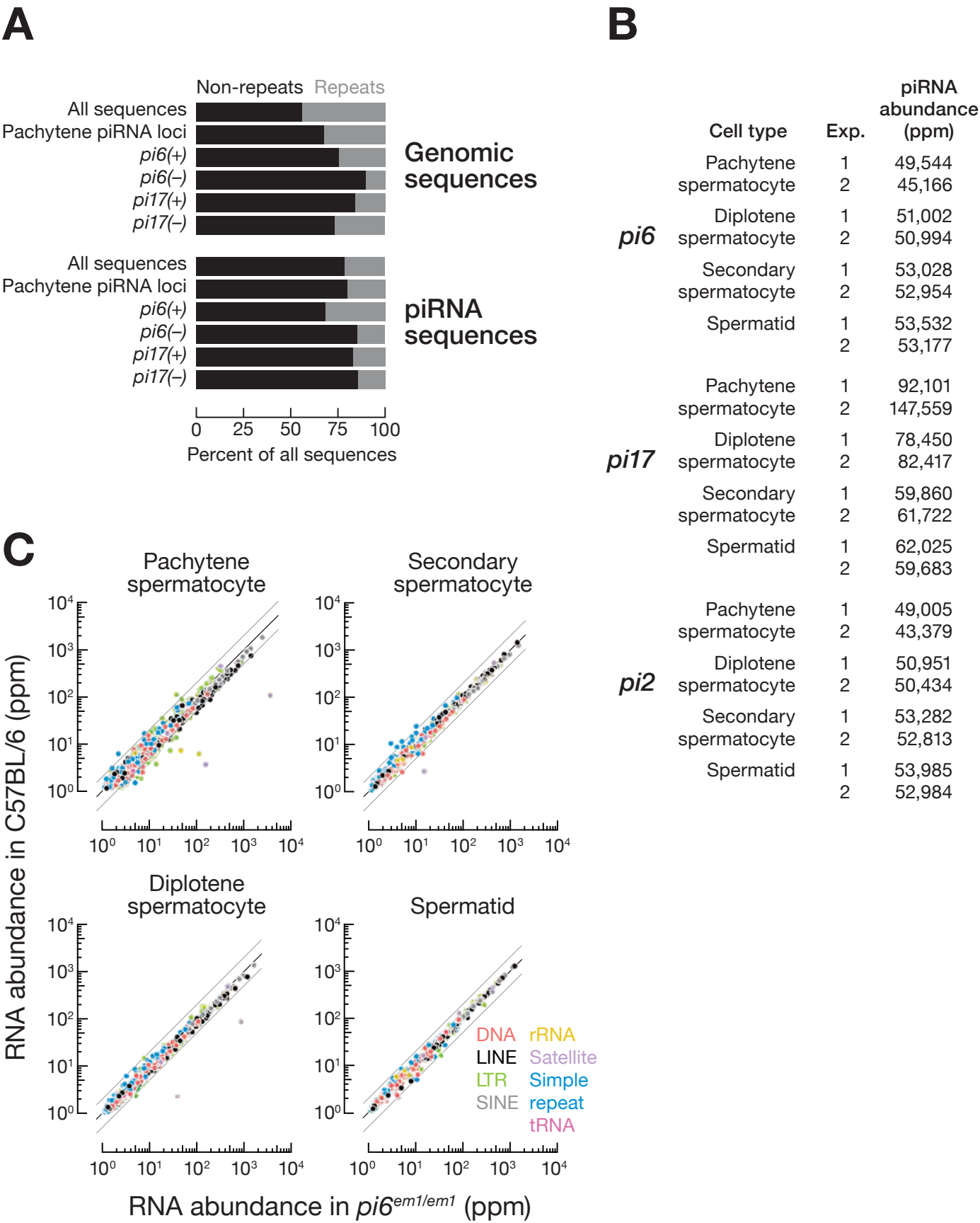
pi17^{-/-} 1 GGGCTGCT-----(Δ 606 bp)-----CCGTCCCTGATAGTGG

pi17^{-/-} 2 GGGCTGCTCTGTCTGACAACG-----(Δ 583 bp)-----TTTA...CCGTCCCTGATAGTGG













pi17^{-/-} 3 GGGCT-----(Δ 543 bp)-----TCTGTGCAG...TCCCTTCACACGGCCGTTTA...CCGTCCCTGATAGTGG

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A

Sperm donor genotype	Trial	Number and placement of two-cell embryos in surrogate mother	Surrogate mothers	Pregnant surrogate mothers
C57BL/6	1		3	3
	2		2	2
	3		1	1
				100%
<i>pi6^{+/-em1}</i>	1		2	2
	2		5	5
	3		5	5
				100%
<i>pi6^{em1/em1}</i>	1		1	0
	2		1	0
	3		1	1
	4		2	1
	5		1	1
	6		1	1
				67%

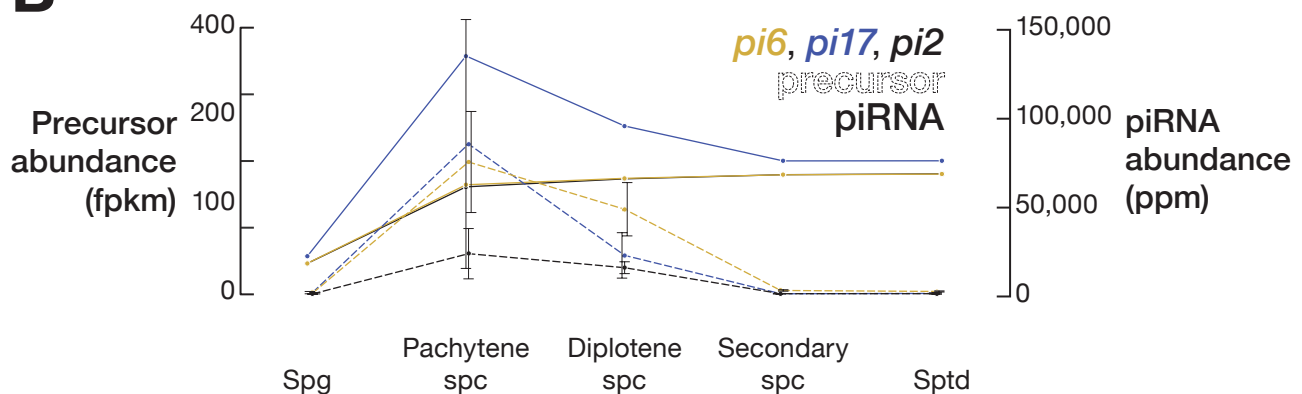
B

Sperm donor genotype	Trial	Number and placement of two-cell embryos in surrogate mother	Surrogate mothers	Pregnant surrogate mothers
<i>pi6^{+/-em1}</i>	1		2	2
	2		1	1
				100%
<i>pi6^{em1/em1}</i>	1		3	2
	2		4	2
				57%

A

Cell type	Number of genes with altered RNA abundance	
	<i>pi6^{em1/em1}</i>	<i>pi17^{-/-}</i>
Pachytene spermatocytes (4C)	875	0
Diplotene spermatocytes (4C)	9	277
Secondary spermatocytes (2C)	20	503
Spermatids (1C)	45	0
Total altered unique genes	928	625

B



C

	Genes	C57BL/6 (fpkm)	<i>pi6^{em1/em1}</i> (fpkm)	<i>pi6^{em1/em1}</i> / C57BL/6	FDR
Meiotic chromosome organization	<i>Atm</i>	3.5	12.3	3.2	2.2×10^{-2}
	<i>Dmc1</i>	1.6	9.2	4.6	2.6×10^{-2}
	<i>Syce1</i>	215.2	71.6	0.3	4.3×10^{-3}
miRNA pathway genes	<i>Lin28a</i>	0.9	7.6	5.6	1.6×10^{-2}
	<i>Zc3h7b</i>	1.6	10.1	5.0	4.3×10^{-3}
	<i>Ajuba</i>	0.6	5.4	5.3	7.0×10^{-3}

Table S1. Statistics of CRISPR injection for *pi6* mutant generation.

Allele	<i>pi6^{em1}</i>				<i>pi6^{em2}</i>
Nucleic acid injected	sgRNA + Cas9 mRNA	pX330 construct	sgRNA + Cas9 mRNA + pX330 construct	Total	sgRNA + Cas9 mRNA
Number of pups screened	55	45	42	142	23
Number of founders	5 (9%)	1 (2%)	2 (5%)	8 (6%)	5 (22%)
Number of female founders	3 (60%)	1 (100%)	1 (50%)	5 (63%)	2 (40%)
Number of male founders	2 (40%)	0 (0%)	1 (50%)	3 (38%)	3 (60%)
Number of surviving founders	5 (100%)	0 (0%)	2 (100%)	7 (88%)	5 (100%)

Table S2. Differentially expressed genes in *pi6^{em1/em1}* germ cells.

Cell type	Ensembl ID	Gene	Genomic Location (mm10)	C57BL/6 (fpkm)	<i>pi6^{em1/em1}</i> (fpkm)	<i>pi6^{em1/em1}</i> C57BL/6	FDR
Pac spc	ENSMUSG0000075014.1	<i>Gm10800</i>	chr2:98666546-98667301	132.8	3644.7	27.3	4.3×10 ⁻³
Pac spc	ENSMUSG0000075015.3	<i>Gm10801</i>	chr2:98662236-98664083	12.7	299.3	22.6	3.3×10 ⁻²
Pac spc	ENSMUSG0000021451.11	<i>Sema4d</i>	chr13:51701245-51793747	0.4	12.6	14.1	4.3×10 ⁻³
Pac spc	ENSMUSG0000031584.12	<i>Gsr</i>	chr8:33652522-33698163	1.8	29.0	13.0	4.3×10 ⁻³
Pac spc	ENSMUSG0000031229.12	<i>Atrx</i>	chrX:105797614-105929397	0.9	18.2	13.0	4.3×10 ⁻³
Pac spc	ENSMUSG0000003949.12	<i>Hlf</i>	chr11:90336535-90390895	0.3	10.3	12.8	3.3×10 ⁻²
Pac spc	ENSMUSG0000032841.11	<i>Prr5l</i>	chr2:101714284-101883256	0.3	9.1	12.8	2.0×10 ⁻²
Pac spc	ENSMUSG0000042105.14	<i>Inpp5f</i>	chr7:128611327-128696425	0.7	14.2	12.2	2.3×10 ⁻²
Pac spc	ENSMUSG0000081327.1	<i>Gm11819</i>	chr4:13444769-13445141	0.0	5.4	11.9	4.3×10 ⁻³
Pac spc	ENSMUSG0000016386.11	<i>Mpped2</i>	chr2:106693268-106868356	0.4	9.4	11.0	1.8×10 ⁻²
Pac spc	ENSMUSG0000083546.1	<i>Tpt1-ps1</i>	chr3:101233459-101233895	0.0	4.8	10.6	4.3×10 ⁻³
Pac spc	ENSMUSG0000031161.11	<i>Hdac6</i>	chrX:7930119-7947889	2.5	30.7	10.4	4.3×10 ⁻³
Pac spc	ENSMUSG0000039428.6	<i>Tmem135</i>	chr7:89139722-89404222	4.1	46.9	10.3	2.2×10 ⁻²
Pac spc	ENSMUSG0000038080.12	<i>Kdm1b</i>	chr13:47025169-47084613	0.6	10.6	10.2	9.2×10 ⁻³
Pac spc	ENSMUSG0000008318.5	<i>Relt</i>	chr7:100845847-100863446	0.3	7.9	10.2	3.1×10 ⁻²
Pac spc	ENSMUSG0000005078.12	<i>Jkamp</i>	chr12:72085588-72185029	0.8	12.2	9.9	3.3×10 ⁻²
Pac spc	ENSMUSG0000059625.6	<i>Sohlh1</i>	chr2:25842994-25847248	0.6	10.4	9.9	2.2×10 ⁻²
Pac spc	ENSMUSG0000032135.10	<i>Mcam</i>	chr9:44123767-44142727	1.5	18.9	9.9	4.3×10 ⁻³
Pac spc	ENSMUSG0000042453.10	<i>Reln</i>	chr5:21884453-22344702	1.6	19.4	9.6	4.3×10 ⁻³
Pac spc	ENSMUSG0000016262.10	<i>Sertad4</i>	chr1:192844487-192856246	0.5	9.5	9.6	4.5×10 ⁻²
Pac spc	ENSMUSG0000039323.14	<i>Igfbp2</i>	chr1:72824502-72852474	1.3	16.9	9.5	2.6×10 ⁻²
Pac spc	ENSMUSG0000028487.14	<i>Bnc2</i>	chr4:84275094-84675275	1.6	19.5	9.5	4.3×10 ⁻³
Pac spc	ENSMUSG0000068270.11	<i>Shroom4</i>	chrX:6399853-6637448	0.3	6.5	9.2	4.9×10 ⁻²
Pac spc	ENSMUSG0000032598.8	<i>Nckipsd</i>	chr9:108808367-108818844	2.0	22.5	9.2	4.3×10 ⁻³
Pac spc	ENSMUSG0000017760.11	<i>Ctsa</i>	chr2:164830731-164857711	0.6	9.9	9.1	4.3×10 ⁻³

Pac spc	ENSMUSG0000019849.10	<i>Prep</i>	chr10:45067205-45158997	1.2	14.6	9.1	4.3×10 ⁻³
Pac spc	ENSMUSG0000026923.11	<i>Notch1</i>	chr2:26445695-26516663	0.1	5.0	8.9	4.3×10 ⁻³
Pac spc	ENSMUSG0000070371.7	<i>Prss36</i>	chr7:127932637-127946725	0.3	6.7	8.9	3.8×10 ⁻²
Pac spc	ENSMUSG0000000247.7	<i>Lhx2</i>	chr2:38339280-38369733	0.1	5.3	8.9	4.3×10 ⁻³
Pac spc	ENSMUSG0000027200.13	<i>Sema6d</i>	chr2:124089968-124667770	0.2	5.3	8.8	4.3×10 ⁻³
Pac spc	ENSMUSG0000018417.10	<i>Myo1b</i>	chr1:51749764-51916071	0.9	12.1	8.8	7.0×10 ⁻³
Pac spc	ENSMUSG0000050708.10	<i>Ftl1</i>	chr7:45457943-45459884	6.6	61.9	8.8	4.3×10 ⁻³
Pac spc	ENSMUSG0000027547.13	<i>Sall4</i>	chr2:168748331-168768108	0.6	9.3	8.7	4.3×10 ⁻³
Pac spc	ENSMUSG0000031431.9	<i>Tsc22d3</i>	chrX:140539527-140600659	3.8	36.4	8.6	4.3×10 ⁻³
Pac spc	ENSMUSG0000071369.6	<i>Map3k5</i>	chr10:19934471-20142753	1.0	12.2	8.5	1.7×10 ⁻²
Pac spc	ENSMUSG0000030796.11	<i>Tead2</i>	chr7:45215752-45239115	0.5	8.0	8.4	4.3×10 ⁻³
Pac spc	ENSMUSG0000022763.12	<i>Aifm3</i>	chr16:17489610-17507485	0.6	8.5	8.4	1.1×10 ⁻²
Pac spc	ENSMUSG0000058454.10	<i>Dhcr7</i>	chr7:143823144-143848410	2.5	24.8	8.4	4.3×10 ⁻³
Pac spc	ENSMUSG0000086481.1	<i>Gm11707</i>	chr11:106972057-106973090	0.0	3.7	8.4	4.3×10 ⁻³
Pac spc	ENSMUSG0000007891.11	<i>Ctsd</i>	chr7:142325836-142388038	3.7	34.1	8.3	4.3×10 ⁻³
Pac spc	ENSMUSG0000025261.13	<i>Huwe1</i>	chrX:151800806-151935417	8.8	76.5	8.3	4.3×10 ⁻³
Pac spc	ENSMUSG0000017386.6	<i>Traf4</i>	chr11:78158498-78165589	0.8	10.0	8.2	9.2×10 ⁻³
Pac spc	ENSMUSG0000053398.7	<i>Phgdh</i>	chr3:98313169-98339990	0.7	9.3	8.2	1.8×10 ⁻²
Pac spc	ENSMUSG0000005672.8	<i>Kit</i>	chr5:75574915-75656722	2.0	20.2	8.1	4.3×10 ⁻³
Pac spc	ENSMUSG0000009376.11	<i>Met</i>	chr6:17463799-17573980	0.3	6.0	8.1	2.1×10 ⁻²
Pac spc	ENSMUSG0000028293.10	<i>Slc35a1</i>	chr4:34663256-34687438	0.9	11.2	8.1	1.5×10 ⁻²
Pac spc	ENSMUSG0000061462.11	<i>Obecn</i>	chr11:58994255-59136402	0.5	7.8	8.0	1.9×10 ⁻²
Pac spc	ENSMUSG0000031353.9	<i>Rbbp7</i>	chrX:162760401-162829454	2.5	23.6	8.0	2.8×10 ⁻²
Pac spc	ENSMUSG0000039382.7	<i>Wdr45</i>	chrX:7714332-7728201	0.7	9.0	8.0	4.3×10 ⁻³
Pac spc	ENSMUSG0000032291.8	<i>Crabp1</i>	chr9:54764747-54773110	2.9	26.6	7.9	7.0×10 ⁻³
Pac spc	ENSMUSG0000027669.10	<i>Gnb4</i>	chr3:32580331-32616585	0.3	5.7	7.9	1.6×10 ⁻²
Pac spc	ENSMUSG0000039683.12	<i>Sdk1</i>	chr5:141241489-142215586	1.7	16.5	7.9	1.5×10 ⁻²
Pac spc	ENSMUSG0000025577.7	<i>Cbx2</i>	chr11:119022961-119031270	0.9	10.7	7.8	4.3×10 ⁻³
Pac spc	ENSMUSG0000030199.12	<i>Etv6</i>	chr6:134035699-134270158	1.4	14.2	7.7	3.8×10 ⁻²

Pac spc	ENSMUSG0000022433.14	<i>Csnk1e</i>	chr15:79417855-79443919	0.6	8.1	7.6	7.0×10^{-3}
Pac spc	ENSMUSG0000001525.10	<i>Tubb5</i>	chr17:35833920-35838306	2.2	19.8	7.6	4.3×10^{-3}
Pac spc	ENSMUSG0000036893.12	<i>Ehmt1</i>	chr2:24790768-24919609	2.4	21.3	7.6	4.3×10^{-3}
Pac spc	ENSMUSG00000031403.10	<i>Dkc1</i>	chrX:75095853-75131016	1.2	12.7	7.6	2.2×10^{-2}
Pac spc	ENSMUSG0000006494.7	<i>Pdk1</i>	chr2:71873223-71903858	0.3	5.7	7.5	2.4×10^{-2}
Pac spc	ENSMUSG0000029177.5	<i>Cenpa</i>	chr5:30666776-30674827	1.2	11.7	7.4	4.8×10^{-2}
Pac spc	ENSMUSG0000035202.7	<i>Lars2</i>	chr9:123366939-123462664	2.7	22.9	7.3	4.3×10^{-3}
Pac spc	ENSMUSG0000002227.11	<i>Mov10</i>	chr3:104794835-104818563	1.4	13.3	7.2	4.3×10^{-3}
Pac spc	ENSMUSG0000042439.8	<i>Zfp532</i>	chr18:65580229-65689443	1.2	11.6	7.2	4.3×10^{-3}
Pac spc	ENSMUSG0000001082.8	<i>Mfsd10</i>	chr5:34633641-34637212	1.1	10.7	7.2	4.3×10^{-3}
Pac spc	ENSMUSG0000041417.11	<i>Pik3r1</i>	chr13:101680562-101768217	0.2	4.5	7.2	1.8×10^{-2}
Pac spc	ENSMUSG0000025272.12	<i>Tro</i>	chrX:150645303-150657583	0.5	6.5	7.2	4.3×10^{-3}
Pac spc	ENSMUSG0000004317.10	<i>Clcn5</i>	chrX:7153809-7319358	0.6	7.8	7.2	1.8×10^{-2}
Pac spc	ENSMUSG0000012123.11	<i>Aim1l</i>	chr4:134065911-134095082	1.5	13.5	7.2	2.7×10^{-2}
Pac spc	ENSMUSG0000024968.9	<i>Rcor2</i>	chr19:7267324-7275225	1.0	10.4	7.1	2.0×10^{-2}
Pac spc	ENSMUSG0000036564.12	<i>Ndrp4</i>	chr8:95676979-95715119	1.6	14.5	7.1	4.3×10^{-3}
Pac spc	ENSMUSG0000004328.11	<i>Hif3a</i>	chr7:17031506-17062427	0.1	3.6	7.1	3.0×10^{-2}
Pac spc	ENSMUSG0000016239.7	<i>Lonrf3</i>	chrX:36328352-36362341	2.1	18.2	7.1	4.3×10^{-3}
Pac spc	ENSMUSG0000002870.7	<i>Mcm2</i>	chr6:88883474-88898780	2.5	20.7	7.1	4.3×10^{-3}
Pac spc	ENSMUSG0000040749.7	<i>Siah1b</i>	chrX:164070704-164076493	1.5	13.6	7.1	4.9×10^{-2}
Pac spc	ENSMUSG0000026956.11	<i>Uap1l1</i>	chr2:25359888-25365682	0.4	6.1	7.1	2.3×10^{-2}
Pac spc	ENSMUSG0000025815.9	<i>Dhtkd1</i>	chr2:5895509-5942792	0.5	6.2	7.0	4.4×10^{-2}
Pac spc	ENSMUSG0000000787.8	<i>Ddx3x</i>	chrX:13280969-13294052	1.0	9.9	7.0	1.5×10^{-2}
Pac spc	ENSMUSG0000030091.13	<i>Nup210</i>	chr6:91013067-91116829	1.7	14.7	7.0	4.3×10^{-3}
Pac spc	ENSMUSG0000000325.11	<i>Arvcf</i>	chr16:18348181-18479073	1.1	10.8	7.0	4.3×10^{-3}
Pac spc	ENSMUSG0000073294.4	<i>AU022751</i>	chrX:6027055-6092269	0.3	5.3	7.0	3.7×10^{-2}
Pac spc	ENSMUSG0000031103.8	<i>Elf4</i>	chrX:48411045-48463132	0.3	5.3	7.0	1.6×10^{-2}
Pac spc	ENSMUSG0000024837.11	<i>Dmrt1</i>	chr19:25505617-25604329	3.8	29.4	7.0	4.3×10^{-3}
Pac spc	ENSMUSG0000000037.12	<i>Scml2</i>	chrX:161117192-161258213	3.2	24.6	6.8	7.0×10^{-3}

Pac spc	ENSMUSG00 000009670.7	<i>Tex11</i>	chrX:10083864 7-101059667	1.5	12.9	6.8	1.3×10^{-2}
Pac spc	ENSMUSG00 000056004.12	<i>9330182L 06Rik</i>	chr5:9266117- 9481825	0.1	3.8	6.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000034168.6	<i>Irf2bpl</i>	chr12:86880702 -86884814	0.6	6.6	6.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000000420.11	<i>Galnt1</i>	chr18:24205343 -24286818	1.9	15.5	6.7	4.3×10^{-3}
Pac spc	ENSMUSG00 000034673.10	<i>Pbx2</i>	chr17:34589805 -34597400	2.1	16.8	6.7	1.8×10^{-2}
Pac spc	ENSMUSG00 000034926.3	<i>Dhcr24</i>	chr4:106561037 -106589113	1.4	11.8	6.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000045374.14	<i>Wdr81</i>	chr11:75440943 -75454717	0.6	7.0	6.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000043993.6	<i>2900052L 18Rik</i>	chr11:12022980 1-120231585	0.3	5.0	6.6	3.9×10^{-2}
Pac spc	ENSMUSG00 000037138.12	<i>Aff3</i>	chr1:38177325- 38664955	0.4	5.8	6.6	3.2×10^{-2}
Pac spc	ENSMUSG00 000030123.11	<i>Plxnd1</i>	chr6:115954810 -115995005	0.8	8.4	6.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000038764.10	<i>Ptpn3</i>	chr4:57190840- 57307305	0.2	4.1	6.6	1.7×10^{-2}
Pac spc	ENSMUSG00 000006378.9	<i>Gcat</i>	chr15:79030873 -79043558	0.8	8.0	6.5	1.8×10^{-2}
Pac spc	ENSMUSG00 000039316.10	<i>Rftn1</i>	chr17:49992256 -50190674	0.8	8.2	6.5	4.9×10^{-2}
Pac spc	ENSMUSG00 000020387.11	<i>Jade2</i>	chr11:51813454 -51857653	0.6	6.4	6.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000051817.8	<i>Sox12</i>	chr2:152393610 -152398063	0.6	6.3	6.5	7.0×10^{-3}
Pac spc	ENSMUSG00 000069053.7	<i>Uba1y</i>	chrY:818648- 847750	2.0	15.3	6.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000030530.11	<i>Furin</i>	chr7:80388584- 80405436	1.0	9.3	6.4	9.2×10^{-3}
Pac spc	ENSMUSG00 000019822.8	<i>Smpd2</i>	chr10:41476313 -41490369	1.6	13.1	6.4	1.7×10^{-2}
Pac spc	ENSMUSG00 000026944.14	<i>Abca2</i>	chr2:25428702- 25448540	2.4	18.3	6.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000028980.10	<i>H6pd</i>	chr4:149979474 -150009023	0.2	3.7	6.4	3.1×10^{-2}
Pac spc	ENSMUSG00 000042506.11	<i>Usp22</i>	chr11:61151784 -61175055	1.9	15.0	6.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000039741.11	<i>Bahcc1</i>	chr11:12023294 6-120292296	1.1	9.4	6.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000015291.6	<i>Gdi1</i>	chrX:74304997- 74311862	0.7	7.3	6.3	1.7×10^{-2}
Pac spc	ENSMUSG00 000006369.10	<i>Fbln1</i>	chr15:85205948 -85286535	1.0	8.9	6.3	2.0×10^{-2}
Pac spc	ENSMUSG00 000046774.12	<i>8030474K 03Rik</i>	chrX:10179465 5-101798642	1.2	10.1	6.2	1.7×10^{-2}
Pac spc	ENSMUSG00 000025764.10	<i>Jade1</i>	chr3:41555730- 41616864	2.0	15.0	6.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000044349.11	<i>Snhg11</i>	chr2:158375637 -158386145	0.2	4.1	6.2	1.7×10^{-2}
Pac spc	ENSMUSG00 000074480.4	<i>Mex3a</i>	chr3:88532394- 88541396	0.5	5.7	6.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000034714.9	<i>Ttyh2</i>	chr11:11467543 0-114720977	0.7	7.0	6.2	9.2×10^{-3}

Pac spc	ENSMUSG00 000022216.12	<i>Psme1</i>	chr14:55578122 -55585302	1.8	13.7	6.2	4.0×10^{-2}
Pac spc	ENSMUSG00 000026074.10	<i>Map4k4</i>	chr1:39900912- 40026310	1.9	14.4	6.2	1.3×10^{-2}
Pac spc	ENSMUSG00 000021466.7	<i>Ptch1</i>	chr13:63508327 -63573598	0.2	3.6	6.1	2.3×10^{-2}
Pac spc	ENSMUSG00 000013033.12	<i>Lphn1</i>	chr8:83900104- 83955205	2.4	17.1	6.1	4.1×10^{-2}
Pac spc	ENSMUSG00 000032312.6	<i>Csk</i>	chr9:57626646- 57645653	0.7	7.0	6.1	1.6×10^{-2}
Pac spc	ENSMUSG00 000099502.1	<i>Gm28640</i>	chr2:74130180- 74130730	0.0	2.5	6.1	4.9×10^{-2}
Pac spc	ENSMUSG00 000025558.11	<i>Dock9</i>	chr14:12154203 8-121797734	1.1	9.5	6.1	4.3×10^{-3}
Pac spc	ENSMUSG00 000023262.8	<i>Acy1</i>	chr9:106432980 -106438319	0.4	5.0	6.0	3.0×10^{-2}
Pac spc	ENSMUSG00 000082670.1	<i>Gm14050</i>	chr2:122207919 -122208265	0.0	2.5	6.0	1.7×10^{-2}
Pac spc	ENSMUSG00 000055780.6	<i>Usp26</i>	chrX:51753958- 51801233	1.6	12.3	6.0	4.3×10^{-3}
Pac spc	ENSMUSG00 000034690.8	<i>Nlrp4c</i>	chr7:6045160- 6105149	0.8	7.3	6.0	1.3×10^{-2}
Pac spc	ENSMUSG00 000019087.9	<i>Atp6ap1</i>	chrX:74297096- 74304721	1.6	11.7	5.9	7.0×10^{-3}
Pac spc	ENSMUSG00 000047945.6	<i>Marcks1</i>	chr4:129513580 -129515985	7.6	47.5	5.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000020806.11	<i>Rhbd2</i>	chr11:11659816 4-116627019	0.7	6.6	5.9	1.8×10^{-2}
Pac spc	ENSMUSG00 000032812.12	<i>Arap1</i>	chr7:101348066 -101412586	0.5	5.1	5.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000020661.11	<i>Dnmt3a</i>	chr12:3806006- 3914443	1.6	11.6	5.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000046574.7	<i>Prr12</i>	chr7:45027706- 45052881	0.9	7.5	5.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000005533.9	<i>Igf1r</i>	chr7:67952858- 68226780	2.5	16.7	5.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000042410.11	<i>Agps</i>	chr2:75832176- 75931350	1.7	12.2	5.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000072944.7	<i>Nup62cl</i>	chrX:14000680 4-140062712	0.8	7.3	5.8	3.4×10^{-2}
Pac spc	ENSMUSG00 000004221.12	<i>Ikkg</i>	chrX:74393289- 74453854	0.2	3.7	5.8	7.0×10^{-3}
Pac spc	ENSMUSG00 000033792.8	<i>Atp7a</i>	chrX:10602727 5-106124926	0.4	4.5	5.8	3.1×10^{-2}
Pac spc	ENSMUSG00 000071773.4	<i>Rhox1</i>	chrX:37213803- 37222258	0.0	2.4	5.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000027359.12	<i>Slc27a2</i>	chr2:126521201 -126588243	0.3	4.0	5.7	2.5×10^{-2}
Pac spc	ENSMUSG00 000025503.4	<i>Taldo1</i>	chr7:141392198 -141402968	2.6	17.1	5.7	1.6×10^{-2}
Pac spc	ENSMUSG00 000019055.11	<i>Plod1</i>	chr4:147909752 -147936767	1.8	12.4	5.7	4.3×10^{-3}
Pac spc	ENSMUSG00 000029223.9	<i>Uchl1</i>	chr5:66626494- 66687231	16.5	96.1	5.7	4.3×10^{-3}
Pac spc	ENSMUSG00 000028782.10	<i>Bai2</i>	chr4:129984869 -130022633	0.4	4.8	5.7	4.3×10^{-3}
Pac spc	ENSMUSG00 000055612.11	<i>Cdca7</i>	chr2:72476158- 72486893	1.8	12.7	5.7	7.0×10^{-3}

Pac spc	ENSMUSG00 000050966.5	<i>Lin28a</i>	chr4:134003329 -134019869	0.9	7.6	5.6	1.6×10^{-2}
Pac spc	ENSMUSG00 000031157.6	<i>Pqbp1</i>	chrX:7894518- 7899269	0.4	4.7	5.6	2.2×10^{-2}
Pac spc	ENSMUSG00 000079487.7	<i>Med12</i>	chrX:10127402 9-101325963	3.0	18.9	5.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000028434.8	<i>Epb4.1l4b</i>	chr4:56991971- 57143437	0.8	6.8	5.6	2.1×10^{-2}
Pac spc	ENSMUSG00 000037344.9	<i>Slc12a9</i>	chr5:137314557 -137333597	1.2	8.8	5.6	1.3×10^{-2}
Pac spc	ENSMUSG00 000028078.10	<i>Dclk2</i>	chr3:86786150- 86920852	0.3	4.1	5.6	1.7×10^{-2}
Pac spc	ENSMUSG00 000016534.11	<i>Lamp2</i>	chrX:38401356- 38456454	2.2	14.3	5.6	4.2×10^{-2}
Pac spc	ENSMUSG00 000057897.10	<i>Camk2b</i>	chr11:5969643- 6066362	0.3	4.0	5.5	2.1×10^{-2}
Pac spc	ENSMUSG00 000002028.8	<i>Kmt2a</i>	chr9:44803354- 44881296	1.2	9.0	5.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000020097.10	<i>Sgpl1</i>	chr10:61098641 -61147703	2.4	15.4	5.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000037824.5	<i>Tspan14</i>	chr14:40906444 -40966807	1.0	7.6	5.5	1.3×10^{-2}
Pac spc	ENSMUSG00 000030084.7	<i>Plxna1</i>	chr6:89304629- 89362613	3.2	20.0	5.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000039262.12	<i>Prrc2b</i>	chr2:32151081- 32236382	1.8	12.0	5.5	1.7×10^{-2}
Pac spc	ENSMUSG00 000066687.4	<i>Zbtb16</i>	chr9:48654310- 48835945	0.9	7.0	5.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000029804.12	<i>Herc3</i>	chr6:58831464- 58920398	0.8	6.5	5.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000020653.7	<i>Klf11</i>	chr12:24651370 -24662774	1.2	8.7	5.5	1.4×10^{-2}
Pac spc	ENSMUSG00 000005413.7	<i>Hmox1</i>	chr8:75093590- 75100596	0.6	5.3	5.4	4.2×10^{-2}
Pac spc	ENSMUSG00 000028032.9	<i>Papss1</i>	chr3:131564767 -131643670	0.8	6.5	5.4	1.3×10^{-2}
Pac spc	ENSMUSG00 000041936.14	<i>Agrn</i>	chr4:156165289 -156197488	0.9	7.2	5.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000045237.5	<i>1110012L 19Rik</i>	chrX:70385876- 70389417	0.0	2.2	5.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000031167.12	<i>Rbm3</i>	chrX:8138974- 8147964	2.4	15.1	5.4	3.3×10^{-2}
Pac spc	ENSMUSG00 000044150.8	<i>A830080D 01Rik</i>	chrX:15952668 7-159593081	1.2	8.4	5.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000017561.12	<i>Crlf3</i>	chr11:80046492 -80080991	1.2	8.5	5.4	3.2×10^{-2}
Pac spc	ENSMUSG00 000045294.10	<i>Insig1</i>	chr5:28071362- 28078662	3.1	19.0	5.4	7.0×10^{-3}
Pac spc	ENSMUSG00 000001506.10	<i>Col1a1</i>	chr11:94936223 -94953042	0.1	3.0	5.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000045659.13	<i>Plekha7</i>	chr7:116123492 -116308376	0.6	5.2	5.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000007379.11	<i>Dennd2c</i>	chr3:103102603 -103169769	0.8	6.5	5.4	3.8×10^{-2}
Pac spc	ENSMUSG00 000033434.11	<i>Gtpbp6</i>	chr5:110099968 -110108197	3.5	20.7	5.4	3.8×10^{-2}
Pac spc	ENSMUSG00 000021996.12	<i>Esd</i>	chr14:74732296 -74750765	4.1	24.0	5.3	3.2×10^{-2}

Pac spc	ENSMUSG0000057541.10	<i>Pus7</i>	chr5:23740647-23783711	1.3	9.2	5.3	2.1×10^{-2}
Pac spc	ENSMUSG0000013089.11	<i>Etv5</i>	chr16:22381308-22439719	0.4	4.3	5.3	1.9×10^{-2}
Pac spc	ENSMUSG0000008489.14	<i>Elavl2</i>	chr4:91250762-91400785	1.2	8.5	5.3	2.5×10^{-2}
Pac spc	ENSMUSG0000022178.10	<i>Ajuba</i>	chr14:54567468-54577661	0.6	5.4	5.3	7.0×10^{-3}
Pac spc	ENSMUSG0000038437.7	<i>Mllt6</i>	chr11:97663216-97685463	1.3	8.7	5.3	4.3×10^{-3}
Pac spc	ENSMUSG0000000838.13	<i>Fmr1</i>	chrX:68678484-68717963	3.1	18.2	5.3	4.3×10^{-3}
Pac spc	ENSMUSG0000028654.9	<i>Mycl</i>	chr4:122995651-123002485	0.1	2.7	5.3	1.9×10^{-2}
Pac spc	ENSMUSG0000034771.11	<i>Tle2</i>	chr10:81572611-81590845	0.2	2.9	5.2	4.3×10^{-3}
Pac spc	ENSMUSG0000025795.7	<i>Rassf3</i>	chr10:121410349-121476250	0.2	3.2	5.2	4.1×10^{-2}
Pac spc	ENSMUSG0000028405.9	<i>Aco1</i>	chr4:40143080-40198338	0.6	5.3	5.2	1.7×10^{-2}
Pac spc	ENSMUSG0000048240.10	<i>Gng7</i>	chr10:80948623-81014945	0.1	2.8	5.2	3.5×10^{-2}
Pac spc	ENSMUSG0000052373.10	<i>Mpp3</i>	chr11:101999651-102028461	0.2	3.2	5.2	4.0×10^{-2}
Pac spc	ENSMUSG0000018899.12	<i>Irf1</i>	chr11:53770013-53778374	0.4	4.1	5.2	1.1×10^{-2}
Pac spc	ENSMUSG0000097119.1	<i>B230354K17Rik</i>	chr17:45433851-45442544	1.5	9.6	5.2	4.3×10^{-3}
Pac spc	ENSMUSG0000034160.9	<i>Ogt</i>	chrX:101640059-101684351	1.7	10.9	5.1	1.6×10^{-2}
Pac spc	ENSMUSG0000037315.10	<i>Jade3</i>	chrX:20425687-20519939	1.2	8.5	5.1	4.0×10^{-2}
Pac spc	ENSMUSG0000036591.11	<i>Arhgap21</i>	chr2:20847918-20968881	1.4	9.4	5.1	1.8×10^{-2}
Pac spc	ENSMUSG0000002059.13	<i>Rab34</i>	chr11:78188429-78192193	0.7	5.8	5.1	2.8×10^{-2}
Pac spc	ENSMUSG0000017009.3	<i>Sdc4</i>	chr2:164424246-164443887	1.4	9.0	5.1	1.9×10^{-2}
Pac spc	ENSMUSG0000029822.11	<i>Osbpl3</i>	chr6:50293329-50456201	0.1	2.7	5.1	1.1×10^{-2}
Pac spc	ENSMUSG0000045411.12	<i>2410002F23Rik</i>	chr7:44246721-44262720	4.7	25.7	5.1	1.8×10^{-2}
Pac spc	ENSMUSG0000102859.1	<i>RP23-20B1.1</i>	chr3:73933045-73934122	0.0	2.0	5.1	4.3×10^{-3}
Pac spc	ENSMUSG0000003070.6	<i>Efna2</i>	chr10:80179481-80190010	0.3	3.3	5.0	4.0×10^{-2}
Pac spc	ENSMUSG0000038072.10	<i>Galnt11</i>	chr5:25222847-25265918	0.9	6.8	5.0	2.2×10^{-2}
Pac spc	ENSMUSG0000022390.10	<i>Zc3h7b</i>	chr15:81744847-81796269	1.6	10.1	5.0	4.3×10^{-3}
Pac spc	ENSMUSG0000031012.13	<i>Cask</i>	chrX:13517079-13851367	0.4	4.0	5.0	2.9×10^{-2}
Pac spc	ENSMUSG0000037706.12	<i>Cd81</i>	chr7:143021783-143067934	2.1	12.3	4.9	3.9×10^{-2}
Pac spc	ENSMUSG0000040732.14	<i>Erg</i>	chr16:95359168-95586593	0.2	3.1	4.9	1.5×10^{-2}
Pac spc	ENSMUSG0000060216.11	<i>Arrb2</i>	chr11:70432634-70440828	0.9	6.5	4.9	4.9×10^{-2}

Pac spc	ENSMUSG00 000031150.8	<i>Ccdc120</i>	chrX:7731713- 7750905	0.1	2.4	4.9	1.1×10^{-2}
Pac spc	ENSMUSG00 000038677.9	<i>Scube3</i>	chr17:28142315 -28174852	0.7	5.2	4.9	1.8×10^{-2}
Pac spc	ENSMUSG00 000020923.13	<i>Ubt1</i>	chr11:10230455 9-102319742	2.7	15.0	4.9	1.3×10^{-2}
Pac spc	ENSMUSG00 000024640.5	<i>Psat1</i>	chr19:15904677 -15947337	2.6	14.7	4.9	1.9×10^{-2}
Pac spc	ENSMUSG00 000103643.1	<i>RP24- 271K21.1</i>	chr3:32260332- 32261104	0.0	1.9	4.9	4.9×10^{-2}
Pac spc	ENSMUSG00 000021318.11	<i>Gli3</i>	chr13:15440301 -15730026	1.1	7.2	4.8	3.9×10^{-2}
Pac spc	ENSMUSG00 000031558.11	<i>Slit2</i>	chr5:47983154- 48306282	0.7	5.2	4.8	4.9×10^{-2}
Pac spc	ENSMUSG00 000079584.2	<i>Gm364</i>	chrX:57409153- 57488767	4.3	22.3	4.8	1.7×10^{-2}
Pac spc	ENSMUSG00 000005125.8	<i>Ndr1</i>	chr15:66929320 -67013039	0.3	3.2	4.8	1.4×10^{-2}
Pac spc	ENSMUSG00 000042515.9	<i>Mum1l1</i>	chrX:13921004 1-139238335	0.8	5.7	4.7	1.3×10^{-2}
Pac spc	ENSMUSG00 000067873.7	<i>Htatsf1</i>	chrX:57053582- 57067183	0.8	5.6	4.7	1.4×10^{-2}
Pac spc	ENSMUSG00 000090673.1	<i>Gm340</i>	chr19:41582369 -41586536	0.9	6.3	4.7	2.9×10^{-2}
Pac spc	ENSMUSG00 000037712.11	<i>Fermt2</i>	chr14:45458791 -45530118	0.8	5.8	4.7	2.6×10^{-2}
Pac spc	ENSMUSG00 000008435.11	<i>Rdh13</i>	chr7:4424769- 4445649	0.3	3.2	4.7	1.7×10^{-2}
Pac spc	ENSMUSG00 000031397.7	<i>Tkt1</i>	chrX:74177258- 74208500	1.6	9.5	4.7	3.1×10^{-2}
Pac spc	ENSMUSG00 000061731.5	<i>Ext1</i>	chr15:53064037 -53346159	0.5	4.1	4.7	2.4×10^{-2}
Pac spc	ENSMUSG00 000017724.10	<i>Etv4</i>	chr11:10176974 1-101785371	0.3	3.3	4.7	2.9×10^{-2}
Pac spc	ENSMUSG00 000024070.11	<i>Prkd3</i>	chr17:78949404 -79020816	2.7	14.6	4.7	1.4×10^{-2}
Pac spc	ENSMUSG00 000031314.13	<i>Taf1</i>	chrX:10153273 3-101601789	2.1	11.7	4.7	4.1×10^{-2}
Pac spc	ENSMUSG00 000031214.9	<i>Ophn1</i>	chrX:98554276- 98891025	1.0	6.5	4.7	1.7×10^{-2}
Pac spc	ENSMUSG00 000032511.13	<i>Scn5a</i>	chr9:119483407 -119579016	0.3	3.4	4.7	4.3×10^{-3}
Pac spc	ENSMUSG00 000025246.9	<i>Tbl1x</i>	chrX:77511012- 77662983	0.7	4.9	4.7	1.9×10^{-2}
Pac spc	ENSMUSG00 000067768.8	<i>Xlr4b</i>	chrX:73107634- 73292976	0.0	2.0	4.6	3.8×10^{-2}
Pac spc	ENSMUSG00 000022429.10	<i>Dmc1</i>	chr15:79561499 -79605084	1.6	9.2	4.6	2.6×10^{-2}
Pac spc	ENSMUSG00 000002900.11	<i>Lamb1</i>	chr12:31265233 -31329644	0.5	4.2	4.6	1.6×10^{-2}
Pac spc	ENSMUSG00 000032936.9	<i>Camkv</i>	chr9:107935076 -107949691	0.4	3.7	4.6	2.6×10^{-2}
Pac spc	ENSMUSG00 000029366.9	<i>Dck</i>	chr5:88764995- 88783281	0.8	5.3	4.6	1.3×10^{-2}
Pac spc	ENSMUSG00 000026860.12	<i>Sh3glb2</i>	chr2:30344808- 30359337	2.4	13.0	4.6	3.0×10^{-2}
Pac spc	ENSMUSG00 000029998.10	<i>Pcyox1</i>	chr6:86386005- 86397150	0.3	3.3	4.6	2.5×10^{-2}

Pac spc	ENSMUSG00 000013936.8	<i>Myl2</i>	chr5:122100950 -122138957	0.0	1.8	4.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000009941.6	<i>Nxf2</i>	chrX:13494452 5-134964754	2.0	10.9	4.6	2.9×10^{-2}
Pac spc	ENSMUSG00 000028080.11	<i>Lrba</i>	chr3:86224679- 86782692	3.0	15.5	4.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000036989.11	<i>Trim3</i>	chr7:105604462 -105633571	1.0	6.1	4.5	4.0×10^{-2}
Pac spc	ENSMUSG00 000027395.11	<i>Polr1b</i>	chr2:129100994 -129126594	3.4	17.1	4.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000026643.12	<i>Nmt2</i>	chr2:3284211- 3328877	6.5	31.2	4.5	7.0×10^{-3}
Pac spc	ENSMUSG00 000024811.7	<i>Tnks2</i>	chr19:36834231 -36893477	5.6	26.9	4.5	4.3×10^{-3}
Pac spc	ENSMUSG00 000020432.8	<i>Tcn2</i>	chr11:3917191- 3932159	0.3	3.0	4.5	3.8×10^{-2}
Pac spc	ENSMUSG00 000063239.12	<i>Grm4</i>	chr17:27422386 -27513341	0.1	2.1	4.5	3.6×10^{-2}
Pac spc	ENSMUSG00 000089989.5	<i>Flt3l</i>	chr7:45125557- 45136432	0.3	3.0	4.5	4.8×10^{-2}
Pac spc	ENSMUSG00 000026192.9	<i>Atic</i>	chr1:71557149- 71579631	2.2	11.6	4.5	9.2×10^{-3}
Pac spc	ENSMUSG00 000037553.10	<i>Zdhc18</i>	chr4:133605298 -133650154	0.7	4.8	4.5	3.9×10^{-2}
Pac spc	ENSMUSG00 000042644.8	<i>Itpr3</i>	chr17:27057303 -27122223	0.7	4.9	4.5	1.1×10^{-2}
Pac spc	ENSMUSG00 000020715.5	<i>Ern1</i>	chr11:10639464 9-106487852	2.1	11.1	4.5	1.1×10^{-2}
Pac spc	ENSMUSG00 000021069.12	<i>Pygl</i>	chr12:70190810 -70234165	0.5	3.8	4.4	4.5×10^{-2}
Pac spc	ENSMUSG00 000047098.13	<i>Rnf31</i>	chr14:55591707 -55610030	2.2	11.5	4.4	2.7×10^{-2}
Pac spc	ENSMUSG00 000030110.9	<i>Ret</i>	chr6:118151747 -118197744	0.1	2.1	4.4	2.8×10^{-2}
Pac spc	ENSMUSG00 000045071.9	<i>E130308A 19Rik</i>	chr4:59626210- 59761439	0.7	4.6	4.4	3.2×10^{-2}
Pac spc	ENSMUSG00 000016757.6	<i>Ttl12</i>	chr15:83575118 -83595157	1.4	8.1	4.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000021109.9	<i>Hif1a</i>	chr12:73901374 -73949785	2.3	11.9	4.4	4.3×10^{-2}
Pac spc	ENSMUSG00 000034311.3	<i>Kif4</i>	chrX:10062288 2-100727214	0.6	4.5	4.4	1.7×10^{-2}
Pac spc	ENSMUSG00 000002058.9	<i>Unc119</i>	chr11:78343481 -78349164	1.6	9.0	4.4	1.5×10^{-2}
Pac spc	ENSMUSG00 000103155.1	<i>RP23- 234G15.1</i>	chr3:54021163- 54021909	0.0	1.7	4.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000062949.9	<i>Atp11c</i>	chrX:60223289- 60807993	1.4	7.6	4.4	1.9×10^{-2}
Pac spc	ENSMUSG00 000049672.10	<i>Zbtb14</i>	chr17:69383049 -69390750	0.3	2.9	4.4	4.6×10^{-2}
Pac spc	ENSMUSG00 000028527.14	<i>Ak4</i>	chr4:101419276 -101466995	1.6	8.9	4.4	9.2×10^{-3}
Pac spc	ENSMUSG00 000015243.4	<i>Abca1</i>	chr4:53030786- 53159895	0.6	4.5	4.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000025105.8	<i>Bnc1</i>	chr7:81966671- 81992618	0.6	4.2	4.4	2.8×10^{-2}
Pac spc	ENSMUSG00 000033295.9	<i>Ptprf</i>	chr4:118208212 -118291405	6.7	31.0	4.4	4.3×10^{-3}

Pac spc	ENSMUSG0000040363.10	<i>Bcor</i>	chrX:12036739-12160355	0.2	2.4	4.4	3.7×10^{-2}
Pac spc	ENSMUSG0000026193.11	<i>Fn1</i>	chr1:71585519-71662843	3.5	16.9	4.3	9.2×10^{-3}
Pac spc	ENSMUSG0000040856.13	<i>Dlk1</i>	chr12:109452822-109463336	0.3	3.2	4.3	3.3×10^{-2}
Pac spc	ENSMUSG0000025854.11	<i>Fam20c</i>	chr5:138754513-138810077	0.0	1.9	4.3	4.6×10^{-2}
Pac spc	ENSMUSG0000024909.10	<i>Efemp2</i>	chr19:5473972-5481853	2.1	10.7	4.3	2.9×10^{-2}
Pac spc	ENSMUSG0000050947.8	<i>Amigo1</i>	chr3:108186334-108192286	0.6	4.3	4.3	1.4×10^{-2}
Pac spc	ENSMUSG0000029096.11	<i>Htra3</i>	chr5:35652040-35679782	0.1	2.0	4.3	1.8×10^{-2}
Pac spc	ENSMUSG0000057530.10	<i>Ece1</i>	chr4:137862236-137965229	0.9	5.5	4.3	4.6×10^{-2}
Pac spc	ENSMUSG0000033170.10	<i>Card10</i>	chr15:78775137-78803042	0.3	3.0	4.3	2.0×10^{-2}
Pac spc	ENSMUSG0000069044.6	<i>Usp9y</i>	chrY:1298960-1459782	0.7	4.5	4.3	4.0×10^{-2}
Pac spc	ENSMUSG0000026641.9	<i>Usf1</i>	chr1:171411312-171420352	1.8	9.1	4.3	4.9×10^{-2}
Pac spc	ENSMUSG0000032366.11	<i>Tpm1</i>	chr9:67022589-67049406	0.7	4.4	4.2	4.3×10^{-3}
Pac spc	ENSMUSG0000022175.8	<i>Lrp10</i>	chr14:54464163-54471497	0.5	3.7	4.2	2.3×10^{-2}
Pac spc	ENSMUSG0000037552.13	<i>Plekhg2</i>	chr7:28359603-28372599	4.5	20.4	4.2	1.1×10^{-2}
Pac spc	ENSMUSG0000020167.10	<i>Tcf3</i>	chr10:80409513-80433647	4.5	20.3	4.2	1.1×10^{-2}
Pac spc	ENSMUSG0000030872.10	<i>Gga2</i>	chr7:121986721-122021222	1.9	9.7	4.2	2.9×10^{-2}
Pac spc	ENSMUSG0000038576.11	<i>Susd4</i>	chr1:182763859-182896591	0.1	2.1	4.2	3.7×10^{-2}
Pac spc	ENSMUSG0000055067.11	<i>Smyd3</i>	chr1:178951959-179518041	5.0	22.4	4.2	3.1×10^{-2}
Pac spc	ENSMUSG0000059895.8	<i>Ptp4a3</i>	chr15:73723144-73758766	2.0	10.0	4.2	1.5×10^{-2}
Pac spc	ENSMUSG0000008682.9	<i>Rpl10</i>	chrX:74270811-74273135	4.7	21.1	4.1	2.6×10^{-2}
Pac spc	ENSMUSG0000039713.12	<i>Plekhg5</i>	chr4:152072497-152115400	0.7	4.6	4.1	2.0×10^{-2}
Pac spc	ENSMUSG0000032311.13	<i>Nrg4</i>	chr9:55208924-55326844	0.3	2.6	4.1	1.3×10^{-2}
Pac spc	ENSMUSG0000053436.10	<i>Mapk14</i>	chr17:28691341-28748404	3.1	14.3	4.1	2.5×10^{-2}
Pac spc	ENSMUSG0000031523.12	<i>Dlc1</i>	chr8:36567750-36953143	0.3	2.9	4.1	4.3×10^{-3}
Pac spc	ENSMUSG0000035284.9	<i>Vps13c</i>	chr9:67840395-67995634	2.3	10.9	4.0	4.3×10^{-3}
Pac spc	ENSMUSG0000063382.5	<i>Bcl9l</i>	chr9:44499135-44510388	0.9	5.0	4.0	1.4×10^{-2}
Pac spc	ENSMUSG0000034708.7	<i>Grn</i>	chr11:102430314-102447682	1.3	6.6	4.0	4.0×10^{-2}
Pac spc	ENSMUSG0000035621.9	<i>Midn</i>	chr10:80148271-80158368	2.6	11.8	4.0	9.2×10^{-3}
Pac spc	ENSMUSG0000056153.10	<i>Socs6</i>	chr18:88665223-88927481	1.5	7.6	4.0	2.1×10^{-2}

Pac spc	ENSMUSG00 000059991.6	<i>Nptx2</i>	chr5:144545886 -144557478	1.7	8.5	4.0	1.1×10^{-2}
Pac spc	ENSMUSG00 000025269.12	<i>Apex2</i>	chrX:15051951 8-150643878	0.3	2.8	4.0	1.9×10^{-2}
Pac spc	ENSMUSG00 000013629.12	<i>Cad</i>	chr5:31054779- 31078479	10.2	42.1	4.0	3.1×10^{-2}
Pac spc	ENSMUSG00 000025019.11	<i>Lcor</i>	chr19:41482644 -41562246	1.3	6.8	4.0	2.5×10^{-2}
Pac spc	ENSMUSG00 000028633.7	<i>Ctps</i>	chr4:120539867 -120570276	3.3	14.8	4.0	2.2×10^{-2}
Pac spc	ENSMUSG00 000070462.4	<i>Mesdc1</i>	chr7:83879872- 83884305	0.1	2.1	4.0	3.9×10^{-2}
Pac spc	ENSMUSG00 000003545.2	<i>Fosb</i>	chr7:19302720- 19310045	0.6	3.9	4.0	3.2×10^{-2}
Pac spc	ENSMUSG00 000032280.12	<i>Tle3</i>	chr9:61372365- 61418497	8.4	34.8	4.0	1.3×10^{-2}
Pac spc	ENSMUSG00 000025612.5	<i>Bach1</i>	chr16:87698944 -87733346	0.5	3.7	4.0	2.7×10^{-2}
Pac spc	ENSMUSG00 000042035.7	<i>Igsf3</i>	chr3:101377124 -101463059	1.6	7.9	4.0	7.0×10^{-3}
Pac spc	ENSMUSG00 000059316.2	<i>Slc27a4</i>	chr2:29802633- 29817522	1.6	7.9	3.9	1.5×10^{-2}
Pac spc	ENSMUSG00 000031386.10	<i>Hcfc1</i>	chrX:73942791- 73966357	2.4	11.0	3.9	1.8×10^{-2}
Pac spc	ENSMUSG00 000001034.13	<i>Mapk7</i>	chr11:61485430 -61494406	7.0	29.1	3.9	7.0×10^{-3}
Pac spc	ENSMUSG00 000027087.7	<i>Itgav</i>	chr2:83724396- 83806916	0.2	2.3	3.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000029767.12	<i>Calu</i>	chr6:29348068- 29388468	4.8	20.4	3.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000041329.9	<i>Atp1b2</i>	chr11:69599735 -69605942	1.0	5.6	3.9	3.0×10^{-2}
Pac spc	ENSMUSG00 000034472.9	<i>Rasd2</i>	chr8:75213943- 75224113	1.8	8.4	3.9	2.7×10^{-2}
Pac spc	ENSMUSG00 000051592.10	<i>Ccnb3</i>	chrX:6979651- 7041619	0.8	4.4	3.9	3.5×10^{-2}
Pac spc	ENSMUSG00 000018651.10	<i>Tada2a</i>	chr11:84078919 -84129600	1.8	8.5	3.9	3.0×10^{-2}
Pac spc	ENSMUSG00 000060671.8	<i>Atp8b2</i>	chr3:89939480- 89963508	3.9	16.5	3.9	1.7×10^{-2}
Pac spc	ENSMUSG00 000028444.13	<i>Cntfr</i>	chr4:41657497- 41697089	0.8	4.4	3.9	2.9×10^{-2}
Pac spc	ENSMUSG00 000042686.5	<i>Jph1</i>	chr1:16898184- 17097889	0.4	3.0	3.9	3.0×10^{-2}
Pac spc	ENSMUSG00 000041263.10	<i>Rusc1</i>	chr3:89083980- 89093363	0.1	1.9	3.9	3.3×10^{-2}
Pac spc	ENSMUSG00 000048752.3	<i>Prss50</i>	chr9:110857966 -110864628	6.6	27.1	3.9	1.1×10^{-2}
Pac spc	ENSMUSG00 000025809.11	<i>Itgb1</i>	chr8:128685653 -128733200	4.5	18.8	3.8	1.6×10^{-2}
Pac spc	ENSMUSG00 000026837.11	<i>Col5a1</i>	chr2:27882924- 28039514	0.9	4.8	3.8	4.3×10^{-3}
Pac spc	ENSMUSG00 000020821.13	<i>Kif1c</i>	chr11:70700547 -70731964	2.2	9.7	3.8	1.6×10^{-2}
Pac spc	ENSMUSG00 000019943.9	<i>Atp2b1</i>	chr10:98915151 -99026143	0.9	4.7	3.8	1.4×10^{-2}
Pac spc	ENSMUSG00 000015501.6	<i>Hivep2</i>	chr10:13966074 -14154446	0.2	2.2	3.8	4.3×10^{-3}

Pac spc	ENSMUSG0000029676.11	<i>Pot1a</i>	chr6:25743736-25809246	2.2	9.7	3.8	4.8×10^{-2}
Pac spc	ENSMUSG0000030201.11	<i>Lrp6</i>	chr6:134446475-134566965	2.1	9.3	3.8	4.3×10^{-3}
Pac spc	ENSMUSG0000032228.12	<i>Tcf12</i>	chr9:71842687-72111871	9.5	36.8	3.8	1.8×10^{-2}
Pac spc	ENSMUSG0000015944.8	<i>Gatsl2</i>	chr5:134099710-134144343	0.5	3.4	3.8	3.5×10^{-2}
Pac spc	ENSMUSG0000048277.11	<i>Syngn2</i>	chr11:117809667-117839908	3.3	13.8	3.7	3.8×10^{-2}
Pac spc	ENSMUSG0000045348.11	<i>Nyap1</i>	chr5:137730882-137741607	0.2	2.1	3.7	3.7×10^{-2}
Pac spc	ENSMUSG0000029207.12	<i>Apbb2</i>	chr5:66298860-66618828	1.1	5.6	3.7	3.3×10^{-2}
Pac spc	ENSMUSG0000025323.9	<i>Sp4</i>	chr12:118234932-118301440	1.2	5.8	3.7	1.7×10^{-2}
Pac spc	ENSMUSG0000027794.4	<i>Sohlh2</i>	chr3:55182027-55209957	4.1	16.6	3.7	4.8×10^{-2}
Pac spc	ENSMUSG0000038212.11	<i>Hiatl1</i>	chr13:65064662-65112982	3.2	13.2	3.7	3.1×10^{-2}
Pac spc	ENSMUSG0000028906.11	<i>Epb4.1</i>	chr4:131923412-132076992	0.9	4.9	3.7	2.9×10^{-2}
Pac spc	ENSMUSG0000052911.5	<i>Lamb2</i>	chr9:108479735-108490530	2.0	8.7	3.7	4.4×10^{-2}
Pac spc	ENSMUSG0000048170.10	<i>Mcmdbp</i>	chr7:128696440-128740495	3.9	15.7	3.7	1.3×10^{-2}
Pac spc	ENSMUSG0000060685.4	<i>Gm14511</i>	chrX:8975709-8976559	0.0	1.3	3.7	4.3×10^{-3}
Pac spc	ENSMUSG0000042364.10	<i>Snx18</i>	chr13:113592179-113618564	1.3	6.0	3.7	1.6×10^{-2}
Pac spc	ENSMUSG0000022436.11	<i>Sh3bp1</i>	chr15:78899666-78919517	1.0	5.1	3.7	1.7×10^{-2}
Pac spc	ENSMUSG0000027353.10	<i>Mcm8</i>	chr2:132816140-132844197	2.6	10.8	3.7	4.2×10^{-2}
Pac spc	ENSMUSG0000032875.7	<i>Arhgef17</i>	chr7:100869745-100932161	0.3	2.5	3.6	1.8×10^{-2}
Pac spc	ENSMUSG0000041415.9	<i>Dicer1</i>	chr12:104687741-104751952	3.0	12.1	3.6	4.3×10^{-3}
Pac spc	ENSMUSG0000003500.9	<i>Impdh1</i>	chr6:29200433-29216364	1.7	7.5	3.6	4.0×10^{-2}
Pac spc	ENSMUSG0000034413.10	<i>Neurl1b</i>	chr17:26414828-26446349	0.1	1.8	3.6	4.0×10^{-2}
Pac spc	ENSMUSG0000037606.13	<i>Osbpl5</i>	chr7:143688761-143756985	0.1	1.6	3.6	3.9×10^{-2}
Pac spc	ENSMUSG0000024130.11	<i>Abca3</i>	chr17:24351949-24414542	1.0	4.8	3.6	4.0×10^{-2}
Pac spc	ENSMUSG0000095078.1	<i>Gm5866</i>	chr5:52582319-52583227	0.0	1.3	3.6	4.9×10^{-2}
Pac spc	ENSMUSG0000071553.6	<i>Cpa2</i>	chr6:30541581-30564476	0.5	3.0	3.6	4.5×10^{-2}
Pac spc	ENSMUSG0000027333.14	<i>Smox</i>	chr2:131491495-131525922	0.5	3.2	3.5	2.9×10^{-2}
Pac spc	ENSMUSG0000018547.8	<i>Pip4k2b</i>	chr11:97715156-97744704	0.6	3.5	3.5	4.0×10^{-2}
Pac spc	ENSMUSG0000032485.10	<i>Scap</i>	chr9:110333292-110384935	3.9	15.2	3.5	4.3×10^{-3}
Pac spc	ENSMUSG0000031295.9	<i>Phka2</i>	chrX:160502165-160598878	3.2	12.7	3.5	4.3×10^{-2}

Pac spc	ENSMUSG0000039967.10	<i>Zfp292</i>	chr4:34803112-34882960	2.2	8.9	3.5	7.0×10^{-3}
Pac spc	ENSMUSG0000025586.12	<i>Cpeb1</i>	chr7:81347025-81455465	5.6	21.2	3.5	1.4×10^{-2}
Pac spc	ENSMUSG0000031310.12	<i>Zmym3</i>	chrX:101404383-101420849	3.2	12.5	3.5	1.4×10^{-2}
Pac spc	ENSMUSG0000045817.8	<i>Zfp36l2</i>	chr17:84183930-84187947	2.3	9.5	3.5	1.1×10^{-2}
Pac spc	ENSMUSG0000033763.10	<i>Mtss1l</i>	chr8:110721475-110741400	1.1	5.3	3.5	4.5×10^{-2}
Pac spc	ENSMUSG0000003410.7	<i>Elavl3</i>	chr9:22015004-22052023	0.3	2.3	3.5	1.5×10^{-2}
Pac spc	ENSMUSG0000001924.11	<i>Uba1</i>	chrX:20658325-20683179	8.6	31.3	3.5	7.0×10^{-3}
Pac spc	ENSMUSG0000050846.8	<i>Zfp623</i>	chr15:75940951-75949377	0.6	3.2	3.5	3.8×10^{-2}
Pac spc	ENSMUSG0000031987.5	<i>Egln1</i>	chr8:124908595-124949254	0.5	2.8	3.5	3.1×10^{-2}
Pac spc	ENSMUSG0000009596.5	<i>Taf7l</i>	chrX:134460117-134476490	8.1	29.5	3.5	4.3×10^{-3}
Pac spc	ENSMUSG0000029478.12	<i>Ncor2</i>	chr5:125017152-125179219	4.5	16.8	3.5	4.3×10^{-3}
Pac spc	ENSMUSG0000054520.11	<i>Sh3bp2</i>	chr5:34525837-34563638	0.4	2.8	3.5	4.0×10^{-2}
Pac spc	ENSMUSG0000022350.6	<i>E430025E21Rik</i>	chr15:59331997-59374167	2.0	8.1	3.5	4.0×10^{-2}
Pac spc	ENSMUSG0000030757.9	<i>Zkscan2</i>	chr7:123479515-123500449	3.4	13.0	3.5	3.1×10^{-2}
Pac spc	ENSMUSG0000063410.7	<i>Stk24</i>	chr14:121286342-121379334	0.6	3.2	3.5	4.8×10^{-2}
Pac spc	ENSMUSG0000024074.7	<i>Crim1</i>	chr17:78200247-78376592	0.5	2.9	3.5	2.6×10^{-2}
Pac spc	ENSMUSG0000051586.10	<i>Mical3</i>	chr6:120931706-121003153	1.6	6.6	3.5	3.6×10^{-2}
Pac spc	ENSMUSG0000022443.12	<i>Myh9</i>	chr15:77760586-77842175	1.1	5.2	3.4	3.1×10^{-2}
Pac spc	ENSMUSG0000026979.12	<i>Psd4</i>	chr2:24367579-24414954	0.1	1.4	3.4	9.2×10^{-3}
Pac spc	ENSMUSG0000044167.6	<i>Foxo1</i>	chr3:52268335-52353221	1.5	6.3	3.4	4.3×10^{-3}
Pac spc	ENSMUSG0000023927.11	<i>Satb1</i>	chr17:51736186-51834723	0.2	1.9	3.4	2.3×10^{-2}
Pac spc	ENSMUSG0000062542.7	<i>Syt9</i>	chr7:107370727-107548656	1.0	4.8	3.4	3.5×10^{-2}
Pac spc	ENSMUSG0000020422.9	<i>Tns3</i>	chr11:8431651-8664535	0.3	2.3	3.4	1.4×10^{-2}
Pac spc	ENSMUSG0000046139.7	<i>Patl1</i>	chr19:11912398-11945096	2.6	10.0	3.4	1.9×10^{-2}
Pac spc	ENSMUSG0000035778.13	<i>Ggta1</i>	chr2:35400178-35463231	0.1	1.7	3.4	3.1×10^{-2}
Pac spc	ENSMUSG0000001507.12	<i>Itga3</i>	chr11:95044473-95076801	0.5	2.9	3.4	2.3×10^{-2}
Pac spc	ENSMUSG0000022673.4	<i>Mcm4</i>	chr16:15623896-15637400	2.6	9.9	3.4	1.6×10^{-2}
Pac spc	ENSMUSG0000037679.8	<i>Inf2</i>	chr12:112588783-112615556	0.4	2.5	3.4	3.8×10^{-2}
Pac spc	ENSMUSG0000028530.10	<i>Jak1</i>	chr4:101068982-101265282	5.7	20.3	3.4	1.6×10^{-2}

Pac spc	ENSMUSG00 000019256.13	<i>Ahr</i>	chr12:35497973 -35535038	0.2	1.7	3.4	4.8×10^{-2}
Pac spc	ENSMUSG00 000074796.6	<i>Slc4a11</i>	chr2:130684112 -130697519	0.2	1.7	3.3	5.0×10^{-2}
Pac spc	ENSMUSG00 000040007.8	<i>Bahd1</i>	chr2:118900376 -118924528	4.3	15.4	3.3	4.8×10^{-2}
Pac spc	ENSMUSG00 000041225.12	<i>Arhgap12</i>	chr18:6024426- 6136098	2.8	10.5	3.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000038160.6	<i>Atg5</i>	chr10:44268357 -44364291	1.7	6.7	3.3	4.0×10^{-2}
Pac spc	ENSMUSG00 000036902.9	<i>Neto2</i>	chr8:85636587- 85690973	0.6	3.1	3.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000053716.9	<i>Dusp7</i>	chr9:106368631 -106375724	1.4	5.9	3.3	3.8×10^{-2}
Pac spc	ENSMUSG00 000025151.12	<i>Maged1</i>	chrX:94535473- 94542143	4.9	17.5	3.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000027070.10	<i>Lrp2</i>	chr2:69424339- 69586065	0.1	1.6	3.3	2.4×10^{-2}
Pac spc	ENSMUSG00 000032392.10	<i>Parp16</i>	chr9:65214689- 65239219	0.5	2.8	3.3	3.7×10^{-2}
Pac spc	ENSMUSG00 000031328.11	<i>Flna</i>	chrX:74223460- 74249820	1.5	6.1	3.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000036523.12	<i>Greb1</i>	chr12:16670614 -16800886	0.2	1.8	3.3	2.9×10^{-2}
Pac spc	ENSMUSG00 000098195.1	<i>Gm7693</i>	chr7:72712633- 72713621	0.0	1.1	3.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000051790.11	<i>Nlgn2</i>	chr11:69823121 -69837784	1.2	4.9	3.2	3.0×10^{-2}
Pac spc	ENSMUSG00 000027340.11	<i>Slc23a2</i>	chr2:132052495 -132220250	1.5	6.0	3.2	3.8×10^{-2}
Pac spc	ENSMUSG00 000054321.6	<i>Taf4b</i>	chr18:14783244 -14900359	3.5	12.4	3.2	1.4×10^{-2}
Pac spc	ENSMUSG00 000027932.10	<i>Slc27a3</i>	chr3:90385238- 90389938	0.6	3.0	3.2	4.1×10^{-2}
Pac spc	ENSMUSG00 000034902.13	<i>Pip5k1c</i>	chr10:81292962 -81319973	5.5	18.8	3.2	1.8×10^{-2}
Pac spc	ENSMUSG00 000028661.8	<i>Epha8</i>	chr4:136929418 -136956816	0.3	2.1	3.2	2.9×10^{-2}
Pac spc	ENSMUSG00 000005373.9	<i>Mlxipl</i>	chr5:135106890 -135138382	0.3	2.1	3.2	3.3×10^{-2}
Pac spc	ENSMUSG00 000048897.11	<i>Zfp710</i>	chr7:80024813- 80092751	0.4	2.5	3.2	5.0×10^{-2}
Pac spc	ENSMUSG00 000024457.12	<i>Trim26</i>	chr17:36837133 -36859398	1.7	6.4	3.2	3.7×10^{-2}
Pac spc	ENSMUSG00 000068876.10	<i>Cgn</i>	chr3:94760068- 94786492	0.9	3.9	3.2	4.8×10^{-2}
Pac spc	ENSMUSG00 000030309.12	<i>Caprin2</i>	chr6:148842491 -148896237	12.0	39.5	3.2	4.1×10^{-2}
Pac spc	ENSMUSG00 000020092.8	<i>Pald1</i>	chr10:61319656 -61383523	0.1	1.5	3.2	4.7×10^{-2}
Pac spc	ENSMUSG00 000010592.8	<i>Dazl</i>	chr17:50279393 -50293599	50.8	162.9	3.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000032902.1	<i>Slc16a1</i>	chr3:104638667 -104658462	4.3	14.7	3.2	1.6×10^{-2}
Pac spc	ENSMUSG00 000040249.11	<i>Lrp1</i>	chr10:12753816 0-127621148	0.2	1.8	3.2	1.1×10^{-2}
Pac spc	ENSMUSG00 000021294.7	<i>Kif26a</i>	chr12:11214620 7-112181747	0.4	2.2	3.2	3.1×10^{-2}

Pac spc	ENSMUSG00 000049699.3	<i>Ucn2</i>	chr9:108986162 -108987164	0.0	1.1	3.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000034218.11	<i>Atm</i>	chr9:53439148- 53536740	3.5	12.3	3.2	2.2×10^{-2}
Pac spc	ENSMUSG00 000055491.9	<i>Pprc1</i>	chr19:46032592 -46072915	9.5	31.1	3.2	3.3×10^{-2}
Pac spc	ENSMUSG00 000005034.11	<i>Prkacb</i>	chr3:146729578 -146812960	3.0	10.5	3.1	1.9×10^{-2}
Pac spc	ENSMUSG00 000017550.10	<i>Atad5</i>	chr11:80089399 -80135794	1.3	5.1	3.1	4.8×10^{-2}
Pac spc	ENSMUSG00 000019877.6	<i>Serinc1</i>	chr10:57515773 -57532530	10.2	32.9	3.1	4.8×10^{-2}
Pac spc	ENSMUSG00 000026478.10	<i>Lamc1</i>	chr1:153218921 -153332786	0.2	1.7	3.1	1.1×10^{-2}
Pac spc	ENSMUSG00 000095123.1	<i>Gm21781</i>	chr10:4391586- 4396424	1.6	5.9	3.1	4.3×10^{-2}
Pac spc	ENSMUSG00 000041351.12	<i>Rap1gap</i>	chr4:137664725 -137729861	2.7	9.4	3.1	4.0×10^{-2}
Pac spc	ENSMUSG00 000019179.6	<i>Mdh2</i>	chr5:135778479 -135790398	16.4	52.0	3.1	1.9×10^{-2}
Pac spc	ENSMUSG00 000071076.5	<i>Jund</i>	chr8:70697738- 70700616	4.3	14.4	3.1	2.6×10^{-2}
Pac spc	ENSMUSG00 000033352.7	<i>Map2k4</i>	chr11:65688242 -65788297	0.9	4.0	3.1	2.8×10^{-2}
Pac spc	ENSMUSG00 000000184.9	<i>Ccnd2</i>	chr6:127125778 -127212411	0.3	2.0	3.1	3.0×10^{-2}
Pac spc	ENSMUSG00 000034903.14	<i>Cobll1</i>	chr2:65088338- 65239675	0.2	1.7	3.1	1.1×10^{-2}
Pac spc	ENSMUSG00 000034762.5	<i>Glis1</i>	chr4:107434571 -107635061	0.5	2.6	3.1	4.1×10^{-2}
Pac spc	ENSMUSG00 000024151.9	<i>Msh2</i>	chr17:87672329 -87723713	3.4	11.6	3.1	3.3×10^{-2}
Pac spc	ENSMUSG00 000033059.7	<i>Pygb</i>	chr2:150786734 -150831758	1.6	6.0	3.1	3.8×10^{-2}
Pac spc	ENSMUSG00 000032898.6	<i>Fbxo21</i>	chr5:117976769 -118010191	4.5	14.7	3.0	1.6×10^{-2}
Pac spc	ENSMUSG00 000028030.8	<i>Tbck</i>	chr3:132684143 -132838506	1.7	6.1	3.0	5.0×10^{-2}
Pac spc	ENSMUSG00 000020782.14	<i>Llgl2</i>	chr11:11582404 8-115855780	1.6	5.8	3.0	4.5×10^{-2}
Pac spc	ENSMUSG00 000004113.14	<i>Cacna1b</i>	chr2:24603886- 24763152	0.9	3.6	3.0	3.6×10^{-2}
Pac spc	ENSMUSG00 000057672.11	<i>Pkn1</i>	chr8:83666832- 83699179	1.9	6.8	3.0	4.0×10^{-2}
Pac spc	ENSMUSG00 000026238.10	<i>Ptma</i>	chr1:86526725- 86530712	18.8	57.0	3.0	4.0×10^{-2}
Pac spc	ENSMUSG00 000022791.12	<i>Tnk2</i>	chr16:32643873 -32683493	3.0	9.9	3.0	2.9×10^{-2}
Pac spc	ENSMUSG00 000015647.9	<i>Lama5</i>	chr2:180176372 -180225859	1.6	5.7	3.0	2.4×10^{-2}
Pac spc	ENSMUSG00 000031657.12	<i>Heatr3</i>	chr8:88137854- 88172027	5.4	17.1	3.0	4.4×10^{-2}
Pac spc	ENSMUSG00 000034282.3	<i>Evpl</i>	chr11:11622055 8-116238077	0.3	1.9	3.0	4.8×10^{-2}
Pac spc	ENSMUSG00 000070570.4	<i>Slc17a7</i>	chr7:45163920- 45176138	1.0	3.9	3.0	3.8×10^{-2}
Pac spc	ENSMUSG00 000052298.8	<i>Cdc42se2</i>	chr11:54717455 -54787675	11.9	36.2	3.0	1.1×10^{-2}

Pac spc	ENSMUSG00 000072825.6	<i>Cep170b</i>	chr12:11272217 3-112746591	1.1	4.1	2.9	2.3×10^{-2}
Pac spc	ENSMUSG00 000032547.8	<i>Ryk</i>	chr9:102834916 -102908305	4.4	13.8	2.9	4.5×10^{-2}
Pac spc	ENSMUSG00 000024098.5	<i>Twsg1</i>	chr17:65923065 -65951187	3.3	10.7	2.9	4.7×10^{-2}
Pac spc	ENSMUSG00 000021910.11	<i>Nisch</i>	chr14:31170929 -31216946	14.0	41.8	2.9	4.3×10^{-3}
Pac spc	ENSMUSG00 000009035.9	<i>Tmem184 b</i>	chr15:79360683 -79403303	1.6	5.6	2.9	3.6×10^{-2}
Pac spc	ENSMUSG00 000023977.10	<i>Ubr2</i>	chr17:46928291 -47010532	3.3	10.7	2.9	2.1×10^{-2}
Pac spc	ENSMUSG00 000021611.8	<i>Tert</i>	chr13:73627000 -73649041	0.4	2.0	2.9	4.4×10^{-2}
Pac spc	ENSMUSG00 000067336.6	<i>Bmpr2</i>	chr1:59763399- 59879014	1.0	3.9	2.9	1.3×10^{-2}
Pac spc	ENSMUSG00 000007817.10	<i>Zmiz1</i>	chr14:25455736 -25666743	0.3	1.9	2.9	3.3×10^{-2}
Pac spc	ENSMUSG00 000036046.10	<i>5031439G 07Rik</i>	chr15:84943935 -84988551	1.4	5.0	2.9	4.8×10^{-2}
Pac spc	ENSMUSG00 000032849.9	<i>Abcc4</i>	chr14:11848269 1-118706219	0.3	1.8	2.8	3.7×10^{-2}
Pac spc	ENSMUSG00 000007564.10	<i>Ppp2r1a</i>	chr17:20945310 -20965916	9.4	27.3	2.8	2.7×10^{-2}
Pac spc	ENSMUSG00 000056724.10	<i>Nbeal2</i>	chr9:110624788 -110654161	1.2	4.2	2.8	4.2×10^{-2}
Pac spc	ENSMUSG00 000029863.9	<i>Casp2</i>	chr6:42264984- 42282508	7.9	23.0	2.8	2.9×10^{-2}
Pac spc	ENSMUSG00 000027646.11	<i>Src</i>	chr2:157418443 -157471862	1.0	3.8	2.8	4.8×10^{-2}
Pac spc	ENSMUSG00 000042978.9	<i>Sbk1</i>	chr7:126272618 -126294999	3.4	10.3	2.8	2.6×10^{-2}
Pac spc	ENSMUSG00 000053617.7	<i>Sh3pxd2a</i>	chr19:47260173 -47464411	0.6	2.5	2.8	1.5×10^{-2}
Pac spc	ENSMUSG00 000033624.6	<i>Pdpr</i>	chr8:111094629 -111145480	5.8	17.0	2.8	1.7×10^{-2}
Pac spc	ENSMUSG00 000035898.9	<i>Uba6</i>	chr5:86110719- 86172803	9.6	27.3	2.7	3.8×10^{-2}
Pac spc	ENSMUSG00 000042700.11	<i>Sipa11i</i>	chr12:82170015 -82451782	5.1	15.0	2.7	1.8×10^{-2}
Pac spc	ENSMUSG00 000063455.12	<i>D630045J 12Rik</i>	chr6:38048482- 38254009	2.0	6.2	2.7	4.5×10^{-2}
Pac spc	ENSMUSG00 000033228.7	<i>Scaf11</i>	chr15:96411697 -96460843	3.0	8.9	2.7	4.0×10^{-2}
Pac spc	ENSMUSG00 000003812.9	<i>Dnase2a</i>	chr8:84908559- 84937359	0.1	1.1	2.7	4.0×10^{-2}
Pac spc	ENSMUSG00 000037410.9	<i>Tbc1d2b</i>	chr9:90163068- 90270804	0.8	2.9	2.7	4.5×10^{-2}
Pac spc	ENSMUSG00 000005802.8	<i>Slc30a4</i>	chr2:122681232 -122721456	4.2	12.3	2.7	4.2×10^{-2}
Pac spc	ENSMUSG00 000061313.7	<i>Ddhd2</i>	chr8:25725323- 25754280	4.4	12.7	2.7	3.6×10^{-2}
Pac spc	ENSMUSG00 000028961.11	<i>Pgd</i>	chr4:149149990 -149166771	10.9	29.7	2.7	3.2×10^{-2}
Pac spc	ENSMUSG00 000005410.5	<i>Mcm5</i>	chr8:75109527- 75128439	9.7	26.4	2.6	3.8×10^{-2}
Pac spc	ENSMUSG00 000053198.9	<i>Prx</i>	chr7:27499323- 27520214	0.1	1.1	2.6	4.9×10^{-2}

Pac spc	ENSMUSG00 000056938.12	<i>Acbd4</i>	chr11:10310168 1-103112200	0.1	1.0	2.6	4.3×10^{-3}
Pac spc	ENSMUSG00 000037815.6	<i>Ctnna1</i>	chr18:35118887 -35254773	4.2	11.8	2.6	4.5×10^{-2}
Pac spc	ENSMUSG00 000052085.6	<i>Dock8</i>	chr19:24999528 -25202432	0.2	1.2	2.6	1.7×10^{-2}
Pac spc	ENSMUSG00 000018846.8	<i>Pank3</i>	chr11:35769483 -35791285	4.6	12.8	2.6	3.1×10^{-2}
Pac spc	ENSMUSG00 000014602.11	<i>Kif1a</i>	chr1:93015463- 93101951	0.3	1.4	2.6	3.6×10^{-2}
Pac spc	ENSMUSG00 000027312.10	<i>Atrn</i>	chr2:130906494 -131030333	6.9	18.4	2.5	4.1×10^{-2}
Pac spc	ENSMUSG00 000009995.13	<i>Taz</i>	chrX:74273216- 74290151	0.5	1.9	2.5	2.8×10^{-2}
Pac spc	ENSMUSG00 000075470.1	<i>Alg10b</i>	chr15:90224310 -90230554	6.6	17.6	2.5	2.9×10^{-2}
Pac spc	ENSMUSG00 000033948.3	<i>Zswim5</i>	chr4:116877375 -116989264	3.8	10.4	2.5	1.8×10^{-2}
Pac spc	ENSMUSG00 000032340.7	<i>Neo1</i>	chr9:58874678- 59036441	4.1	11.0	2.5	3.5×10^{-2}
Pac spc	ENSMUSG00 000003316.10	<i>Glg1</i>	chr8:111154420 -111259216	11.4	29.1	2.5	3.1×10^{-2}
Pac spc	ENSMUSG00 000033767.10	<i>D930015E 06Rik</i>	chr3:83897654- 84040175	7.9	20.0	2.4	4.7×10^{-2}
Pac spc	ENSMUSG00 000041859.10	<i>Mcm3</i>	chr1:20802967- 20820312	11.1	27.4	2.4	5.0×10^{-2}
Pac spc	ENSMUSG00 000062296.4	<i>Trank1</i>	chr9:111311738 -111395774	3.1	8.2	2.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000033253.14	<i>Szt2</i>	chr4:118359989 -118409273	8.7	20.9	2.3	4.0×10^{-2}
Pac spc	ENSMUSG00 000038644.10	<i>Pold1</i>	chr7:44532745- 44548849	22.1	51.8	2.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000063146.7	<i>Clip2</i>	chr5:134489385 -134552434	0.2	1.2	2.3	4.2×10^{-2}
Pac spc	ENSMUSG00 000032267.7	<i>Usp28</i>	chr9:48985384- 49042517	6.9	16.3	2.3	4.2×10^{-2}
Pac spc	ENSMUSG00 000050310.8	<i>Rictor</i>	chr15:6708380- 6800398	8.2	19.2	2.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000027878.10	<i>Notch2</i>	chr3:98013537- 98150367	3.4	8.3	2.2	3.6×10^{-2}
Pac spc	ENSMUSG00 000029512.7	<i>Ulk1</i>	chr5:110784487 -110810097	7.0	15.9	2.2	4.3×10^{-2}
Pac spc	ENSMUSG00 000005469.9	<i>Prkaca</i>	chr8:83972977- 83996445	55.2	25.9	0.5	4.4×10^{-2}
Pac spc	ENSMUSG00 000030086.12	<i>Chchd6</i>	chr6:89383145- 89595652	157.2	74.1	0.5	4.8×10^{-2}
Pac spc	ENSMUSG00 000032396.13	<i>Dis3l</i>	chr9:64306755- 64341288	162.8	76.5	0.5	4.8×10^{-2}
Pac spc	ENSMUSG00 000028937.10	<i>Acot7</i>	chr4:152178133 -152271855	332.0	154.5	0.5	4.9×10^{-2}
Pac spc	ENSMUSG00 000021771.9	<i>Vdac2</i>	chr14:21831268 -21856926	249.6	115.8	0.5	4.7×10^{-2}
Pac spc	ENSMUSG00 000024897.8	<i>Apba1</i>	chr19:23758875 -23949597	58.8	27.0	0.5	3.3×10^{-2}
Pac spc	ENSMUSG00 000036211.3	<i>Hist1h1t</i>	chr13:23695813 -23696542	1424.2	658.2	0.5	3.8×10^{-2}
Pac spc	ENSMUSG00 000040548.11	<i>Tex2</i>	chr11:10650214 6-106613423	125.0	56.6	0.5	3.8×10^{-2}

Pac spc	ENSMUSG00 000000552.9	<i>Zfp385a</i>	chr15:10331389 4-103340086	77.0	34.7	0.5	3.8×10^{-2}
Pac spc	ENSMUSG00 000074734.2	<i>4933416C 03Rik</i>	chr10:11601821 2-116274932	129.5	58.4	0.5	4.8×10^{-2}
Pac spc	ENSMUSG00 000022622.4	<i>Acr</i>	chr15:89568325 -89574585	125.8	56.7	0.5	4.0×10^{-2}
Pac spc	ENSMUSG00 000030357.6	<i>Fkbp4</i>	chr6:128429734 -128438677	229.3	102.8	0.4	3.6×10^{-2}
Pac spc	ENSMUSG00 000058297.12	<i>Spock2</i>	chr10:60106218 -60135198	29.4	12.9	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000020078.11	<i>Vps26a</i>	chr10:62454842 -62486805	97.4	43.4	0.4	4.2×10^{-2}
Pac spc	ENSMUSG00 000022092.10	<i>Ppp3cc</i>	chr14:70217897 -70289449	89.0	39.5	0.4	3.5×10^{-2}
Pac spc	ENSMUSG00 000023456.10	<i>Tpi1</i>	chr6:124808660 -124814296	100.4	44.4	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000034274.7	<i>Thoc5</i>	chr11:4895319- 4928867	62.8	27.5	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000033213.12	<i>AA467197</i>	chr2:122636985 -122641191	367.2	162.0	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000031554.13	<i>Adam5</i>	chr8:24727092- 24824369	289.5	126.8	0.4	3.5×10^{-2}
Pac spc	ENSMUSG00 000026163.13	<i>Sphkap</i>	chr1:83254138- 83408200	27.9	12.0	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000063229.10	<i>Ldha</i>	chr7:46841474- 46855627	571.8	250.6	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000036196.11	<i>Slc26a8</i>	chr17:28637782 -28689987	55.6	24.0	0.4	3.8×10^{-2}
Pac spc	ENSMUSG00 000025171.1	<i>Ubtd1</i>	chr19:41981762 -42034641	75.8	32.8	0.4	4.4×10^{-2}
Pac spc	ENSMUSG00 000040734.10	<i>Ppp1r13l</i>	chr7:19359748- 19378533	64.3	27.7	0.4	4.3×10^{-2}
Pac spc	ENSMUSG00 000072295.5	<i>Als2cr11</i>	chr1:59014223- 59094900	151.0	65.0	0.4	4.4×10^{-2}
Pac spc	ENSMUSG00 000025509.11	<i>Pnpla2</i>	chr7:141455197 -141460743	164.1	70.6	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000022246.9	<i>Rai14</i>	chr15:10568978 -10714631	87.2	37.3	0.4	3.1×10^{-2}
Pac spc	ENSMUSG00 000045466.14	<i>Zfp956</i>	chr6:47943170- 47965300	78.6	33.5	0.4	4.2×10^{-2}
Pac spc	ENSMUSG00 000051768.8	<i>Xrcc1</i>	chr7:24547149- 24573438	54.9	23.1	0.4	4.2×10^{-2}
Pac spc	ENSMUSG00 000024206.10	<i>Rfx2</i>	chr17:56775896 -56831008	182.8	77.6	0.4	3.8×10^{-2}
Pac spc	ENSMUSG00 000039183.5	<i>Nubp2</i>	chr17:24882610 -24886350	126.2	53.4	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000075706.6	<i>Gpx4</i>	chr10:80047165 -80056439	509.6	216.5	0.4	3.5×10^{-2}
Pac spc	ENSMUSG00 000029131.10	<i>Dnajb6</i>	chr5:29735636- 29786478	150.3	63.3	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000017843.9	<i>Ppp2r5c</i>	chr12:11048573 8-110583061	117.1	49.2	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00 000028878.7	<i>Fam76a</i>	chr4:132899212 -132922558	33.4	13.7	0.4	4.8×10^{-2}
Pac spc	ENSMUSG00 000049792.6	<i>Bag5</i>	chr12:11170948 7-111713257	114.8	47.9	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000039936.14	<i>Pik3cd</i>	chr4:149649167 -149702571	16.8	6.8	0.4	4.0×10^{-2}

Pac spc	ENSMUSG0000035211.8	<i>Xrra1</i>	chr7:99859217-99917824	82.9	34.4	0.4	4.0×10^{-2}
Pac spc	ENSMUSG0000042246.4	<i>Tmc7</i>	chr7:118535842-118584736	16.6	6.6	0.4	4.9×10^{-2}
Pac spc	ENSMUSG0000002102.11	<i>Psmc3</i>	chr2:91054008-91070417	344.2	142.9	0.4	3.5×10^{-2}
Pac spc	ENSMUSG00000027550.10	<i>Lrrcc1</i>	chr3:14533787-14572658	76.1	31.3	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00000024154.6	<i>Gtf2a1l</i>	chr17:88668659-88715152	119.6	49.4	0.4	3.3×10^{-2}
Pac spc	ENSMUSG0000056665.2	<i>Them6</i>	chr15:74721203-74728034	52.6	21.5	0.4	3.4×10^{-2}
Pac spc	ENSMUSG0000033210.12	<i>Slc9c1</i>	chr16:45535308-45607001	40.4	16.4	0.4	3.6×10^{-2}
Pac spc	ENSMUSG0000045107.4	<i>Saysd1</i>	chr14:20075645-20083172	49.4	20.1	0.4	3.8×10^{-2}
Pac spc	ENSMUSG0000013822.6	<i>Elof1</i>	chr9:22112988-22117148	314.9	129.8	0.4	3.8×10^{-2}
Pac spc	ENSMUSG0000020520.10	<i>Galnt10</i>	chr11:57623697-57787514	25.1	10.1	0.4	2.3×10^{-2}
Pac spc	ENSMUSG0000027363.11	<i>Usp8</i>	chr2:126707327-126783458	111.1	45.5	0.4	2.6×10^{-2}
Pac spc	ENSMUSG0000024474.5	<i>Ik</i>	chr18:36744655-36757639	120.9	49.4	0.4	1.8×10^{-2}
Pac spc	ENSMUSG0000025035.8	<i>Arl3</i>	chr19:46531108-46573085	184.1	75.4	0.4	3.1×10^{-2}
Pac spc	ENSMUSG0000035890.8	<i>Rnf126</i>	chr10:79758514-79766952	266.5	109.1	0.4	2.3×10^{-2}
Pac spc	ENSMUSG0000020472.10	<i>Zkscan17</i>	chr11:59485519-59526751	62.4	25.3	0.4	4.9×10^{-2}
Pac spc	ENSMUSG0000053624.3	<i>Gykl1</i>	chr18:52693678-52695668	118.9	48.2	0.4	2.6×10^{-2}
Pac spc	ENSMUSG0000027378.12	<i>Nphp1</i>	chr2:127740731-127788897	348.5	141.4	0.4	2.5×10^{-2}
Pac spc	ENSMUSG0000025793.11	<i>Hgs</i>	chr11:120467634-120483984	99.1	40.0	0.4	4.9×10^{-2}
Pac spc	ENSMUSG0000022013.3	<i>Dnajc15</i>	chr14:77826216-77874917	151.1	61.0	0.4	3.9×10^{-2}
Pac spc	ENSMUSG0000062732.6	<i>Lypd4</i>	chr7:24864619-24869941	210.4	85.0	0.4	2.2×10^{-2}
Pac spc	ENSMUSG0000058741.3	<i>Prr19</i>	chr7:25301358-25304133	55.7	22.3	0.4	2.5×10^{-2}
Pac spc	ENSMUSG0000039886.4	<i>Tmem120a</i>	chr5:135735484-135744271	92.6	37.2	0.4	2.9×10^{-2}
Pac spc	ENSMUSG0000040097.11	<i>Flywch1</i>	chr17:23755422-23771591	119.6	48.1	0.4	2.4×10^{-2}
Pac spc	ENSMUSG0000025218.6	<i>Poll</i>	chr19:45552274-45560531	44.5	17.7	0.4	2.9×10^{-2}
Pac spc	ENSMUSG0000035560.4	<i>Wdr20rt</i>	chr12:65225516-65228454	60.9	24.3	0.4	2.0×10^{-2}
Pac spc	ENSMUSG0000084883.1	<i>Ccdc85c</i>	chr12:108206344-108275417	19.4	7.5	0.4	3.2×10^{-2}
Pac spc	ENSMUSG0000042156.11	<i>Dzip1</i>	chr14:118875519-118925314	37.5	14.8	0.4	1.7×10^{-2}
Pac spc	ENSMUSG0000019834.11	<i>Slc22a16</i>	chr10:40570335-40604132	96.9	38.7	0.4	2.6×10^{-2}
Pac spc	ENSMUSG0000030096.7	<i>Slc6a6</i>	chr6:91684066-91759063	6.0	2.1	0.4	4.8×10^{-2}

Pac spc	ENSMUSG00 000045211.4	<i>Nudt18</i>	chr14:70577846 -70582571	54.4	21.6	0.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000025337.6	<i>Sbds</i>	chr5:130245730 -130255530	66.6	26.4	0.4	4.8×10^{-2}
Pac spc	ENSMUSG00 000029310.9	<i>Nudt9</i>	chr5:104046305 -104065379	42.8	16.9	0.4	2.9×10^{-2}
Pac spc	ENSMUSG00 000016982.6	<i>Pom121l2</i>	chr13:21981193 -21988734	150.6	60.0	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000026331.9	<i>Slco6c1</i>	chr1:97059037- 97128301	91.6	36.3	0.4	3.2×10^{-2}
Pac spc	ENSMUSG00 000027702.7	<i>Lrrc34</i>	chr3:30624266- 30672431	77.7	30.8	0.4	4.8×10^{-2}
Pac spc	ENSMUSG00 000030216.10	<i>Wbp11</i>	chr6:136813653 -136828233	303.5	121.1	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00 000058709.7	<i>Egln2</i>	chr7:27153713- 27166802	263.5	105.0	0.4	3.3×10^{-2}
Pac spc	ENSMUSG00 000031553.11	<i>Adam3</i>	chr8:24677224- 24725852	182.1	72.4	0.4	3.1×10^{-2}
Pac spc	ENSMUSG00 000069805.6	<i>Fbp1</i>	chr13:62864752 -62888282	387.3	153.8	0.4	1.9×10^{-2}
Pac spc	ENSMUSG00 000050035.6	<i>Fhl4</i>	chr10:85097018 -85102495	573.4	226.2	0.4	1.5×10^{-2}
Pac spc	ENSMUSG00 000074749.6	<i>Kiz</i>	chr2:146855863 -146970097	100.3	39.3	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000070953.9	<i>Rabepk</i>	chr2:34777555- 34799912	66.4	25.9	0.4	4.9×10^{-2}
Pac spc	ENSMUSG00 000025762.10	<i>Larp1b</i>	chr3:40950630- 41040234	194.3	76.4	0.4	1.9×10^{-2}
Pac spc	ENSMUSG00 000024304.10	<i>Cdh2</i>	chr18:16588876 -16809246	25.9	9.9	0.4	3.5×10^{-2}
Pac spc	ENSMUSG00 000029147.7	<i>Ppm1g</i>	chr5:31202667- 31220545	243.8	95.8	0.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000024158.13	<i>Hagh</i>	chr17:24840142 -24864450	183.5	71.7	0.4	3.1×10^{-2}
Pac spc	ENSMUSG00 000024654.8	<i>Asrgl1</i>	chr19:9109867- 9279175	282.2	110.2	0.4	1.6×10^{-2}
Pac spc	ENSMUSG00 000030792.7	<i>Dkk1</i>	chr7:45207524- 45211883	833.7	326.1	0.4	3.3×10^{-2}
Pac spc	ENSMUSG00 000031631.11	<i>Cfap97</i>	chr8:46033260- 46195590	165.1	64.2	0.4	2.2×10^{-2}
Pac spc	ENSMUSG00 000034932.4	<i>Mrpl54</i>	chr10:81264712 -81266934	103.2	39.9	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000019906.10	<i>Lin7a</i>	chr10:10727184 2-107425143	30.4	11.6	0.4	2.9×10^{-2}
Pac spc	ENSMUSG00 000020462.10	<i>Cfap36</i>	chr11:29221531 -29247409	195.0	75.6	0.4	4.4×10^{-2}
Pac spc	ENSMUSG00 000022671.8	<i>Mzt2</i>	chr16:15848440 -15863369	74.4	28.6	0.4	4.1×10^{-2}
Pac spc	ENSMUSG00 000042797.8	<i>Aqp11</i>	chr7:97726378- 97738247	123.6	47.6	0.4	4.5×10^{-2}
Pac spc	ENSMUSG00 000073730.2	<i>4933415F 23Rik</i>	chr1:23048294- 23235673	149.2	57.4	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000038026.8	<i>Kcnj9</i>	chr1:172320500 -172329318	29.9	11.2	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000032239.9	<i>Rp9</i>	chr9:22448310- 22468356	99.1	37.7	0.4	4.5×10^{-2}
Pac spc	ENSMUSG00 000022085.3	<i>Pebp4</i>	chr14:69840419 -70059886	190.7	72.7	0.4	1.8×10^{-2}

Pac spc	ENSMUSG00 000032497.11	<i>Lrrfip2</i>	chr9:111118110 -111225668	30.9	11.5	0.4	2.9×10^{-2}
Pac spc	ENSMUSG00 000055720.9	<i>Ubl7</i>	chr9:57910985- 57929968	171.4	65.2	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000033128.8	<i>Gga1</i>	chr15:78877189 -78894585	49.8	18.7	0.4	2.0×10^{-2}
Pac spc	ENSMUSG00 000016626.8	<i>Nlrp14</i>	chr7:107166989 -107198102	73.3	27.6	0.4	3.9×10^{-2}
Pac spc	ENSMUSG00 000019944.10	<i>Rhobtb1</i>	chr10:69151433 -69291791	15.7	5.7	0.4	4.4×10^{-2}
Pac spc	ENSMUSG00 000020434.4	<i>4921536K 21Rik</i>	chr11:3886087- 3895098	72.1	26.9	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000027088.6	<i>Phospho2</i>	chr2:69789622- 69800005	177.7	66.6	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000053030.7	<i>Spink2</i>	chr5:77205106- 77211471	391.6	146.7	0.4	7.0×10^{-3}
Pac spc	ENSMUSG00 000050623.4	<i>Tex40</i>	chr19:6922425- 6925380	236.1	88.2	0.4	1.7×10^{-2}
Pac spc	ENSMUSG00 000001794.8	<i>Capns1</i>	chr7:30186941- 30195164	128.2	47.7	0.4	2.7×10^{-2}
Pac spc	ENSMUSG00 000016526.8	<i>Dyrk3</i>	chr1:131127454 -131138340	36.5	13.3	0.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000031839.6	<i>Hsbp1</i>	chr8:119344537 -119348927	279.4	104.1	0.4	9.2×10^{-3}
Pac spc	ENSMUSG00 000037617.7	<i>Spag1</i>	chr15:36179367 -36235610	29.3	10.6	0.4	2.4×10^{-2}
Pac spc	ENSMUSG00 000039168.11	<i>Dap</i>	chr15:31224313 -31274341	36.2	13.2	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00 000050553.2	<i>Gk2</i>	chr5:97392439- 97588125	204.0	75.6	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000009115.5	<i>Spatc1l</i>	chr10:76562271 -76570532	25.2	9.0	0.4	4.9×10^{-2}
Pac spc	ENSMUSG00 000030030.4	<i>1700003E 16Rik</i>	chr6:83156403- 83162975	214.5	79.3	0.4	1.3×10^{-2}
Pac spc	ENSMUSG00 000075227.6	<i>Znhit2</i>	chr19:6061191- 6062472	140.2	51.7	0.4	2.0×10^{-2}
Pac spc	ENSMUSG00 000050996.6	<i>Cetn1</i>	chr18:9615523- 9619478	198.1	73.1	0.4	1.3×10^{-2}
Pac spc	ENSMUSG00 000052566.7	<i>Hook2</i>	chr8:84990594- 85003364	20.6	7.3	0.4	4.2×10^{-2}
Pac spc	ENSMUSG00 000028294.11	<i>1700003M 02Rik</i>	chr4:34688558- 34730206	279.3	103.2	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000033368.8	<i>Trim69</i>	chr2:122120107 -122186189	58.7	21.4	0.4	2.9×10^{-2}
Pac spc	ENSMUSG00 000030801.9	<i>Kat8</i>	chr7:127912516 -127930113	68.5	25.0	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000040794.5	<i>C1qtnf4</i>	chr2:90885859- 90890525	106.5	38.9	0.4	9.2×10^{-3}
Pac spc	ENSMUSG00 000028392.11	<i>Bspry</i>	chr4:62480052- 62497298	98.6	36.0	0.4	1.8×10^{-2}
Pac spc	ENSMUSG00 000025324.7	<i>Atp10a</i>	chr7:58658201- 58829426	8.9	3.0	0.4	1.7×10^{-2}
Pac spc	ENSMUSG00 000047383.7	<i>Als2cr11</i>	chr1:58997314- 59006218	62.1	22.5	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000022972.5	<i>1110004E 09Rik</i>	chr16:90925808 -90934927	138.7	50.6	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000027793.2	<i>Ccna1</i>	chr3:55045468- 55055055	33.7	12.0	0.4	3.4×10^{-2}

Pac spc	ENSMUSG00 000029073.5	<i>Ctp</i>	chr4:155864722 -155869440	70.9	25.7	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000052075.6	<i>1700029F 12Rik</i>	chr13:97021863 -97034362	291.8	106.2	0.4	4.3×10^{-3}
Pac spc	ENSMUSG00 000024937.10	<i>Ehbp11</i>	chr19:5707375- 5726317	31.2	11.1	0.4	1.4×10^{-2}
Pac spc	ENSMUSG00 000022525.9	<i>Hrasls</i>	chr16:29209694 -29230531	84.8	30.5	0.4	4.7×10^{-2}
Pac spc	ENSMUSG00 000026807.8	<i>Ak8</i>	chr2:28700163- 28813165	88.2	31.7	0.4	7.0×10^{-3}
Pac spc	ENSMUSG00 000061032.8	<i>Rrp1</i>	chr10:78400361 -78413043	245.9	88.9	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000037979.9	<i>Ccdc92</i>	chr5:124834417 -124862424	269.0	96.9	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00 000042404.12	<i>Dennd4b</i>	chr3:90265184- 90280669	16.5	5.6	0.4	1.5×10^{-2}
Pac spc	ENSMUSG00 000038587.8	<i>Akap12</i>	chr10:4266328- 4359468	86.7	31.0	0.4	1.9×10^{-2}
Pac spc	ENSMUSG00 000026790.15	<i>Odf2</i>	chr2:29889220- 29931746	609.6	217.8	0.4	1.6×10^{-2}
Pac spc	ENSMUSG00 000023170.10	<i>Gps2</i>	chr11:69913887 -69916591	120.5	42.8	0.4	1.9×10^{-2}
Pac spc	ENSMUSG00 000050957.4	<i>Insl6</i>	chr19:29321343 -29325356	137.4	48.8	0.4	1.1×10^{-2}
Pac spc	ENSMUSG00 000028576.8	<i>Ift74</i>	chr4:94614490- 94693229	68.2	24.0	0.4	2.3×10^{-2}
Pac spc	ENSMUSG00 000031786.6	<i>Drc7</i>	chr8:95055102- 95078141	36.5	12.7	0.4	7.0×10^{-3}
Pac spc	ENSMUSG00 000047104.4	<i>Pbp2</i>	chr6:135309783 -135310347	119.8	42.3	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000022375.6	<i>Lrrc6</i>	chr15:66379857 -66500910	44.1	15.4	0.4	2.6×10^{-2}
Pac spc	ENSMUSG00 000045246.7	<i>Kcng4</i>	chr8:119623853 -119635680	8.0	2.5	0.4	2.2×10^{-2}
Pac spc	ENSMUSG00 000035314.8	<i>Gdpd5</i>	chr7:99381548- 99460983	3.2	0.8	0.4	4.5×10^{-2}
Pac spc	ENSMUSG00 000024387.9	<i>Csnk2b</i>	chr17:35116195 -35128855	719.3	254.7	0.4	1.6×10^{-2}
Pac spc	ENSMUSG00 000068854.7	<i>Hist2h2be</i>	chr3:96221118- 96223738	17.1	5.7	0.4	2.9×10^{-2}
Pac spc	ENSMUSG00 000046447.3	<i>Camk2n1</i>	chr4:138454313 -138460123	7.8	2.4	0.4	2.5×10^{-2}
Pac spc	ENSMUSG00 000074384.3	<i>Al429214</i>	chr8:36993574- 36995531	35.6	12.2	0.4	4.0×10^{-2}
Pac spc	ENSMUSG00 000048707.9	<i>Tprn</i>	chr2:25262617- 25269885	104.4	36.4	0.4	2.2×10^{-2}
Pac spc	ENSMUSG00 000029798.9	<i>Herc6</i>	chr6:57580991- 57665136	4.5	1.2	0.4	4.4×10^{-2}
Pac spc	ENSMUSG00 000062270.9	<i>Morf4l1</i>	chr9:90091664- 90114774	622.7	218.1	0.4	1.5×10^{-2}
Pac spc	ENSMUSG00 000037001.10	<i>Zfp39</i>	chr11:58888152 -58904225	43.3	14.9	0.4	1.6×10^{-2}
Pac spc	ENSMUSG00 000031027.11	<i>Stk33</i>	chr7:109279222 -109444893	180.4	62.6	0.3	1.5×10^{-2}
Pac spc	ENSMUSG00 000054428.8	<i>Atpif1</i>	chr4:132530554 -132533659	159.8	55.1	0.3	3.3×10^{-2}
Pac spc	ENSMUSG00 000026650.11	<i>Meig1</i>	chr2:3409042- 3422648	953.3	329.8	0.3	9.2×10^{-3}

Pac spc	ENSMUSG00 000042293.7	<i>Gm5617</i>	chr9:48495344- 48495964	406.6	140.4	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000038782.4	<i>1700028J 19Rik</i>	chr7:44229932- 44236122	318.6	109.7	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000073758.6	<i>Sh3d21</i>	chr4:126150601 -126163491	37.7	12.7	0.3	3.1×10^{-2}
Pac spc	ENSMUSG00 000041399.3	<i>1700013G 24Rik</i>	chr4:137453283 -137455461	53.7	18.1	0.3	3.4×10^{-2}
Pac spc	ENSMUSG00 000045835.4	<i>Hdgfl1</i>	chr13:26768172 -26770119	180.7	61.6	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000038729.16	<i>Akap2</i>	chr4:57434246- 57896984	1.3	0.1	0.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000034227.7	<i>Foxj1</i>	chr11:11633070 3-116335399	15.4	4.9	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000038949.8	<i>Cnst</i>	chr1:179546369 -179627478	12.8	4.0	0.3	1.4×10^{-2}
Pac spc	ENSMUSG00 000027517.9	<i>Ankrd60</i>	chr2:173568665 -173578365	44.8	15.0	0.3	3.7×10^{-2}
Pac spc	ENSMUSG00 000042249.7	<i>Adrbk2</i>	chr5:112910477 -113015514	8.4	2.5	0.3	2.4×10^{-2}
Pac spc	ENSMUSG00 000073471.2	<i>Rsph3a</i>	chr17:7881105- 7979824	89.2	30.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000046487.6	<i>Mospd4</i>	chr18:46465214 -46465790	85.8	28.8	0.3	2.9×10^{-2}
Pac spc	ENSMUSG00 000037418.5	<i>Best1</i>	chr19:9985173- 10001633	19.9	6.4	0.3	2.1×10^{-2}
Pac spc	ENSMUSG00 000050107.2	<i>Gsg2</i>	chr11:73090582 -73147446	161.2	54.2	0.3	2.5×10^{-2}
Pac spc	ENSMUSG00 000029151.10	<i>Slc30a3</i>	chr5:31086105- 31112526	91.4	30.5	0.3	4.2×10^{-2}
Pac spc	ENSMUSG00 000034552.4	<i>Zswim2</i>	chr2:83915078- 83941228	26.7	8.7	0.3	2.8×10^{-2}
Pac spc	ENSMUSG00 000026255.11	<i>Efh1</i>	chr1:87264362- 87310839	280.4	94.2	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000078627.5	<i>43169</i>	chr11:10536079 7-105456735	296.4	99.5	0.3	1.5×10^{-2}
Pac spc	ENSMUSG00 000031849.8	<i>Comp</i>	chr8:70373547- 70382065	42.8	14.1	0.3	1.9×10^{-2}
Pac spc	ENSMUSG00 000024565.8	<i>Sall3</i>	chr18:80966375 -80988575	3.6	0.9	0.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000099958.1	<i>1700010B 13Rik</i>	chr15:73645851 -73652347	19.3	6.2	0.3	4.9×10^{-2}
Pac spc	ENSMUSG00 000039963.14	<i>Ccdc40</i>	chr11:11922857 1-119265236	68.8	22.8	0.3	3.1×10^{-2}
Pac spc	ENSMUSG00 000021997.4	<i>Lrrc63</i>	chr14:75084302 -75130881	37.7	12.3	0.3	1.8×10^{-2}
Pac spc	ENSMUSG00 000047841.8	<i>BC051628</i>	chr2:181220012 -181222854	37.4	12.2	0.3	3.0×10^{-2}
Pac spc	ENSMUSG00 000068860.5	<i>Gm128</i>	chr3:95236919- 95251193	229.1	76.2	0.3	1.7×10^{-2}
Pac spc	ENSMUSG00 000025480.4	<i>Syce1</i>	chr7:140777228 -140787854	215.2	71.6	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000070424.7	<i>Art5</i>	chr7:102096878 -102111148	26.8	8.6	0.3	3.0×10^{-2}
Pac spc	ENSMUSG00 000028555.11	<i>Ttc39a</i>	chr4:109406622 -109444745	16.1	5.1	0.3	3.5×10^{-2}
Pac spc	ENSMUSG00 000037910.2	<i>1700018B 24Rik</i>	chr3:48605731- 48609102	192.6	63.8	0.3	1.4×10^{-2}

Pac spc	ENSMUSG00 000020878.6	<i>Lrrc46</i>	chr11:97034601 -97041407	383.9	127.5	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000022442.11	<i>Ttll1</i>	chr15:83483771 -83510893	21.5	6.8	0.3	2.9×10^{-2}
Pac spc	ENSMUSG00 000024033.9	<i>Rsph1</i>	chr17:31255018 -31277356	743.0	246.0	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000064280.9	<i>Ccdc146</i>	chr5:21292960- 21424677	27.4	8.7	0.3	4.7×10^{-2}
Pac spc	ENSMUSG00 000035420.6	<i>Fam170a</i>	chr18:50278368 -50283019	32.3	10.4	0.3	4.8×10^{-2}
Pac spc	ENSMUSG00 000036398.9	<i>Ppp1r11</i>	chr17:36948355 -36951741	298.8	98.6	0.3	3.3×10^{-2}
Pac spc	ENSMUSG00 000040424.11	<i>Hipk4</i>	chr7:27523266- 27531175	16.4	5.1	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000032334.9	<i>Loxl1</i>	chr9:58287722- 58313212	4.1	1.0	0.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000044566.11	<i>Cage1</i>	chr13:38006051 -38061433	128.1	42.0	0.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000043621.9	<i>Ubxn10</i>	chr4:138709836 -138746132	89.4	29.1	0.3	1.8×10^{-2}
Pac spc	ENSMUSG00 000006930.11	<i>Hap1</i>	chr11:10034732 6-100356128	27.3	8.6	0.3	1.4×10^{-2}
Pac spc	ENSMUSG00 000028976.6	<i>Slc2a5</i>	chr4:150119282 -150144169	223.2	72.7	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000021660.10	<i>Btf3</i>	chr13:98309895 -98324415	173.5	56.4	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000031518.6	<i>Spata4</i>	chr8:54550330- 54610098	555.1	180.8	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000017195.11	<i>Zpbp2</i>	chr11:98551096 -98558665	133.8	43.2	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000031893.6	<i>Tsnaxip1</i>	chr8:105827743 -105844676	60.8	19.4	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000024430.9	<i>Cabyr</i>	chr18:12741323 -12755146	56.3	17.9	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000035785.5	<i>Cmtm2b</i>	chr8:104322236 -104330756	245.4	79.1	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000003354.5	<i>Ccdc65</i>	chr15:98708206 -98723326	121.7	39.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000074575.4	<i>Kcng1</i>	chr2:168260116 -168281736	6.3	1.7	0.3	2.0×10^{-2}
Pac spc	ENSMUSG00 000050677.2	<i>Ccdc96</i>	chr5:36484587- 36488172	46.2	14.5	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000026578.6	<i>Ccdc181</i>	chr1:164275584 -164287847	149.5	47.6	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000027528.8	<i>Fabp9</i>	chr3:10179850- 10197283	1302.0	415.4	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000080268.3	<i>Brms1</i>	chr19:5041403- 5049917	65.1	20.4	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000041566.3	<i>Tssk1</i>	chr16:17894222 -17897922	14.4	4.2	0.3	1.8×10^{-2}
Pac spc	ENSMUSG00 000024973.12	<i>Hrasls5</i>	chr19:7612540- 7639642	480.9	152.5	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000087122.1	<i>4930403D 09Rik</i>	chr11:34226814 -34783892	111.3	34.9	0.3	4.3×10^{-2}
Pac spc	ENSMUSG00 000073380.1	<i>Arrdc5</i>	chr17:56294112 -56300286	23.4	7.1	0.3	3.8×10^{-2}
Pac spc	ENSMUSG00 000044581.7	<i>4932415D 10Rik</i>	chr10:82282115 -82285278	16.0	4.7	0.3	2.4×10^{-2}

Pac spc	ENSMUSG00 000000942.10	<i>Hoxa4</i>	chr6:52162510- 52221854	30.8	9.4	0.3	2.3×10^{-2}
Pac spc	ENSMUSG00 000045915.11	<i>Ccdc42</i>	chr11:68587020 -68597966	58.3	18.0	0.3	2.5×10^{-2}
Pac spc	ENSMUSG00 000033739.8	<i>Fkbp1</i>	chr17:34644763 -34646324	62.3	19.2	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000052273.2	<i>Dnah3</i>	chr7:119922716 -120095177	8.4	2.3	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000022445.6	<i>Cyp2d26</i>	chr15:82790106 -82794245	7.7	2.1	0.3	4.6×10^{-2}
Pac spc	ENSMUSG00 000084135.3	<i>Pom121l1 2</i>	chr11:14599313 -14599862	79.2	24.4	0.3	1.8×10^{-2}
Pac spc	ENSMUSG00 000030672.8	<i>Mylpf</i>	chr7:127211607 -127214298	1.1	0.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000035085.5	<i>1700020L 24Rik</i>	chr11:83437676 -83463071	25.5	7.6	0.3	4.0×10^{-2}
Pac spc	ENSMUSG00 000024175.1	<i>Tekt4</i>	chr17:25471589 -25476594	51.7	15.7	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000029188.10	<i>Slc34a2</i>	chr5:53038081- 53071664	28.2	8.4	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000026546.12	<i>Cfap45</i>	chr1:172520800 -172563717	62.6	19.1	0.3	2.0×10^{-2}
Pac spc	ENSMUSG00 000021977.7	<i>1700129C 05Rik</i>	chr14:59133039 -59142893	104.2	31.9	0.3	1.4×10^{-2}
Pac spc	ENSMUSG00 000042190.8	<i>Cmklr1</i>	chr5:113612353 -113650426	10.4	2.9	0.3	3.6×10^{-2}
Pac spc	ENSMUSG00 000021258.9	<i>Ccnk</i>	chr12:10817973 7-108203359	174.0	53.4	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000027030.11	<i>Stk39</i>	chr2:68210444- 68472268	207.1	63.5	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000056223.7	<i>Spata31</i>	chr13:64917405 -64923184	14.8	4.2	0.3	3.8×10^{-2}
Pac spc	ENSMUSG00 000049985.10	<i>Ankrd55</i>	chr13:11228845 0-112384002	6.6	1.7	0.3	3.3×10^{-2}
Pac spc	ENSMUSG00 000100075.1	<i>1700018L 02Rik</i>	chr19:29020832 -29048729	53.7	16.1	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000030189.11	<i>Ybx3</i>	chr6:131364857 -131388450	619.0	189.5	0.3	2.0×10^{-2}
Pac spc	ENSMUSG00 000029517.9	<i>Ankrd7</i>	chr6:18866317- 18879586	56.9	17.0	0.3	2.0×10^{-2}
Pac spc	ENSMUSG00 000030590.10	<i>Fam98c</i>	chr7:29134853- 29156920	142.6	43.2	0.3	1.6×10^{-2}
Pac spc	ENSMUSG00 000022439.5	<i>Parvg</i>	chr15:84324025 -84342978	4.5	1.0	0.3	3.6×10^{-2}
Pac spc	ENSMUSG00 000090843.2	<i>Gm17673</i>	chr12:83954498 -83984852	6.5	1.6	0.3	4.2×10^{-2}
Pac spc	ENSMUSG00 000102758.1	<i>RP23- 349M18.1</i>	chr3:23804334- 23939477	1.1	0.0	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000074127.5	<i>Cmtm2a</i>	chr8:104281041 -104310145	397.0	120.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000078907.1	<i>Fam186b</i>	chr15:99271017 -99287180	50.9	15.1	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000043986.5	<i>Spata31d 1d</i>	chr13:59725924 -59731752	6.3	1.6	0.3	2.1×10^{-2}
Pac spc	ENSMUSG00 000046173.2	<i>Pabpc6</i>	chr17:9666496- 9669704	224.3	67.5	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000045573.9	<i>Penk</i>	chr4:4133530- 4188703	39.2	11.5	0.3	2.2×10^{-2}

Pac spc	ENSMUSG00 000020679.7	<i>Hnf1b</i>	chr11:83850062 -83905819	4.6	1.0	0.3	4.8×10^{-2}
Pac spc	ENSMUSG00 000049115.10	<i>Agtr1a</i>	chr13:30336440 -30382867	7.7	2.0	0.3	3.8×10^{-2}
Pac spc	ENSMUSG00 000008482.8	<i>Rnf151</i>	chr17:24715838 -24718057	31.6	9.1	0.3	3.3×10^{-2}
Pac spc	ENSMUSG00 000028560.7	<i>Usp1</i>	chr4:98923809- 98935543	138.2	41.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000053783.5	<i>1700016K 19Rik</i>	chr11:75999911 -76003569	103.3	30.5	0.3	2.1×10^{-2}
Pac spc	ENSMUSG00 000046755.5	<i>Kif2b</i>	chr11:91575314 -91577558	42.6	12.3	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000026125.5	<i>Prss39</i>	chr1:34498409- 34503063	68.8	20.1	0.3	1.4×10^{-2}
Pac spc	ENSMUSG00 000031841.14	<i>Cdh13</i>	chr8:118283732 -119324921	1.9	0.2	0.3	2.5×10^{-2}
Pac spc	ENSMUSG00 000021643.10	<i>Serf1</i>	chr13:10010679 4-100114571	403.1	119.2	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000028813.2	<i>CK137956</i>	chr4:127927591 -127970951	71.5	20.8	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000057816.3	<i>1700007G 11Rik</i>	chr5:98329353- 98801910	96.1	28.1	0.3	3.3×10^{-2}
Pac spc	ENSMUSG00 000073102.3	<i>Drc1</i>	chr5:30281387- 30366708	39.1	11.2	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000043913.10	<i>Ccdc60</i>	chr5:116123613 -116288985	185.4	54.5	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000046750.12	<i>BC089491</i>	chr7:28284651- 28291186	35.3	10.1	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000029679.7	<i>Hyal6</i>	chr6:24733244- 24745452	39.7	11.4	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000027968.7	<i>Larp7</i>	chr3:127536953 -127553348	118.1	34.5	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000032204.9	<i>Aqp9</i>	chr9:71110658- 71168682	77.4	22.4	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000038555.7	<i>Reep2</i>	chr18:34840588 -34847463	31.4	8.8	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000071234.2	<i>Syndig1l</i>	chr12:84677277 -84698807	5.5	1.3	0.3	3.6×10^{-2}
Pac spc	ENSMUSG00 000020475.3	<i>Pgam2</i>	chr11:5801639- 5803733	601.0	175.4	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000022269.9	<i>43170</i>	chr15:26309047 -26409576	256.1	74.3	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000070980.4	<i>Actl7b</i>	chr4:56740004- 56741443	157.5	45.6	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000020799.12	<i>Tekt1</i>	chr11:72344721 -72362442	128.5	36.9	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000078442.2	<i>Ccdc105</i>	chr10:78746923 -78753067	27.7	7.6	0.3	1.3×10^{-2}
Pac spc	ENSMUSG00 000028314.6	<i>Toporsl</i>	chr4:52596273- 52612430	36.7	10.2	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000036557.4	<i>1700011E 24Rik</i>	chr17:87389570 -87427741	297.1	84.8	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000037568.8	<i>Vash2</i>	chr1:190947645 -190979296	16.8	4.4	0.3	2.9×10^{-2}
Pac spc	ENSMUSG00 000038398.7	<i>Upf3a</i>	chr8:13785614- 13798538	108.0	30.3	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000021585.8	<i>Cast</i>	chr13:74694285 -74807921	12.7	3.2	0.3	3.8×10^{-2}

Pac spc	ENSMUSG00 000050114.7	<i>Prdx6b</i>	chr2:80292471- 80295356	131.5	36.9	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000021552.6	<i>Gkap1</i>	chr13:58233350 -58274188	202.5	56.9	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000038025.7	<i>Phf2</i>	chr13:48801749 -48870885	46.5	12.7	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000040829.10	<i>Zmynd15</i>	chr11:70453982 -70466202	38.5	10.5	0.3	7.0×10 ⁻³
Pac spc	ENSMUSG00 000074764.7	<i>Sel1l2</i>	chr2:140229854 -140389706	21.0	5.5	0.3	2.2×10 ⁻²
Pac spc	ENSMUSG00 000063971.6	<i>1700011A 15Rik</i>	chr15:10144774 4-101453909	30.5	8.2	0.3	4.9×10 ⁻²
Pac spc	ENSMUSG00 000029624.10	<i>Ptcd1</i>	chr5:145140361 -145167108	40.5	11.0	0.3	3.8×10 ⁻²
Pac spc	ENSMUSG00 000030847.7	<i>Bag3</i>	chr7:128523582 -128546977	10.6	2.6	0.3	7.0×10 ⁻³
Pac spc	ENSMUSG00 000029235.10	<i>Pdcl2</i>	chr5:76312114- 76331156	291.3	81.0	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000036463.7	<i>4930544G 11Rik</i>	chr6:65952570- 65954012	146.2	40.4	0.3	7.0×10 ⁻³
Pac spc	ENSMUSG00 000037638.5	<i>Zbtb42</i>	chr12:11267882 7-112682747	22.5	5.9	0.3	1.3×10 ⁻²
Pac spc	ENSMUSG00 000039540.8	<i>4921524L 21Rik</i>	chr18:6603632- 6638966	45.6	12.3	0.3	1.9×10 ⁻²
Pac spc	ENSMUSG00 000021545.4	<i>1700067P 10Rik</i>	chr17:48089631 -48090920	28.2	7.5	0.3	4.7×10 ⁻²
Pac spc	ENSMUSG00 000034675.13	<i>Dbn1</i>	chr13:55473428 -55488111	9.3	2.2	0.3	3.9×10 ⁻²
Pac spc	ENSMUSG00 000028845.11	<i>Tekt2</i>	chr4:126322120 -126325688	85.5	23.3	0.3	1.6×10 ⁻²
Pac spc	ENSMUSG00 000039335.7	<i>Spata16</i>	chr3:26637619- 26983212	159.5	43.6	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000021846.8	<i>Peli2</i>	chr14:48120868 -48260883	14.6	3.7	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000028310.2	<i>Ppp3r2</i>	chr4:49661610- 49845744	132.7	35.9	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000036214.9	<i>Znrd1as</i>	chr17:36958591 -36965622	57.3	15.3	0.3	4.3×10 ⁻²
Pac spc	ENSMUSG00 000024116.5	<i>Prss21</i>	chr17:23868055 -23873114	30.1	7.9	0.3	1.6×10 ⁻²
Pac spc	ENSMUSG00 000053868.3	<i>Gm5142</i>	chr14:59158502 -59178749	88.4	23.8	0.3	1.4×10 ⁻²
Pac spc	ENSMUSG00 000042581.10	<i>Thsd7b</i>	chr1:129273301 -130219278	11.5	2.8	0.3	1.8×10 ⁻²
Pac spc	ENSMUSG00 000021499.8	<i>Catsper3</i>	chr13:55784567 -55808998	12.6	3.1	0.3	4.9×10 ⁻²
Pac spc	ENSMUSG00 000070331.9	<i>Qrich2</i>	chr11:11644132 4-116455237	207.4	56.2	0.3	4.3×10 ⁻³
Pac spc	ENSMUSG00 000059810.14	<i>Rgs3</i>	chr4:62559846- 62704001	15.4	3.8	0.3	1.6×10 ⁻²
Pac spc	ENSMUSG00 000028637.11	<i>Ccdc30</i>	chr4:119322892 -119415521	166.0	44.3	0.3	2.6×10 ⁻²
Pac spc	ENSMUSG00 000033579.12	<i>Fa2h</i>	chr8:111345134 -111393824	21.1	5.3	0.3	9.2×10 ⁻³
Pac spc	ENSMUSG00 000032680.7	<i>6820408C 15Rik</i>	chr2:152415586 -152444330	25.1	6.3	0.3	1.5×10 ⁻²
Pac spc	ENSMUSG00 000023873.8	<i>1700010I 4Rik</i>	chr17:8988332- 9008319	313.4	83.5	0.3	4.3×10 ⁻³

Pac spc	ENSMUSG00 000044362.7	<i>Ccdc89</i>	chr7:90426311- 90428660	47.0	12.2	0.3	1.1×10^{-2}
Pac spc	ENSMUSG00 000067367.5	<i>Lyar</i>	chr5:38220469- 38234306	529.1	140.6	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000031831.6	<i>Dnaaf1</i>	chr8:119575234 -119605222	308.3	81.6	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000097863.1	<i>1010001B 22Rik</i>	chr5:109995510 -109996398	1.4	0.0	0.3	1.8×10^{-2}
Pac spc	ENSMUSG00 000051732.2	<i>Pabpc2</i>	chr18:39773496 -39776082	280.5	73.2	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000029999.10	<i>Tgfa</i>	chr6:86195250- 86275639	8.3	1.8	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000031493.9	<i>Ggn</i>	chr7:29170219- 29173933	150.0	38.6	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000035522.3	<i>Tsga8</i>	chrX:82948869- 85206141	40.9	10.2	0.3	3.8×10^{-2}
Pac spc	ENSMUSG00 000049476.8	<i>1700104B 16Rik</i>	chr8:33730533- 33731819	64.0	16.2	0.3	2.6×10^{-2}
Pac spc	ENSMUSG00 000037621.7	<i>Atoh8</i>	chr6:72206176- 72235577	18.2	4.3	0.3	9.2×10^{-3}
Pac spc	ENSMUSG00 000059395.4	<i>Nkapl</i>	chr13:21467046 -21468509	87.3	22.1	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000030549.5	<i>Rhcg</i>	chr7:79593362- 79617657	14.8	3.4	0.3	2.6×10^{-2}
Pac spc	ENSMUSG00 000000632.9	<i>Sez6</i>	chr11:77930799 -77979048	6.5	1.3	0.3	1.5×10^{-2}
Pac spc	ENSMUSG00 000017417.10	<i>Plxdc1</i>	chr11:97923237 -97986444	14.5	3.4	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000071104.5	<i>Ccdc110</i>	chr8:45934618- 45944145	20.5	4.9	0.3	1.5×10^{-2}
Pac spc	ENSMUSG00 000023949.6	<i>Tcte1</i>	chr17:45523433 -45549677	71.1	17.8	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000071636.6	<i>Rimbp3</i>	chr16:17208134 -17213921	123.3	31.1	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000062075.9	<i>Lmnb2</i>	chr10:80901202 -80918245	12.1	2.7	0.3	3.9×10^{-2}
Pac spc	ENSMUSG00 000022620.10	<i>Arsa</i>	chr15:89472475 -89484847	99.8	24.9	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000040866.9	<i>Rsph6a</i>	chr7:19054689- 19074447	92.8	23.1	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000030292.7	<i>Smco2</i>	chr6:146850103 -146871406	62.5	15.4	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000024209.9	<i>1700061G 19Rik</i>	chr17:56875476 -56888904	17.2	3.9	0.3	7.0×10^{-3}
Pac spc	ENSMUSG00 000022915.3	<i>1700093J 21Rik</i>	chr16:96082675 -96089070	1.5	0.0	0.3	4.3×10^{-3}
Pac spc	ENSMUSG00 000079334.4	<i>Nat6</i>	chr9:107575819 -107587425	15.5	3.5	0.3	4.4×10^{-2}
Pac spc	ENSMUSG00 000048988.7	<i>Elfn1</i>	chr5:139907942 -139974711	7.0	1.4	0.2	2.5×10^{-2}
Pac spc	ENSMUSG00 000017832.2	<i>Hspb9</i>	chr11:10071384 9-100714575	352.7	87.7	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000022441.13	<i>Efcab6</i>	chr15:83866711 -84065379	70.3	17.1	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000038246.6	<i>Fam50b</i>	chr13:34734849 -34747613	67.2	16.3	0.2	1.8×10^{-2}
Pac spc	ENSMUSG00 000034683.8	<i>Ppp1r1c</i>	chr2:79707779- 79818496	22.3	5.1	0.2	3.8×10^{-2}

Pac spc	ENSMUSG00 000034706.12	<i>Dnaic2</i>	chr11:11472740 7-114757889	18.4	4.2	0.2	7.0×10^{-3}
Pac spc	ENSMUSG00 000078127.2	<i>Fam170b</i>	chr14:32833961 -32836789	18.9	4.3	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000044117.8	<i>2900011O 08Rik</i>	chr16:13981701 -14101500	10.6	2.2	0.2	4.8×10^{-2}
Pac spc	ENSMUSG00 000012042.4	<i>4930579F 01Rik</i>	chr3:138164134 -138186713	12.1	2.6	0.2	4.8×10^{-2}
Pac spc	ENSMUSG00 000026649.10	<i>1700009P 17Rik</i>	chr1:171113917 -171126967	42.3	9.8	0.2	1.5×10^{-2}
Pac spc	ENSMUSG00 000079523.4	<i>Tmsb10</i>	chr6:72957346- 72958748	655.0	156.7	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000100937.1	<i>1700020D 05Rik</i>	chr19:5495277- 5510489	122.8	29.0	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000085464.1	<i>Gm16208</i>	chr8:107029674 -107031188	1.6	0.0	0.2	2.6×10^{-2}
Pac spc	ENSMUSG00 000043859.4	<i>1700049L 16Rik</i>	chr10:71979889 -71980694	22.5	5.0	0.2	1.5×10^{-2}
Pac spc	ENSMUSG00 000027518.3	<i>1700021F 07Rik</i>	chr2:173522585 -173528501	54.5	12.6	0.2	2.9×10^{-2}
Pac spc	ENSMUSG00 000035179.3	<i>Ppp1r32</i>	chr19:10474256 -10482897	48.4	11.1	0.2	7.0×10^{-3}
Pac spc	ENSMUSG00 000047025.4	<i>Ccer1</i>	chr10:97693058 -97694926	46.2	10.5	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000028610.12	<i>Dmrtb1</i>	chr4:107676289 -107684230	370.7	86.9	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000039330.4	<i>Tsga10ip</i>	chr19:5390048- 5394401	78.3	18.0	0.2	1.8×10^{-2}
Pac spc	ENSMUSG00 000036168.11	<i>Ccdc38</i>	chr10:93540631 -93605245	123.1	28.5	0.2	1.7×10^{-2}
Pac spc	ENSMUSG00 000021056.7	<i>Tex21</i>	chr12:76198691 -76246746	19.1	4.1	0.2	1.8×10^{-2}
Pac spc	ENSMUSG00 000055602.12	<i>Tcp10b</i>	chr17:13061103 -13082481	47.8	10.7	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000083649.5	<i>Rasl2-9</i>	chr7:5124937- 5125950	72.2	16.3	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000022602.10	<i>Arc</i>	chr15:74669082 -74672570	69.8	15.7	0.2	7.0×10^{-3}
Pac spc	ENSMUSG00 000039391.7	<i>Ccdc81</i>	chr7:89866147- 89903629	16.9	3.5	0.2	1.9×10^{-2}
Pac spc	ENSMUSG00 000030544.5	<i>Mesp1</i>	chr7:79792240- 79793788	44.4	9.7	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000020023.13	<i>Tmcc3</i>	chr10:94311948 -94612084	9.5	1.8	0.2	2.6×10^{-2}
Pac spc	ENSMUSG00 000001948.9	<i>Spa17</i>	chr9:37603294- 37613720	164.8	36.8	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000018776.9	<i>Slc35g3</i>	chr11:69759889 -69761968	16.5	3.3	0.2	1.6×10^{-2}
Pac spc	ENSMUSG00 000038498.3	<i>Catsper1</i>	chr19:5335740- 5344153	15.1	3.0	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000081360.1	<i>Gm11718</i>	chr11:10719109 3-107191630	1.8	0.0	0.2	2.4×10^{-2}
Pac spc	ENSMUSG00 000020268.9	<i>Lyrm7</i>	chr11:54826865 -54860916	15.3	3.0	0.2	4.0×10^{-2}
Pac spc	ENSMUSG00 000090273.3	<i>Prr22</i>	chr17:56770249 -56772208	27.7	5.7	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000084938.1	<i>BB557941</i>	chr2:57127478- 57181754	1.8	0.0	0.2	1.3×10^{-2}

Pac spc	ENSMUSG00 000071322.8	<i>Tcp10a</i>	chr17:7324645- 7345974	80.2	17.2	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000011263.11	<i>Exoc3l2</i>	chr7:19489055- 19496760	10.0	1.8	0.2	1.4×10^{-2}
Pac spc	ENSMUSG00 000023165.9	<i>Ssxb2</i>	chrX:8454344- 8461726	1.8	0.0	0.2	1.4×10^{-2}
Pac spc	ENSMUSG00 000021534.7	<i>1700001L 19Rik</i>	chr13:68597438 -68614231	14.8	2.8	0.2	4.6×10^{-2}
Pac spc	ENSMUSG00 000052469.8	<i>Tcp10c</i>	chr17:13354571 -13377223	65.1	13.6	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000043036.9	<i>Ccdc63</i>	chr5:122100950 -122138957	22.1	4.3	0.2	1.8×10^{-2}
Pac spc	ENSMUSG00 000101963.1	<i>1700001J 11Rik</i>	chr9:40050364- 40053028	188.7	39.7	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000042189.5	<i>Tekt3</i>	chr11:63061653 -63094964	63.2	13.0	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000104111.1	<i>RP23- 71J17.3</i>	chr1:160041700 -160044331	1.9	0.0	0.2	3.6×10^{-2}
Pac spc	ENSMUSG00 000036598.3	<i>Ccdc113</i>	chr8:95534099- 95558888	106.7	22.1	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000032023.7	<i>4931429I1 1Rik</i>	chr9:40894848- 40964118	24.5	4.7	0.2	2.9×10^{-2}
Pac spc	ENSMUSG00 000027505.2	<i>Fam209</i>	chr2:172472519 -172474331	39.6	7.9	0.2	1.5×10^{-2}
Pac spc	ENSMUSG00 000084837.1	<i>1700108N 11Rik</i>	chr2:144305174 -144332639	43.2	8.5	0.2	4.5×10^{-2}
Pac spc	ENSMUSG00 000046585.8	<i>Cfap58</i>	chr19:47937711 -48035379	11.3	1.9	0.2	1.9×10^{-2}
Pac spc	ENSMUSG00 000062154.9	<i>Tex33</i>	chr15:78378399 -78395912	40.9	7.9	0.2	9.2×10^{-3}
Pac spc	ENSMUSG00 000024306.8	<i>Ccdc178</i>	chr18:21810896 -22171396	18.1	3.3	0.2	4.0×10^{-2}
Pac spc	ENSMUSG00 000097562.1	<i>Gm26639</i>	chr13:65590292 -65591561	2.0	0.0	0.2	2.4×10^{-2}
Pac spc	ENSMUSG00 000091955.2	<i>Gm9844</i>	chr7:24862212- 24862697	2.0	0.0	0.2	2.0×10^{-2}
Pac spc	ENSMUSG00 000087510.1	<i>1700112K 13Rik</i>	chr4:127810637 -127812173	2.0	0.0	0.2	1.4×10^{-2}
Pac spc	ENSMUSG00 000072878.4	<i>1700123L 14Rik</i>	chr6:96113153- 96657198	254.1	49.8	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000012211.9	<i>Tex22</i>	chr12:11307450 1-113088917	102.9	19.8	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000080059.4	<i>Rps19- ps3</i>	chr4:147821776 -147822202	2.1	0.0	0.2	2.7×10^{-2}
Pac spc	ENSMUSG00 000021338.13	<i>Lrrc16a</i>	chr13:24012343 -24280795	11.2	1.7	0.2	1.7×10^{-2}
Pac spc	ENSMUSG00 000100585.1	<i>1700108J 01Rik</i>	chr14:12218169 3-122402232	181.0	33.8	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000049526.7	<i>Tmem202</i>	chr9:59518685- 59525501	28.7	5.0	0.2	7.0×10^{-3}
Pac spc	ENSMUSG00 000029784.9	<i>Ssmem1</i>	chr6:30509848- 30520254	90.5	16.0	0.2	4.3×10^{-3}
Pac spc	ENSMUSG00 000084475.1	<i>Gm25782</i>	chr16:8449497- 8449786	2.5	0.0	0.2	3.8×10^{-2}
Pac spc	ENSMUSG00 000087335.2	<i>4930526F 13Rik</i>	chr13:54926762 -54930256	6.0	0.6	0.2	4.7×10^{-2}
Pac spc	ENSMUSG00 000097066.1	<i>Gm26758</i>	chr13:65780904 -65867305	2.9	0.0	0.1	2.1×10^{-2}

Pac spc	ENSMUSG00 000086443.1	4933421A 08Rik	chr4:122961308 -122963475	6.6	0.5	0.1	5.0×10 ⁻²
Pac spc	ENSMUSG00 000087332.1	Gm12690	chr4:99569499- 99573011	2.9	0.0	0.1	2.3×10 ⁻²
Pac spc	ENSMUSG00 000030617.8	Ccdc83	chr7:90223877- 90265432	38.7	5.1	0.1	1.8×10 ⁻²
Pac spc	ENSMUSG00 000094338.1	Hist1h2bl	chr13:21715762 -21716143	3.4	0.0	0.1	4.3×10 ⁻³
Pac spc	ENSMUSG00 000053896.9	4933409G 03Rik	chr2:68582412- 68616387	74.9	8.9	0.1	1.9×10 ⁻²
Pac spc	ENSMUSG00 000103011.1	RP23- 241J7.2	chr3:9072766- 9073211	4.3	0.0	0.1	1.4×10 ⁻²
Pac spc	ENSMUSG00 000095331.3	Ptma-ps1	chr7:24063831- 24064140	4.6	0.0	0.1	2.6×10 ⁻²
Pac spc	ENSMUSG00 000084372.1	Gm13988	chr2:123273923 -123274211	10.1	0.0	0.0	9.2×10 ⁻³
Pac spc	ENSMUSG00 000048559.4	4930555K 19Rik	chr15:41173700 -41173871	50.6	0.0	0.0	1.5×10 ⁻²
Dip spc	ENSMUSG00 000075014.1	Gm10800	chr2:98666546- 98667301	52.6	1072.4	20.2	4.9×10 ⁻²
Dip spc	ENSMUSG00 000075015.3	Gm10801	chr2:98662236- 98664083	5.6	84.6	14.0	4.9×10 ⁻²
Dip spc	ENSMUSG00 000000278.10	Scpep1	chr11:88905927 -88955465	13.6	61.1	4.4	4.9×10 ⁻²
Dip spc	ENSMUSG00 000023572.12	Ccndbp1	chr2:121008402 -121016904	4.0	17.7	4.1	4.9×10 ⁻²
Dip spc	ENSMUSG00 000058569.7	Tmed9	chr13:55593134 -55597663	8.2	29.1	3.4	4.9×10 ⁻²
Dip spc	ENSMUSG00 000097164.1	Cep83os	chr10:94673492 -94688613	38.4	125.2	3.2	4.9×10 ⁻²
Dip spc	ENSMUSG00 000022136.7	Dnajc3	chr14:11893793 1-118981702	21.8	61.6	2.8	4.9×10 ⁻²
Dip spc	ENSMUSG00 000022501.5	Prm1	chr16:10796325 -10796886	126.4	308.2	2.4	4.9×10 ⁻²
Dip spc	ENSMUSG00 000038015.6	Prm2	chr16:10791379 -10796134	107.0	248.8	2.3	4.9×10 ⁻²
Secondary spc	ENSMUSG00 000023572.12	Ccndbp1	chr2:121008402 -121016904	0.2	12.0	17.3	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000033713.7	Foxn3	chr12:99194979 -99450111	1.2	15.3	9.4	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000000278.10	Scpep1	chr11:88905927 -88955465	4.9	33.9	6.3	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000022136.7	Dnajc3	chr14:11893793 1-118981702	4.2	29.2	6.3	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000022300.9	Dcaf13	chr15:39112864 -39146856	2.0	12.6	5.2	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000048310.8	Pskh1	chr8:105900440 -105931778	2.2	10.2	4.0	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000028684.10	Urod	chr4:116989964 -116994413	2.4	10.0	3.7	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000058569.7	Tmed9	chr13:55593134 -55597663	0.9	4.3	3.5	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000025134.2	Alyref	chr11:12059212 0-120598365	9.0	31.6	3.4	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000074997.3	Pin1rt1	chr2:104713925 -104716379	3.7	10.9	2.7	3.1×10 ⁻²
Secondary spc	ENSMUSG00 000083282.2	Ctsf	chr19:4855128- 4860912	0.4	1.9	2.7	3.1×10 ⁻²

Secondary spc	ENSMUSG0000053453.8	<i>Thoc7</i>	chr14:13918443-13961225	37.5	100.8	2.7	3.1×10^{-2}
Secondary spc	ENSMUSG0000079606.1	<i>Gm595</i>	chrX:48841465-48877713	18.5	45.3	2.4	3.1×10^{-2}
Secondary spc	ENSMUSG0000019210.8	<i>Atp6v1e1</i>	chr6:120795244-120822685	7.9	18.7	2.3	3.1×10^{-2}
Secondary spc	ENSMUSG0000102483.1	<i>RP23-474A1.1</i>	chr1:177808549-177962233	14.7	31.9	2.1	3.1×10^{-2}
Secondary spc	ENSMUSG0000021534.7	<i>1700001L19Rik</i>	chr13:68597438-68614231	108.1	48.8	0.5	3.1×10^{-2}
Secondary spc	ENSMUSG0000001948.9	<i>Spa17</i>	chr9:37603294-37613720	529.1	239.1	0.5	3.1×10^{-2}
Secondary spc	ENSMUSG0000099863.1	<i>1700031L13Rik</i>	chr5:82122407-82124713	103.6	36.1	0.4	3.1×10^{-2}
Secondary spc	ENSMUSG0000036249.12	<i>Rbm43</i>	chr2:51924447-51935163	22.0	6.9	0.3	3.1×10^{-2}
Secondary spc	ENSMUSG0000064288.4	<i>Hist1h4k</i>	chr13:21750193-21750505	1.5	0.0	0.3	3.1×10^{-2}
Sptd	ENSMUSG0000023572.12	<i>Ccndbp1</i>	chr2:121008402-121016904	0.3	9.5	12.5	2.4×10^{-2}
Sptd	ENSMUSG0000022136.7	<i>Dnajc3</i>	chr14:118937931-118981702	4.0	24.1	5.5	2.4×10^{-2}
Sptd	ENSMUSG0000002985.11	<i>Apoe</i>	chr7:19696108-19699166	3.0	18.6	5.4	2.4×10^{-2}
Sptd	ENSMUSG0000058252.6	<i>1700008I05Rik</i>	chrX:135654697-135693790	16.2	87.7	5.3	2.4×10^{-2}
Sptd	ENSMUSG0000022300.9	<i>Dcaf13</i>	chr15:39112864-39146856	1.5	9.5	5.0	2.4×10^{-2}
Sptd	ENSMUSG0000000278.10	<i>Scpep1</i>	chr11:88905927-88955465	2.9	15.3	4.6	2.4×10^{-2}
Sptd	ENSMUSG0000047654.6	<i>Tssk6</i>	chr8:69887787-69903518	82.3	378.9	4.6	2.4×10^{-2}
Sptd	ENSMUSG0000048310.8	<i>Pskh1</i>	chr8:105900440-105931778	2.0	11.1	4.6	2.4×10^{-2}
Sptd	ENSMUSG0000053453.8	<i>Thoc7</i>	chr14:13918443-13961225	18.4	83.6	4.4	2.4×10^{-2}
Sptd	ENSMUSG0000019210.8	<i>Atp6v1e1</i>	chr6:120795244-120822685	2.8	14.2	4.4	2.4×10^{-2}
Sptd	ENSMUSG0000045217.5	<i>Ppp1r2-ps9</i>	chrX:15110584-15111466	18.7	82.6	4.3	2.4×10^{-2}
Sptd	ENSMUSG0000029766.4	<i>1700012A03Rik</i>	chr6:32050245-32058921	32.5	136.3	4.1	2.4×10^{-2}
Sptd	ENSMUSG0000036002.8	<i>Fam214b</i>	chr4:43027689-43053253	10.2	43.7	4.1	2.4×10^{-2}
Sptd	ENSMUSG0000051896.4	<i>Tex37</i>	chr6:70913086-70918927	55.7	232.4	4.1	2.4×10^{-2}
Sptd	ENSMUSG0000036918.11	<i>Ttc7</i>	chr17:87282885-87381769	14.1	58.6	4.1	2.4×10^{-2}
Sptd	ENSMUSG0000031085.11	<i>Gm498</i>	chr7:143866870-143897506	31.3	127.5	4.0	3.7×10^{-2}
Sptd	ENSMUSG0000026473.11	<i>Glul</i>	chr1:153849541-153909723	63.6	255.3	4.0	4.8×10^{-2}
Sptd	ENSMUSG0000076438.5	<i>Oxct2b</i>	chr4:123105164-123139951	47.5	190.9	4.0	2.4×10^{-2}
Sptd	ENSMUSG0000050087.3	<i>Cby3</i>	chr11:50354461-50359699	14.3	57.6	3.9	4.8×10^{-2}
Sptd	ENSMUSG0000076436.1	<i>Oxct2a</i>	chr4:123312644-123343252	44.3	173.4	3.9	2.4×10^{-2}

Sptd	ENSMUSG00 000027562.8	<i>Car2</i>	chr3:14886272- 14900770	29.2	112.3	3.8	2.4×10^{-2}
Sptd	ENSMUSG00 000047394.7	<i>Odf3b</i>	chr15:89377449 -89379254	10.0	38.4	3.7	2.4×10^{-2}
Sptd	ENSMUSG00 000049653.4	<i>Spatc1</i>	chr15:76268088 -76292572	38.1	139.6	3.6	3.7×10^{-2}
Sptd	ENSMUSG00 000078346.3	<i>Gm5132</i>	chrX:14211147- 14211661	13.0	47.7	3.6	3.7×10^{-2}
Sptd	ENSMUSG00 000003178.7	<i>Mical3</i>	chr6:121007240 -121081609	41.8	148.6	3.5	2.4×10^{-2}
Sptd	ENSMUSG00 000000125.5	<i>Wnt3</i>	chr11:10377414 9-103817957	5.2	18.8	3.4	3.7×10^{-2}
Sptd	ENSMUSG00 000074259.6	<i>Gramd2</i>	chr9:59680143- 59718874	2.3	8.9	3.4	2.4×10^{-2}
Sptd	ENSMUSG00 000021791.6	<i>Dydc2</i>	chr14:41049208 -41069074	13.9	47.5	3.3	2.4×10^{-2}
Sptd	ENSMUSG00 000027482.8	<i>Bpifa3</i>	chr2:154130335 -154138356	29.1	98.1	3.3	2.4×10^{-2}
Sptd	ENSMUSG00 000036046.10	<i>5031439G 07Rik</i>	chr15:84943935 -84988551	8.1	27.7	3.3	2.4×10^{-2}
Sptd	ENSMUSG00 000021194.5	<i>Chga</i>	chr12:10255496 8-102565027	0.6	2.9	3.2	2.4×10^{-2}
Sptd	ENSMUSG00 000020307.10	<i>Cdc34</i>	chr10:79682194 -79688394	102.2	325.7	3.2	3.7×10^{-2}
Sptd	ENSMUSG00 000031770.11	<i>Herpud1</i>	chr8:94377920- 94395377	49.9	157.5	3.1	2.4×10^{-2}
Sptd	ENSMUSG00 000056508.5	<i>1700001K 19Rik</i>	chr12:11066768 8-110682619	49.4	153.8	3.1	4.8×10^{-2}
Sptd	ENSMUSG00 000050721.8	<i>Plekho2</i>	chr9:65554385- 65580040	5.3	16.9	3.0	3.7×10^{-2}
Sptd	ENSMUSG00 000058794.8	<i>Nfe2</i>	chr15:10324821 1-103258403	0.5	2.6	3.0	3.7×10^{-2}
Sptd	ENSMUSG00 000031930.10	<i>Wwp2</i>	chr8:107436397 -107558594	13.0	39.9	3.0	4.8×10^{-2}
Sptd	ENSMUSG00 000071076.5	<i>Jund</i>	chr8:70697738- 70700616	13.6	41.3	3.0	2.4×10^{-2}
Sptd	ENSMUSG00 000048038.6	<i>4932418E 24Rik</i>	chr2:26271645- 26294557	31.4	91.7	2.9	4.8×10^{-2}
Sptd	ENSMUSG00 000024197.9	<i>Plin3</i>	chr17:56278961 -56290511	1.9	5.9	2.6	3.7×10^{-2}
Sptd	ENSMUSG00 000083282.2	<i>Ctsf</i>	chr19:4855128- 4860912	0.2	1.4	2.6	3.7×10^{-2}
Sptd	ENSMUSG00 000014791.9	<i>Elmo3</i>	chr8:105305600 -105310623	0.3	1.3	2.3	2.4×10^{-2}
Sptd	ENSMUSG00 000036949.12	<i>Slc39a12</i>	chr2:14388315- 14494977	4.7	1.4	0.4	2.4×10^{-2}
Sptd	ENSMUSG00 000099508.1	<i>1700030L 20Rik</i>	chr3:136435269 -136449349	16.5	5.3	0.3	4.8×10^{-2}
Sptd	ENSMUSG00 000102758.1	<i>RP23- 349M18.1</i>	chr3:23804334- 23939477	8.4	2.4	0.3	2.4×10^{-2}

Table S3. Expression of piRNA pathway genes in *pi6^{em1/em1}* cells.

Gene	Ensembl ID	C57BL/6 (fpkm)	<i>pi6^{em1/em1}</i> (fpkm)	<i>pi6^{em1/em1}</i> / C57BL/6	FDR
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Pachytene Spermatocyte

<i>Piwi1</i>	ENSMUSG00000029423.6	491.0	377.3	0.8	0.7
<i>Piwi2</i>	ENSMUSG00000033644.4	154.5	237.4	1.5	0.4
<i>Mov10l1</i>	ENSMUSG00000015365.11	100.0	164.5	1.6	0.5
<i>A-Myb</i>	ENSMUSG00000025912.12	51.6	49.8	1.0	1.0
<i>Tdrd1</i>	ENSMUSG00000025081.9	188.6	194.1	1.0	1.0
<i>Tdrd6</i>	ENSMUSG00000040140.10	272.3	117.1	0.4	0.1
<i>UAP56/Ddx39b</i>	ENSMUSG00000019432.11	90.5	115.8	1.3	0.6
<i>PLD6</i>	ENSMUSG00000043648.7	121.0	85.9	0.7	0.5
<i>Papi/Tdrkh</i>	ENSMUSG00000041912.8	29.4	36.4	1.2	0.7
<i>Tdrd12</i>	ENSMUSG00000030491.12	109.4	119.1	1.1	0.9
<i>Ddx4</i>	ENSMUSG00000021758.9	259.6	220.5	0.8	0.8
<i>Piwi4</i>	ENSMUSG00000036912.13	0.0	1.8	4.4	0.5
<i>Mael</i>	ENSMUSG00000040629.4	600.4	340.9	0.6	0.2
<i>Rnf17</i>	ENSMUSG00000000365.8	85.1	99.4	1.2	0.8
<i>Henmt1</i>	ENSMUSG00000045662.12	37.1	30.7	0.8	0.8
<i>PNLDC1</i>	ENSMUSG00000073460.4	8.0	11.3	1.4	0.6

Diplotene Spermatocyte

<i>Piwi1</i>	ENSMUSG00000029423.6	270.5	344.8	1.3	1.0
<i>Piwi2</i>	ENSMUSG00000033644.4	54.6	75.7	1.4	1.0
<i>Mov10l1</i>	ENSMUSG00000015365.11	33.9	43.2	1.3	1.0
<i>A-Myb</i>	ENSMUSG00000025912.12	43.2	47.4	1.1	1.0
<i>Tdrd1</i>	ENSMUSG00000025081.9	79.7	109.9	1.4	1.0
<i>Tdrd6</i>	ENSMUSG00000040140.10	473.1	473.7	1.0	1.0
<i>UAP56/Ddx39b</i>	ENSMUSG00000019432.11	42.4	54.3	1.3	1.0
<i>PLD6</i>	ENSMUSG00000043648.7	90.7	110.3	1.2	1.0
<i>Papi/Tdrkh</i>	ENSMUSG00000041912.8	14.8	17.6	1.2	1.0
<i>Tdrd12</i>	ENSMUSG00000030491.12	62.5	78.4	1.3	1.0
<i>Ddx4</i>	ENSMUSG00000021758.9	216.5	190.6	0.9	1.0
<i>Piwi4</i>	ENSMUSG00000036912.13	0.0	0.0	1.0	1.0
<i>Mael</i>	ENSMUSG00000040629.4	673.1	637.9	0.9	1.0
<i>Rnf17</i>	ENSMUSG00000000365.8	36.4	48.7	1.3	1.0
<i>Henmt1</i>	ENSMUSG00000045662.12	40.7	45.4	1.1	1.0
<i>PNLDC1</i>	ENSMUSG00000073460.4	4.6	4.7	1.0	1.0

Secondary Spermatocyte

<i>Piwil1</i>	ENSMUSG00000029423.6	33.3	40.7	1.2	1.0
<i>Piwil2</i>	ENSMUSG00000033644.4	12.7	21.6	1.7	0.6
<i>Mov10l1</i>	ENSMUSG00000015365.11	10.2	15.0	1.5	1.0
<i>A-Myb</i>	ENSMUSG00000025912.12	30.6	34.5	1.1	1.0
<i>Tdrd1</i>	ENSMUSG00000025081.9	9.7	13.8	1.4	1.0
<i>Tdrd6</i>	ENSMUSG00000040140.10	444.0	489.6	1.1	1.0
<i>UAP56/Ddx39b</i>	ENSMUSG00000019432.11	14.3	17.0	1.2	1.0
<i>PLD6</i>	ENSMUSG00000043648.7	20.5	32.0	1.5	1.0
<i>Papi/Tdrkh</i>	ENSMUSG00000041912.8	5.5	5.1	0.9	1.0
<i>Tdrd12</i>	ENSMUSG00000030491.12	20.7	22.9	1.1	1.0
<i>Ddx4</i>	ENSMUSG00000021758.9	294.1	223.8	0.8	1.0
<i>Piwil4</i>	ENSMUSG00000036912.13	0.0	0.0	0.9	1.0
<i>Mael</i>	ENSMUSG00000040629.4	797.2	797.4	1.0	1.0
<i>Rnf17</i>	ENSMUSG00000000365.8	38.0	30.3	0.8	1.0
<i>Henmt1</i>	ENSMUSG00000045662.12	22.7	28.5	1.3	1.0
<i>PNLDC1</i>	ENSMUSG00000073460.4	1.9	1.6	0.9	1.0

Spermatid

<i>Piwil1</i>	ENSMUSG00000029423.6	14.2	21.0	1.5	0.7
<i>Piwil2</i>	ENSMUSG00000033644.4	7.8	12.2	1.5	0.7
<i>Mov10l1</i>	ENSMUSG00000015365.11	8.0	6.6	0.8	0.9
<i>A-Myb</i>	ENSMUSG00000025912.12	12.9	18.3	1.4	0.8
<i>Tdrd1</i>	ENSMUSG00000025081.9	14.8	16.7	1.1	1.0
<i>Tdrd6</i>	ENSMUSG00000040140.10	283.6	389.5	1.4	0.9
<i>UAP56/Ddx39b</i>	ENSMUSG00000019432.11	21.1	15.2	0.7	0.8
<i>PLD6</i>	ENSMUSG00000043648.7	24.0	15.8	0.7	0.7
<i>Papi/Tdrkh</i>	ENSMUSG00000041912.8	4.5	5.6	1.2	0.9
<i>Tdrd12</i>	ENSMUSG00000030491.12	14.8	16.7	1.1	1.0
<i>Ddx4</i>	ENSMUSG00000021758.9	34.1	60.6	1.8	0.6
<i>Piwil4</i>	ENSMUSG00000036912.13	0.0	0.0	1.0	1.0
<i>Mael</i>	ENSMUSG00000040629.4	997.0	728.6	0.7	0.8
<i>Rnf17</i>	ENSMUSG00000000365.8	35.1	26.7	0.8	0.8
<i>Henmt1</i>	ENSMUSG00000045662.12	28.1	17.9	0.6	0.7
<i>PNLDC1</i>	ENSMUSG00000073460.4	2.2	1.1	0.6	0.6

Table S4. Transcription factors with altered mRNA abundance in *pi6^{em1/em1}* pachytene spermatocytes.

Genes	Ensembl ID	C57BL/6 (fpkm)	<i>pi6^{em1/em1}</i> (fpkm)	$\frac{pi6^{em1/em1}}{C57BL/6}$	FDR
<i>Sohlh1</i>	ENSMUSG000000059625.6	0.6	10.4	9.9	2.2×10^{-2}
<i>Sall4</i>	ENSMUSG000000027547.13	0.6	9.3	8.7	4.3×10^{-3}
<i>Etv6</i>	ENSMUSG000000030199.12	1.4	14.2	7.7	3.8×10^{-2}
<i>Elf4</i>	ENSMUSG000000031103.8	0.3	5.3	7.0	1.6×10^{-2}
<i>Dmrt1</i>	ENSMUSG000000024837.11	3.8	29.4	7.0	4.3×10^{-3}
<i>Pbx2</i>	ENSMUSG000000034673.10	2.1	16.8	6.7	1.8×10^{-2}
<i>Lin28a</i>	ENSMUSG000000050966.5	0.9	7.6	5.6	1.6×10^{-2}
<i>Erg</i>	ENSMUSG000000040732.14	0.2	3.1	4.9	1.5×10^{-2}
<i>Ubtf</i>	ENSMUSG000000020923.13	2.7	15.0	4.9	1.3×10^{-2}
<i>Gli3</i>	ENSMUSG000000021318.11	1.1	7.2	4.8	3.9×10^{-2}
<i>Hif1a</i>	ENSMUSG000000021109.9	2.3	11.9	4.4	4.3×10^{-2}
<i>Usf1</i>	ENSMUSG000000026641.9	1.8	9.1	4.3	4.9×10^{-2}
<i>Tcf3</i>	ENSMUSG000000020167.10	4.5	20.3	4.2	1.1×10^{-2}
<i>Tcf12</i>	ENSMUSG000000032228.12	9.5	36.8	3.8	1.8×10^{-2}
<i>Sohlh2</i>	ENSMUSG000000027794.4	4.1	16.6	3.7	4.8×10^{-2}
<i>Zfp292</i>	ENSMUSG000000039967.10	2.2	8.9	3.5	7.0×10^{-3}
<i>Foxo1</i>	ENSMUSG000000044167.6	1.5	6.3	3.4	4.3×10^{-3}
<i>Mlxipl</i>	ENSMUSG000000005373.9	0.3	2.1	3.2	3.3×10^{-2}
<i>Jund</i>	ENSMUSG000000071076.5	4.3	14.4	3.1	2.6×10^{-2}
<i>Notch2</i>	ENSMUSG000000027878.10	3.4	8.3	2.2	3.6×10^{-2}
<i>Rfx2</i>	ENSMUSG000000024206.10	182.8	77.6	0.4	3.8×10^{-2}
<i>Hoxa4</i>	ENSMUSG000000000942.10	30.8	9.4	0.3	2.3×10^{-2}
<i>Foxj1</i>	ENSMUSG000000034227.7	15.4	4.9	0.3	1.6×10^{-2}

References

Goertz et al., 2011; Howard et al., 2014; Hough et al., 2014; Kistler et al., 2015; Lacorazza et al., 2006; McIntyre et al., 2013; Saleh et al., 2000; Sakashita et al., 2018; Selleri et al., 2004; Stauber et al., 2017; Suzuki et al., 2012; Thépot et al., 2000; Wang et al., 2011; Yamaguchi et al., 2015; Yu et al., 2008; Zhang et al., 2016; Zheng et al., 2009; Zhou et al., 2017

Table S5. Gene Ontology of genes with decreased expression in *pi6^{em1/em1}* pachytene spermatocytes.

GO Biological process	Mus musculus reference list (22,262 genes)	Number of genes	Expected enrichment	Observed enrichment	p-value	FDR
Cilium organization (GO:0044782)	292	27	4.54	5.95	7.46×10^{-13}	1.44×10^{-9}
Cilium assembly (GO:0060271)	261	25	4.06	6.16	2.66×10^{-12}	4.13×10^{-9}
Cell projection assembly (GO:0030031)	363	27	5.64	4.79	7.85×10^{-11}	8.68×10^{-8}
Plasma membrane bounded cell projection assembly (GO:0120031)	350	26	5.44	4.78	1.83×10^{-10}	1.89×10^{-7}
Axonemal dynein complex assembly (GO:0070286)	33	9	0.51	17.55	1.19×10^{-8}	1.08×10^{-5}
Axoneme assembly (GO:0035082)	65	11	1.01	10.89	2.17×10^{-8}	1.68×10^{-5}
Microtubule bundle formation (GO:0001578)	95	11	1.48	7.45	7.01×10^{-7}	4.17×10^{-4}
Cell projection organization (GO:0030030)	1059	36	16.46	2.19	1.97×10^{-5}	7.45×10^{-3}
Sperm motility (GO:0097722)	84	17	1.31	13.02	2.34×10^{-13}	6.03×10^{-10}
Flagellated sperm motility (GO:0030317)	80	15	1.24	12.06	1.60×10^{-11}	1.90×10^{-8}
Cilium movement (GO:0003341)	55	11	0.85	12.87	4.67×10^{-9}	4.52×10^{-6}
Cilium or flagellum-dependent cell motility (GO:0001539)	24	8	0.37	21.45	2.12×10^{-8}	1.73×10^{-5}
Cilium-dependent cell motility (GO:0060285)	24	8	0.37	21.45	2.12×10^{-8}	1.82×10^{-5}
Cilium movement involved in cell motility (GO:0060294)	12	5	0.19	26.81	4.34×10^{-6}	2.04×10^{-3}
Microtubule-based movement (GO:0007018)	240	15	3.73	4.02	1.00×10^{-5}	4.45×10^{-3}
Regulation of cilium movement (GO:0003352)	15	5	0.23	21.45	1.05×10^{-5}	4.50×10^{-3}
Regulation of microtubule-based movement (GO:0060632)	29	6	0.45	13.31	1.37×10^{-5}	5.60×10^{-3}
Fertilization (GO:0009566)	166	16	2.58	6.2	2.26×10^{-8}	1.67×10^{-5}
Single fertilization (GO:0007338)	123	12	1.91	6.28	1.17×10^{-6}	6.48×10^{-4}
Binding of sperm to zona pellucida (GO:0007339)	38	7	0.59	11.85	5.09×10^{-6}	2.32×10^{-3}
Sperm-egg recognition (GO:0035036)	43	7	0.67	10.47	1.05×10^{-5}	4.40×10^{-3}
Sperm capacitation (GO:0048240)	31	6	0.48	12.45	1.92×10^{-5}	7.42×10^{-3}
Sexual reproduction (GO:0019953)	806	49	12.53	3.91	1.53×10^{-15}	2.38×10^{-11}
Spermatogenesis (GO:0007283)	529	39	8.22	4.74	4.90×10^{-15}	2.53×10^{-11}

Multi-organism reproductive process (GO:0044703)	929	52	14.44	3.6	4.55×10^{-15}	3.52×10^{-11}
Male gamete generation (GO:0048232)	549	39	8.53	4.57	1.51×10^{-14}	5.84×10^{-11}
Multicellular organismal reproductive process (GO:0048609)	786	45	12.22	3.68	1.84×10^{-13}	5.70×10^{-10}
Multicellular organism reproduction (GO:0032504)	798	45	12.4	3.63	3.03×10^{-13}	6.71×10^{-10}
Gamete generation (GO:0007276)	664	40	10.32	3.88	1.01×10^{-12}	1.74×10^{-9}
Reproduction (GO:0000003)	1334	57	20.73	2.75	9.11×10^{-12}	1.18×10^{-8}
Reproductive process (GO:0022414)	1333	57	20.72	2.75	8.86×10^{-12}	1.25×10^{-8}
Spermatid differentiation (GO:0048515)	217	18	3.37	5.34	2.58×10^{-8}	1.82×10^{-5}
Spermatid development (GO:0007286)	209	17	3.25	5.23	8.23×10^{-8}	5.31×10^{-5}
Germ cell development (GO:0007281)	313	17	4.86	3.49	1.49×10^{-5}	5.91×10^{-3}
Organelle assembly (GO:0070925)	620	28	9.64	2.91	9.23×10^{-7}	5.30×10^{-4}
Microtubule-based process (GO:0007017)	628	27	9.76	2.77	3.51×10^{-6}	1.70×10^{-3}

Table S6. Genes with reduced expression in *pi6^{em1/em1}* pachytene spermatocytes that are mapped to major Gene Ontology categories.

Gene	Cilium assembly	Sperm motility	Fertilization
<i>Acr</i>			+
<i>Adam3</i>		+	+
<i>Arl3</i>	+	+	
<i>Arsa</i>			+
<i>Cabyr</i>			+
<i>Cast</i>			+
<i>Catsper1</i>		+	+
<i>Catsper3</i>		+	+
<i>Ccdc40</i>	+	+	
<i>Ccdc63</i>	+	+	
<i>Ccdc65</i>	+	+	
<i>Ccdc113</i>	+		
<i>Cdh13</i>	+		
<i>Dkk1</i>			+
<i>Dnaaf1</i>	+	+	
<i>Dnah3</i>		+	
<i>Dnaic2</i>	+	+	
<i>Drc1</i>	+	+	
<i>Dzip1</i>	+		
<i>Efh1</i>	+		
<i>Fbp1</i>	+		
<i>Foxj1</i>	+		
<i>Gdpd5</i>	+		
<i>Hap1</i>	+	+	
<i>Hist1h1t</i>		+	+
<i>Ift74</i>	+	+	
<i>Insl6</i>		+	+
<i>Kif2b</i>		+	
<i>Lrrc6</i>	+	+	
<i>Lrrc46</i>	+		

<i>Lrrcc1</i>	+		
<i>Nphp1</i>	+		
<i>Nubp2</i>	+		
<i>Odf2</i>	+		
<i>Parvg</i>	+		
<i>Pbp2</i>			+
<i>Prkaca</i>			+
<i>Rfx2</i>	+		
<i>Rimbp3</i>			+
<i>Rsph1</i>	+		
<i>Slc9c1</i>		+	
<i>Slc22a16</i>		+	+
<i>Slc26a8</i>		+	+
<i>Spa17</i>			+
<i>Spata4</i>		+	
<i>Spag1</i>			+
<i>Spink2</i>			+
<i>Tcp10a</i>	+		
<i>Tcp10b</i>	+		
<i>Tcp10c</i>	+		
<i>Tcte1</i>		+	
<i>Tekt1</i>	+	+	
<i>Tekt2</i>	+	+	
<i>Tekt3</i>	+	+	
<i>Tekt4</i>	+	+	
<i>Tex40</i>		+	+
<i>Tprn</i>	+		
<i>Tsga10ip</i>	+		
<i>Ttll1</i>	+	+	
<i>Ubxn10</i>	+		
<i>Vdac2</i>			+
<i>Ybx3</i>			+
<i>Zpbp2</i>			+

Table S8. Published male fertility genes with altered expression in *pi6^{em1/em1}* cells.

Gene	ENSEMBL ID	Reference	C57BL/6 (fpkm)	<i>pi6^{em1/em1}</i> (fpkm)	<i>pi6^{em1/em1}</i> C57BL/6	FDR
<i>Adam3</i>	ENSMUSG00000031553.11	Yamaguchi et al., 2009	182.1	72.4	0.4	3×10^{-2}
<i>Catsper1</i>	ENSMUSG00000038498.3	Ren et al., 2009; Avenarius et al., 2009; Qi et al., 2007	15.1	3.0	0.2	9×10^{-3}
<i>Catsper3</i>	ENSMUSG00000021499.8	Qi et al., 2007	12.6	3.1	0.3	5×10^{-2}
<i>Ccdc40</i>	ENSMUSG00000039963.14	Antony et al., 2013; Becker-Heck et al., 2011	68.8	22.8	0.3	3×10^{-2}
<i>Ccdc42</i>	ENSMUSG00000045915.11	Pasek et al., 2016	58.3	18.0	0.3	3×10^{-2}
<i>Ccdc65</i>	ENSMUSG00000003354.5	Horani et al., 2013	121.7	39.0	0.3	4×10^{-3}
<i>Ccna1</i>	ENSMUSG00000027793.2	Liu et al., 1998	33.7	12.0	0.4	3×10^{-2}
<i>Dnaic2</i>	ENSMUSG00000034706.12	Guichard et al., 2001	18.4	4.2	0.2	7×10^{-3}
<i>Drc1</i>	ENSMUSG00000073102.3	Wirschell et al., 2013	39.1	11.2	0.3	1×10^{-2}
<i>Gga1</i>	ENSMUSG00000033128.8	International Mouse Phenotyping Consortium	49.8	18.7	0.4	2×10^{-2}
<i>Hnf1b</i>	ENSMUSG00000020679.7	Mieusset et al., 2017	4.6	1.0	0.3	5×10^{-2}
<i>Ift74</i>	ENSMUSG00000028576.8	San Agustin et al., 2015	68.2	24.0	0.4	2×10^{-2}
<i>Lrrcc1</i>	ENSMUSG00000027550.10	International Mouse Phenotyping Consortium	76.1	31.3	0.4	2×10^{-2}
<i>Meig1</i>	ENSMUSG00000026650.11	Zhang et al., 2009; Salzberg et al., 2010	953.3	329.8	0.3	9×10^{-3}
<i>Ppp3cc</i>	ENSMUSG00000022092.10	Miyata et al., 2015	89.0	39.5	0.4	3×10^{-2}
<i>Ppp3r2</i>	ENSMUSG00000028310.2	International Mouse Phenotyping Consortium	132.7	35.9	0.3	4×10^{-3}
<i>Prm1</i>	ENSMUSG00000022501.5	Haueter et al., 2010	126.4	308.2	2.4	5×10^{-2}
<i>Rfx2</i>	ENSMUSG00000024206.10	Kistler et al., 2015; Shawlot et al., 2015	182.8	77.6	0.4	4×10^{-2}
<i>Spink2</i>	ENSMUSG00000053030.7	International Mouse Phenotyping Consortium	391.6	146.7	0.4	7×10^{-3}
<i>Stk33</i>	ENSMUSG00000031027.11	Martins et al., 2018	180.4	62.6	0.3	2×10^{-2}
<i>Syce1</i>	ENSMUSG00000025480.4	Bolcun-Filas et al., 2009; Maor-Sagie et al., 2015	215.2	71.6	0.3	4×10^{-3}
<i>Tekt2</i>	ENSMUSG00000028845.11	Iguchi et al., 1999; Tanaka et al., 2004	85.5	23.3	0.3	2×10^{-2}
<i>Tekt3</i>	ENSMUSG00000042189.5	Roy et al., 2009	63.2	13.0	0.2	4×10^{-3}
<i>Tekt4</i>	ENSMUSG00000024175.1	Roy et al., 2007	51.7	15.7	0.3	7×10^{-3}
<i>Ttll1</i>	ENSMUSG00000022442.11	Vogel et al., 2010	22.0	7.3	0.3	3×10^{-2}

<i>Zbp2</i>	ENSMUSG000 00017195.11	Lin et al., 2007	133.8	43.2	0.3	1×10^{-2}
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