

On Matters Of Nature and Science

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Chapter 1

Introduction

As an entirely unexceptional man, here is my fittingly unexceptional glimpse into the universe as it was during my moment in time.

-L A Liggett

Chapter 2

Genetics and Genomics

2.1 Introduction

A haplotype block is a set of closely linked alleles or markers on a chromosome that tend to be inherited together over evolutionary time.

Across Eukaryotes, the frequency of recombination is inversely proportional to overall genome size. The result is that yeast have a recombination rate a few orders of magnitude higher than that of humans (She and Jarosz, 2018).

2.1.1 Subpoint

This is some sub info

2.1.2 Second subpoint

A haplotype block is a set of closely linked alleles or markers on a chromosome that tend to be inherited together over evolutionary time.

Across Eukaryotes, the frequency of recombination is inversely proportional to overall genome size. The result is that yeast have a recombination rate a few orders of magnitude higher than that of humans (She and Jarosz, 2018).

2.2 DNA Replication

When the origin of replication(s) is removed from bacteria or eukaryotes, growth and division is restricted or entirely eliminated, but in some strains of archaea like *H. volcanii*, deletion of the origin of replication accelerates cell growth rates. It turns out that this archaea can use a process that is similar to homologous recombination to create a replication fork and replicate its chromosome (Hawkins et al., 2013).

2.3 Mutation Rate

2.3.1 Observed Mutation Rates

Using whole-genome sequencing or next-gen sequencing to determine mutation rates by base, it appears that C>T mutations at CpG sites mutate at a frequency of 10^{-7} changes/cell division, and all other sites are within the range of $10^{-8} - 10^{-9}$ base changes per division (Arnheim and Calabrese, 2009, 2016; Campbell and Eichler, 2013; Ségurel et al., 2014; Kong et al. (2012); Ségurel et al. (2014)).

It appears that humans have the highest germline mutation rate of all analyzed species (Lynch, 2016). It also appears from trio sequencing that both human and chimp mutation rates are in the range of $1.0 - 1.25 \times 10^{-8}$ mutations per site per generation (Kong et al., 2012).

While germline mutation rates are similar in chimps and humans, there are important differences, one example being that CpG mutations are more prevalent in the chimp germline (Venn et al., 2014).

Possibly supporting the somatic theory of aging, increases and reductions in DNA damage rates may accelerate and decelerate, respectively, some aspects of aging (Behjati et al., 2014; Altieri et al., 2008).

2.3.2 Mutation Rate Evolution

Providing an example of how human mutation rates can differ by geographic origination, Europeans compared to African/Asian populations have a 1.6 increased mutation rate of a TCC->TTC transitions (Harris, 2015). This change in DNA replication fidelity appears to have happened 40-80kya when Europeans and Asians diverged and illustrates that DNA repair rates have not remained entirely stable throughout human evolution.

Just as in humans show a number of different mutational likelihoods, the great apes apes also show evolution in the rates of different triplet-context mutation rates (Harris and Pritchard, 2017). It would be interesting to investigate how these different rates have constrained evolution, if at all.

Killifish seem to exhibit an elevation in mutation rates, and exhibit chromosomal expansions and deleterious mutations especially in mitochondrial genes and nuclear genes important for late life. It seems that killifish show evidence of their lifespan being limited by many deleterious mutations of small effect-size in a manner that is compatible with neutral theory of evolution (Ohta and Kimura, 1973; Kimura et al., 1968). The overall idea is that when adapting to annual niches, killifish experienced intense selection on genes affecting traits important for early life, and a corresponding relaxation of selection on traits affecting later life in a manner compatible with neutral theory (Cui et al., 2019). It is important to note that the authors do not test for antagonistic pleiotropy, so this effect may be playing an important role in the development of detrimental aging-related mutations (Charlesworth and Charlesworth, 2000; Williams, 1957).

2.4 Mutation Hotspots

There are a number of sporadic mutation hotspots associated with disease incidence, like achondroplasia which has a sporadic incidence rate of 4.5×10^{-5} per generation (Arnheim and Calabrese, 2016; Waller et al., 2008). This disease originates from a single mutation in the FGFR3 gene at a mutation rate ~450 times higher than what would ordinarily be expected at a CpG site (Bellus et al., 1995; Rousseau et al., 1994; Shiang et al., 1994).

2.5 Mutation Detection

Pyrophosphorylation-activated polymerization is a mutation detection method that can detect a single mutant molecule of DNA within 25,000 genomes (Liu and Sommer, 2004; Qin et al., 2007).

Detecting cancer from cfDNA is often done by mutation detection alone, however, fragment size of the cfDNA seems to be non-randomly linked to malignant state. Using the ratio of short to long cfDNA fragments calculated for 5MB windows, combined with mutation detection within collected cfDNA seems to quite accurately predict cancerous state for a number of different solid cancers (Cristiano et al., 2019). It appears that in individuals without cancer, the majority of cfDNA originates from leukocytes, and is fragmented in a manner that is dependent on nucleosomal patterns. As solid tissue burden grows and the associated cells release cfDNA, the DNA fragments according to the solid tissue nucleosomal patterns, and this seems to be sufficiently distinct from the fragmentation patterns of leukocyte DNA.

2.6 Genetic Modifications

Caffeine was cloned to allow for caffeine-deficient coffee and teas without the decaffeination process (Kato et al., 2000).

When a DNA-associating protein from tardigrades was cloned into mammalian cells, they became about 40% more tolerant to radiation (Hashimoto et al., 2016).

2.7 Sequencing Methods

Using a new sequencing method called sci-RNA-seq, the transcriptome of every cell of 762 cells in C Elegans was sequenced to yield single-cell sequencing results and transcriptome profiling of every cell in the body. The way this is done is by methanol fixing nuclei and then incorporating a UMI when converting to cDNA, then mixing cells again and incorporating another UMI when synthesizing the other strand (Cao et al., 2017).

It appears that DAPI does not increase sequencing error rates by Illumina sequencing (Leung et al., 2016).

One group came up with a method that is essentially identical to mine in which they use barcoded probes to detect leukemia but they tracked the mutation manually and ignored background (Wong et al. 2015)

2.7.1 Lineage Tracing

Because mutation rates in mitochondrial DNA are higher than for genomic DNA, and they are heterogeneous, single cell ATAC-Seq of the mitochondrial can be effectively used alone or in combination with RNASeq for lineage tracing (Ludwig et al., 2019). This is an especially advantageous approach, as it requires no alterations to the organism of interest, allowing its application in humans.

2.8 Diagnostics

In Li and Snyder Cell 2018, the EHR from hospitals is used to integrate with a machine learning algorithm trained on aneurysm detection. Patients are then whole genome sequenced, and the genome sequencing plus the lifestyle of the individual on EHR is then used to predict if the person has an aneurysm. They were able to achieve pretty robust detection results that could then be used in a prediction setting in the clinic.

2.9 Detecting Common Diseases

Much of the following information comes from this review: (Shendure et al., 2019).

Linkage disequilibrium studies were designed to detect Mendelian diseases GWAS designed back in 1996 to detect non-mendelian multigenic traits that have much less penetrant effects The promise that GWAS could risk stratify people for diseases has been challenging because most diseases seem to be driven by an extremely large number of variants with small effects that will likely require extremely large sample sizes There exists a problem of missing heritability, and it was often believed that common SNPs only held part of the puzzle, and more rare variants accounted for a great deal of heritability, but this does not yet seem to be the case, and SNPs seem to have a much greater effect size Another problem with GWAS is it is haplotype specific in that it can implicate a stretch of DNA inherited from one parent, but is blind to the individual effect sizes of each of the individual variants A challenge raised by Jonathan Pritchard is that gene regulatory networks are so interconnected that variants in one gene may actually cause changes in other genes and are therefore only peripherally relevant to a phenotype One continued promise of the utility of GWAS to identify the causal genetics behind diseases is that most of the strongest GWAS associations came from small studies of european populations that identified mutations of large effect sizes. By expanding studies to populations, especially those like african populations that have less linkage disequilibrium many more variants of large effect sizes could be identified and used to tease out relationships of smaller effect sizes in other populations. Methods are also improving fo linking regulatory elements to the genes they regulate like (Gasperini et al. 2018; Gasperini et al. 2019). Linking regulatory elements to their corresponding genes can be quite helpful, because this information can be incorporated into GWAS calculations to refine causal linkage probabilities. Polygenic risk scores have often been used to predict phenotypic variance in plants and animals, and have yet to really be applied to human genomics (Khera et al. 2018). Training of PRSs seem to not require fine-mapping, and their use has been aided by the UK Biobank (Bycroft et al. 2018).

2.10 Detecting Rare Diseases

There are some 7k Mendelian monogenic disorders that impact about 0.5% of live births, but contribute to about 70% of pediatric hospital admissions An important surprise has been that de-novo mutations account for a substantial amount of intellectual disabilities and autism, where as many as 30-60% of ASD is caused by de-novo mutations Currently as many as half of acutely ill inpatient infants can be diagnosed from WGS. There are currently 59 genes designated by the American College of Medical Genetics as being sufficiently clinically actionable as to warrant sequencing and reporting in patients (Kalia et al. 2017).

2.11 Tissue Evolution

By sequencing 7,664 tumors spanning 29 different cancer types, it appears that unlike species evolution, the force of positive selection in developing tumors outweighs that of negative selection as evidenced by the loss of less than 1 coding nucleotide substitution per tumor (Martincorena et al., 2017). The number of mutations per cancer varied from 1 per thyroid and testicle cancer to over 10 per endometrial and colorectal cancers. This information helps to answer how many mutations are needed to effectively create cancers and how this can vary with across tissue types. A number of groups have tried to answer these questions in the past by mathematically estimating the number of rate limiting steps required in the process of oncogenesis (Armitage and Doll, 1954; Tomasetti and Vogelstein, 2015). There are two important problems with this approach, first that not all driver mutations need to be rate-limiting (Yates et al., 2015), and not all rate limiting steps in oncogenesis need to be driver mutations (Martincorena et al., 2015). It has also been problematic to sequence tumors and count the number of high frequency mutations in oncogenic genes, but this has the added challenges of distinguishing passenger from driver mutations and is limited to current lists of oncogenes. Lists of genes involved in cancer have become increasingly detailed, but are still limited (Lawrence et al., 2014; Kandoth et al., 2013). The absence of negative selection in cancer may well indicate how dispensable the majority of genes are for somatic cells.

In their paper, Martincorena and Campbell show that the dN/dS ratio for somatic tissues and cancer tissue is 1 or greater showing that the effect of negative selection is minimal. In contrast, the dN/dS for germline

species evolution is less than 0.5 showing a much greater effect of negative selection. Surprisingly, the non-synonymous mutations showed a dN/dS ration of 1 whether they existed in haploid or diploid regions suggesting the cells were not simply tolerating the mutations by having two copies.

Using sequencing of blood to find spontaneous mutations and go back and use population biology to calculate the number of HSCs, it was found that there were between 50k-200k HSCs contributing to hematopoiesis at any given time (Lee-Six et al., 2018).

Using a method they developed called RNA-MuTect, mutations from RNA are found and matched with germline DNA. Using samples within TCGA that had DNA and RNA extractions from the same individual from multiple tissues, RNA-MuTect identifies multiple putatively oncogenic mutations from across otherwise normal tissues (Yizhak et al., 2019). The numbers of detected oncogenic mutations was dependent upon tissue exposure to mutagens, proliferation rate, and tissue architecture.

2.12 Mutational Processes in Cancer

Most cancers carry between 1,000 and 20,000 somatic point mutations and a few hundred insertions, deletions, and rearrangements (Martincorena and Campbell, 2015). Leukemias and pediatric brain cancers typically contain the lowest numbers of mutations while those tissues exposed to mutagens like lung and skin cancers tend to have the highest numbers (Stephens et al., 2009; Alexandrov et al., 2013; Lawrence et al., 2013; Vogelstein et al., 2013). It is interesting to note that from the Cancer Gene Census database, it appears that only three genes; TP53, PIK3CA, and BRAF are mutated in 10% or more patients (Martincorena and Campbell, 2015).

Carcinogens or particular mutations often cause identifiable mutational patterns. BRCA1 and BRCA2 mutations commonly associated with breast, ovarian, and pancreatic cancers are associated with particular substitution patterns, small indels, and large chromosome duplications (Nik-Zainal et al., 2012).

While mutations in TP53 and NOTCH1 can cause an imbalance in the division symmetry of stem cells in intestinal crypts by increasing the ratio of proliferation to differentiation(Klein et al., 2010; Alcolea et al., 2014), mutations like APC and KRAS can increase the rates of crypt fission to allow multiple crypts to become clonal (Preston et al., 2003; Snippert et al., 2014).

2.13 Mutagenesis in Cancer

2.13.1 Mutation Rates

Substitution rates in B/T lymphocytes appears to be on the order of 2 to 10 mutations per diploid genome per cell division, a rate which may be about 10 times higher than that occurring in germ cells (Lynch, 2010).

2.13.2 Mutation Load

Sun exposed skin cells can carry thousands of point mutations, and about 25-30% of these cells have acquired at least one driver mutation, and yet, while positive selection is evident as the clones expand, clone sizes are relatively similar across individuals suggesting that some mechanism is constraining the expansion of driver clones (Martincorena and Campbell, 2015).

The progression of Barrett's esophagus to esophageal adenocarcinoma shows no significant increase in mutation load. This may mean that Barrett's esophagus is an advanced precancerous lesion, but some other step in the tissue is required for it to transition into such a stage (Gusev et al., 2014).

2.14 Genetic Manipulation

2.14.1 Cloning

A macaque was the first primate to be cloned by SCNT (Liu et al., 2018).

2.14.2 Gene Therapy

X-linked severe combined immunodeficiency (SCID-X1) (commonly referred to as bubble-boy disease) is caused by mutations within the IL2RG gene which impairs the receptor for IL-2, IL-4, IL-7, IL-9, IL-15 and IL-21. The result of these mutations is that T and NK cells fail to develop. This disease is often treated with bone marrow transplant which involves irradiation. Instead of such a treatment, low-dose busulfan has been used in combination with WT IL2TG DNA carrying lentivirus to give HSCs a functional copy of the receptor. This treatment seems to allow T and NK cells to develop with minimal harm to the patient (Mamcarz et al., 2019).

The use of CRISPR technology to edit RNA may have significant therapeutic potential gene expression could be transiently controlled. One concern of RNA editing is that the CRISPR system would likely have to be activated in a human the entire time an effect is desired. This long-term CRISPR activation would likely cause an immune response against the bacterial Cas protein. Rauch et al developed a largely humanized Cas protein using human proteins which may significantly reduce the immunogenic potential (Rauch et al., 2019).

2.14.3 Genetic Rescue

Inbreeding of a population can result in an accumulation of deleterious mutations. The accompanying loss in fitness can be mitigated through outbreeding, as it can increase heterozygosity and thereby mask recessive deleterious alleles (Keller and Waller, 2002; Ingvarsson, 2001; Vila et al., 2003). This effect depends on the principle of overdominance or heterozygous vigour, which is a condition where a heterozygous offspring has a higher fitness than either of the parents.

Using a modeling approach, it appears that genetic rescue of a species will result in a substantial loss of the original genes of an organism. According to the models, the degree of genetic replacement of additive genes will proportionally match the genetic rescue, while the replacement of recessive genes may not need to occur as much as they will be masked by the foreign alleles (Harris et al., 2019). One caveat to this, is that even if a large fraction of the genome in the inbred organism is recessive, it is likely that a substantial portion of it must be lost to restore fitness, as it is more likely that most of the recessive mutations contribute to the reduction in fitness, each with a small fitness effect, rather than only a handful of the mutations contributing with a large fitness effect.

2.14.4 Mitochondria

While the mechanism appears to still be unclear (Chen, 2013), mtDNA can undergo recombination, direct evidence of which was first found in an individual that was heterologous for paternal and maternal inheritance of mitochondria (Kraytsberg et al., 2004).

2.14.5 Evolution

In the codfish, it appears that the one of the genes they use to allow them to freeze without damaging cells did not evolve from the duplication of a different gene that was then altered to produce its current function, but rather, it appears to have evolved from a non-functional portion of the genome (Baalsrud et al., 2017).

This constitutes some of the first evidence that genes can result from the de-novo use of junk DNA to create an entirely novel gene, rather than repurposing another gene.

Chapter 3

Neuroscience

3.1 Alzheimer's Disease

It seems that the bacteria *Porphyromonas gingivalis* may be partially responsible for exacerbating symptoms in people with AD. Observation of the bacteria in the brains of people with AD showed evidence that the bacteria secreted proteases called gingipains that increased A_β production and were also neurotoxic. Inhibition of the proteases reduced neuroinflammation and rescued neurons in the hippocampus (Dominy et al., 2019).

Tied both to sleep and AD, it appears that chronic sleep deprivation increases the formation of A_β plaques, perhaps suggesting that sleep is protective against the formation of the plaques that eventually lead to AD (Holth et al., 2019).

3.2 Parkinson's Disease

Early onset PD is associated with mutations in PINK1 kinase and PRKN ubiquitin ligase. Inactivating mutations within these genes cause nearly 100% penetrance of PD in humans, but had not previously shown the same penetrance in mice. It turns out that exposure to gram-negative bacteria causes antigen presentation of mitochondrial proteins in the mutant mice, resulting in the brain infiltration of CD8 cells which target these mitochondrial antigens. These CD8 T cells in the brain kill dopaminergic neurons and result in PD symptoms. It therefore appears that PD incidence is the result of infection (Matheoud et al., 2019).

3.3 Sleep

Sleep deprivation results in the global phosphorylation of the brain proteome, an effect which is reversed by sleep. A mouse mutant for SIK3 causes mice to sleep more, and may play an important role in the cause of sleep desire (Wang et al., 2018).

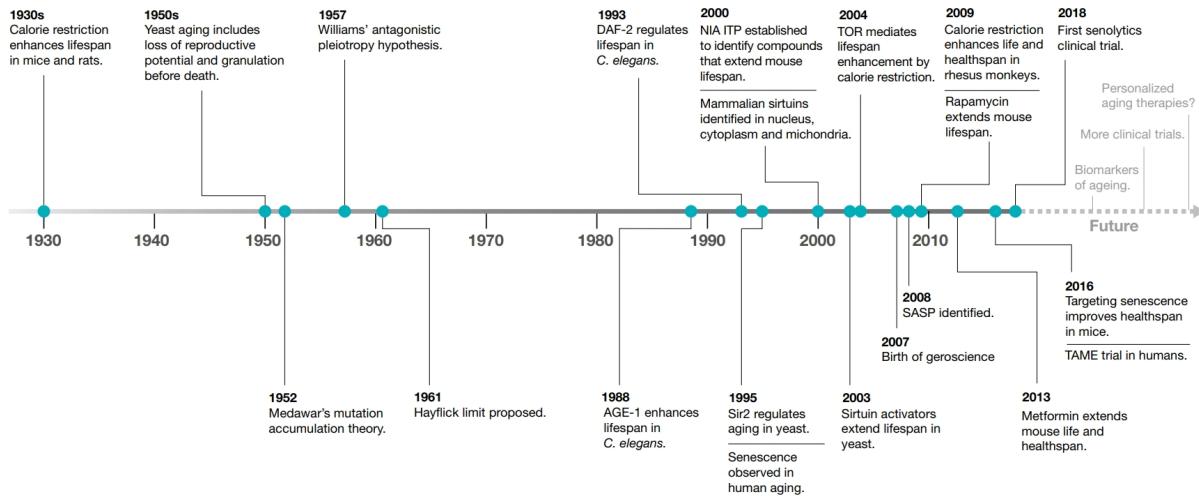
Chapter 4

Aging

4.1 Introduction

Below is a nice timeline of some major milestones in aging research (Campisi et al., 2019).

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4.2 Somatic Mutation Theory

In their study covering 7,664 tumors, Martincorena and Campbell illustrate an almost complete absence of negative selection against somatic mutations (Martincorena et al., 2017). This lack of negative selection is quite different from the force at the population level where it acts quite strongly on the germline. This result may be an important finding for the somatic theory of aging (Morley, 1995), as it may be an indication that point mutations are largely of negligible effect size within somatic cells. As such, if point mutations do play a role in aging, it seems that this may be limited to those that are neutral or advantageous to a cell.

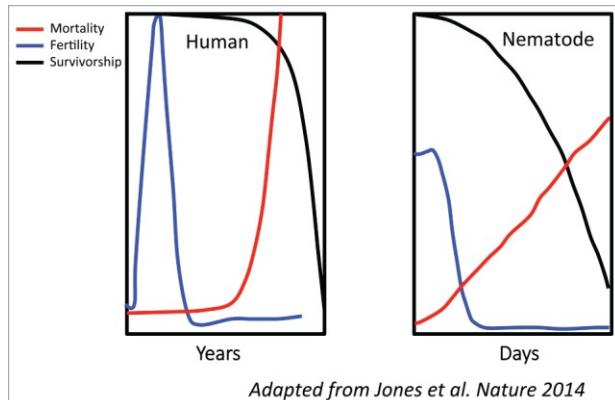
4.3 Calorie Restriction

1939 was the first time that calorie restriction was shown in mice and rates to increase lifespan (McCay et al., 1935). This effect of longevity has also been reproduced in primates (Pifferi et al., 2018; Mattison et al., 2017).

4.4 Genetics of Aging

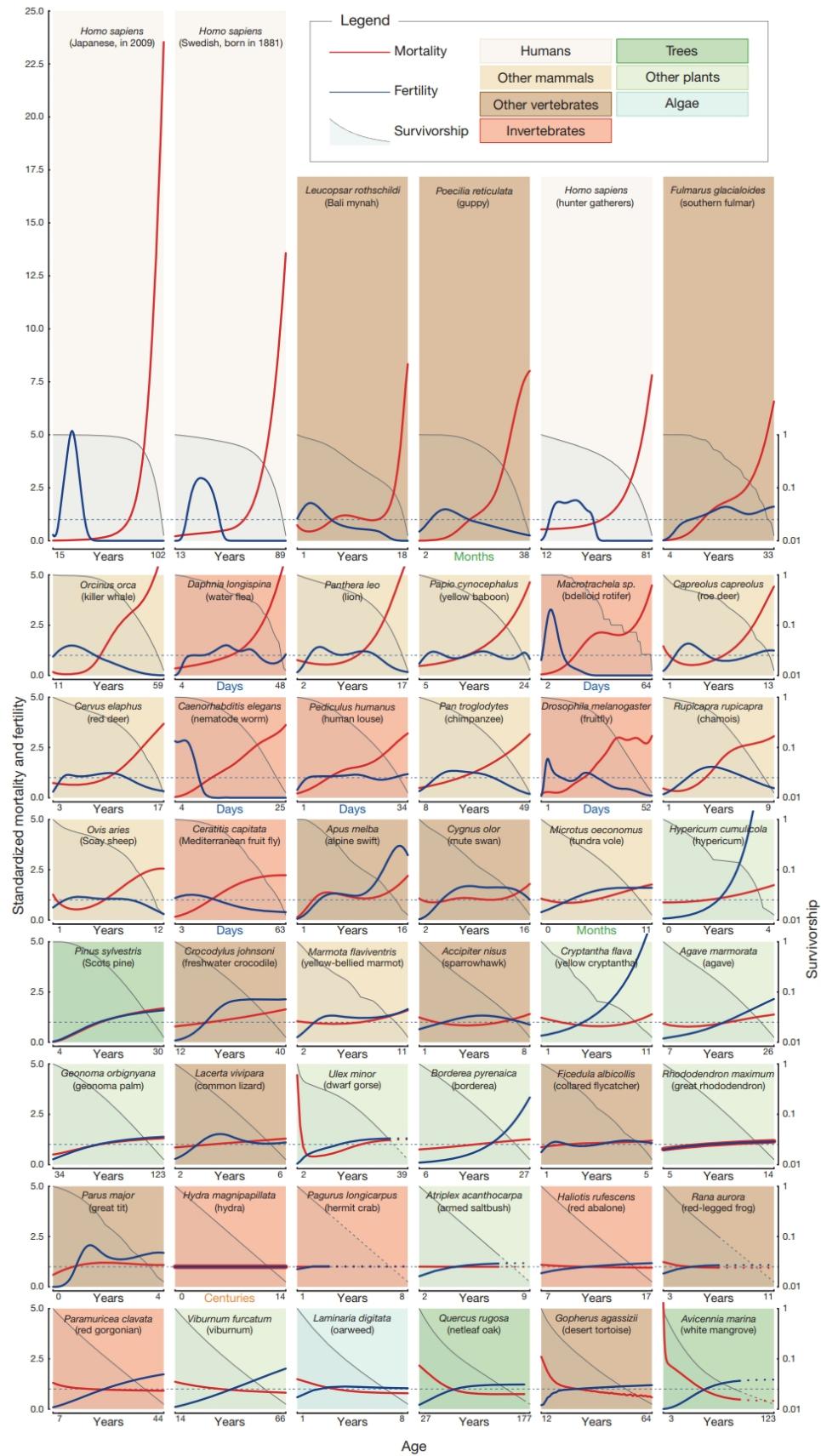
Peter Medawar proposed in 1952 that aging is the result of a reduction in the force of natural selection for a species after its reproductive years (Medawar, 1952). In part this theory seems a bit obvious as at its core it really seems to state that organisms evolve to their niches. Furthermore, it may seem a bit simplified to me as organisms appear to have significantly different fertility loss and survivorship relationships. In the following figure the fertility rates in humans and *C. elegans* appear to be rather similar, but their mortality curves appear to be strikingly different (Aguilaniu, 2015).

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Here is a more comprehensive understanding of the relationship between fertility and mortality (Jones et al., 2014). The diversity in the following figure makes me inclined to wonder if Medawar was fundamentally flawed in assumption that fertility rates decrease as a function of age and it and other losses in functionality are the result of a systemic relaxation in the forces of selection with the age of an organism.

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In part, motivated by the theories begun by Medawar, selection experiments were performed in *Drosophila* to select for late breeding, and this yielded a nearly two-fold increase in maximum lifespan (Rose and Charlesworth, 1980). In part, this illustrates that lifespan can be significantly dependent on genetics and or epigenetics. At least 800 genes have been directly implicated in lifespan regulation in *C. elegans* (though in light of Jonathan Pritchard's work, I can only imagine this number will continue to climb until it reaches the total gene count in each organism), and these genes can be found here.

Supercentenarians and the oldest populations concentrate nicely within areas that have no birth certificates and a shorter mean lifespan than the general country (Newman, 2019). Examples of this trend are Okinawa, Sardinia, and Ikaria. It may be possible that part of the reason for the substantial increase in maximum lifespan is due to fraud especially as people that get payments from the government like social security can be useful to people that just claim to be an elderly person that has died.

4.5 Aging Pathways and Processes

In 1993 a *C. elegans* mutation in *daf-2* which is orthologous to mammalian genes for insulin and insulin-like growth factor was found to nearly double the lifespan of the organism (Kenyon et al., 1993).

Target of rapamycin (TOR) proteins have important metabolic effects that also impact maximum lifespan. A common evolutionary hypothesis for the general role of TOR in modulation of maximum lifespan is that it shifts metabolic investment from reproduction and growth into somatic maintenance, and that this switch increases the longevity of an organism (Kapahi et al., 2010).

In 1995 Brian Kennedy identified the epigenetic silencing factors, sirtuins (Sir) in yeast (Kennedy et al., 1995). Sir2 is a protein deacetylase that depends on the coenzyme nicotinamide adenine dinucleotide (NAD⁺) (Imai et al., 2000). On the basis that NAD⁺ levels increase during conditions that are typically associated with longevity such as exercise, fasting, and dietary restriction, it is commonly suggested that NAD⁺ supplementation may increase lifespan (though this idea seems a bit simple to me) (Mouchiroud et al., 2013).

Chapter 5

Cell Competition

5.1 Introduction

One of the first examples of cell competition was the discovery of Minutes heterozygous cells ($M^{+/-}$) in 1975 (Morata Dev Bio 1975 and Gogna Ann Rev Gen 2015). This along with Myc and Wnt mediated cell competition provide a good understanding of what it takes for certain cells to survive instead of their peers, but recent deep sequencing has revealed that alone, the Minutes mechanism may not always be sufficient to understand cell competition.

5.2 Trophic Theory

Phenotypically, Drosophila with $M^{+/-}$ showed a reduced growth rate, but eventually reached full size with no noticeable defects. If $M^{+/-}$ were induced early during development, they were subsequently lost, and only retained into adulthood if they were induced late in development (Simpson Dev Bio 1979). Moreover, the number of WT or $M^{+/-}$ that were recovered at any given point were as would be predicted by just the difference in growth rates alone. 25 years later, this process of elimination was found to be apoptosis dependent, and driven by reduced Decapentaplegic (Dpp) pathway activation in $M^{+/-}$ cells (Moreno Nature 2002) (The Dpp morphogen is ortholog of the vertebrate Bone Morphogenetic Protein (BMP) and is necessary for patterning of the 15 imaginal discs in Drosophila). These experiments demonstrated how the Minutes gene switches between a ‘winner’ and a ‘loser’ phenotype. In the resultant ‘ligand capture model’, WT cells can outcompete Minutes cells because they can bind up the prosurvival trophic factor Dpp, while depriving the Minutes cells of this signal, leading to their apoptosis.

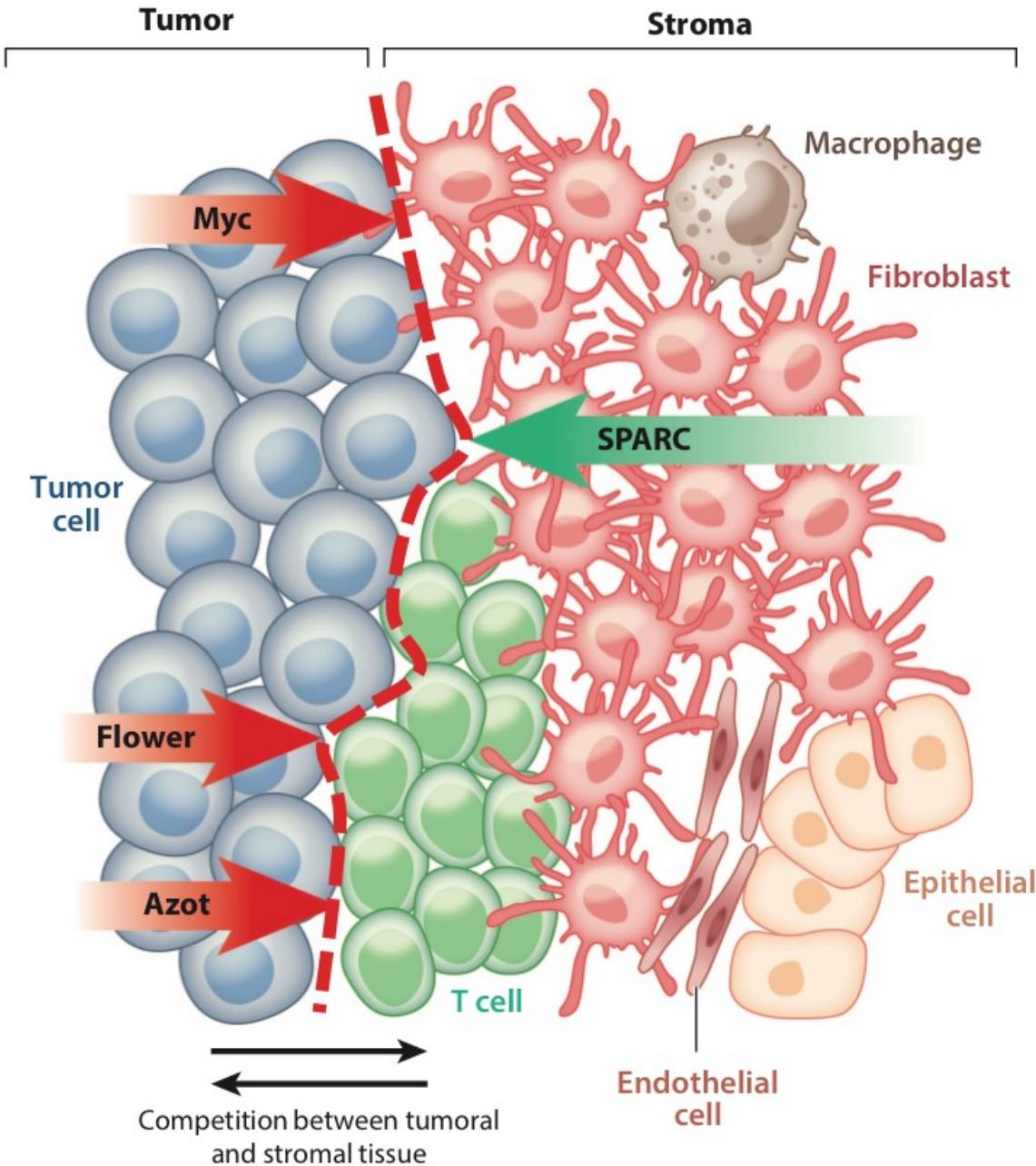
This idea of supercompetitors has been demonstrated with the proto-oncogene Myc in Drosophila. When Myc is overexpressed in developing Drosophila the Myc overexpressing cells grow rapidly and cause the elimination of surrounding WT cells through induction of apoptosis, as seen in the outcompetition of the Minutes cells (de la Cova C Cell 2004 and Moreno Cell 2008). The idea of supercompetitors is that the particular mutation carried by a cell confers on it some significant advantage over its peers, yet when Myc is downregulated, cells are at a disadvantage and are lost (Johnston Cell 1999). It appears that population levels of Myc regulate the fitness of a cell such that a cell must have more Myc than its peers to have an advantage, and the number of copies of Myc a cell has over its peers determines the magnitude of its advantage (Moreno Cell 2004).

People have continued to explore the ‘trophic theory’ of cell competition, finding other supporting evidence in the Wingless (Wg, Wnt ortholog) pathway. Just as Minute cells and Myc overexpressing cells do, Wg overexpressing cells in Drosophila induce JNK mediated apoptosis (Vincent Dev Cell 2011) in peers as a means of outcompeting them (Giraldez Development 2003).

5.3 Modern Theory

Secreted protein acidic and rich in cysteine (SPARC, osteonectin) is often expressed by loser cells (Portela Drosophila 2010), and as a secreted protein that modulates cell-cell and cell-ECM interactions, it is induced during morphogenesis, injury remodeling, and development (Clark J Cell Biochem 2008) and during cancer progression (Bradshaw Int J Biochem Cell Bio 2012). SPARC is important for cell competition because it raises the threshold for caspase activation in loser cells, thereby protecting cells of otherwise reduced fitness (Portela Drosophila 2010). SPARC can be a biomarker of certain types of cancer (Chlenski Semin Cell Dev Bio 2010) and may play a significant role in competition regulation during oncogenesis (Yamada Med Mol Morph 2015). SPARC is often associated with a number of cancers including breast cancer (Witkiewicz Cancer Bio Ther 2010, Bergamaschi J Path 2008), melanoma (Fenouille Pigment Cell Melanoma Res 2011, Massi Human Path 1999), osteosarcoma (Dalla-Torre BMC Cancer 2006), glioblastoma (Rich Cancer Res 2005), and bladder cancer (Yamanaka J Urol 2001). SPARC expression in surrounding stromal cells is indicative of a better prognosis in NSCLC (Koukourakis Cancer Res 2003), colon cancer (Lian J Mol Cell Card 2003), and pancreatic adenocarcinoma (Mantoni Cancer Bio Ther 2008).

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Flower is a putative transmembrane protein that has three isoforms, two are losers and one is a winner in Drosophila growing disc epithelium (Rhiner Drosophila Dev Cell 2010). RNAi against the losers is sufficient to make a cell a winner and vice versa for flower expressing cells in Drosophila epithelium. When DMBA-TPA is used to promote papilloma formation in mice, loser flower isotypes are expressed by surrounding stromal cells, while winner flower isotypes are expressed by the papilloma, suggesting that this mechanism is conserved from flies to vertebrates (Petrova Dis Models Mech 2012).

Azot is an intracellular protein that integrates the information from flower and SPARC both from the same cell and from surrounding cells and decide if its cell should apoptose (Petrova et al., 2011). If cells have low

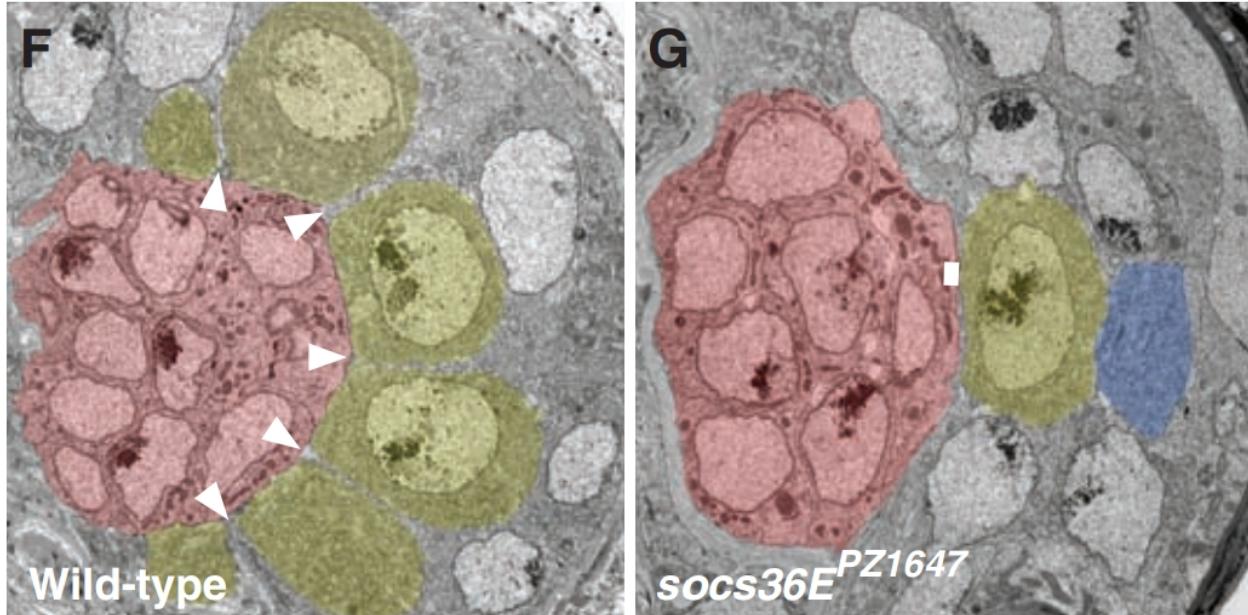
expression levels of loser flower isoform or high SPARC, or surrounding cells have higher expression levels of loser flower, azot is not transcribed and the cell will survive (Merino et al., 2015).

It might be possible that while tumor cells are growing and expanding, they express fitness impacting genes like flower, Azot, and Myc, which gives them a competitive advantage over surrounding stromal cells.

5.4 Localization

In the Drosophila gonad, both germline stem cells (GSCs) and somatic stem cells (cyst progenitor cells, CPCs) share a niche created by stromal cells that make up the hub and both share a requirement for JAK-STAT signaling to maintain their stemness. This system provides an understanding for how a single niche with multiple cell types is not overrun by the one that cycles the most rapidly.

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In the Drosophila testis, suppressor of cytokine signaling (SOCS36E) which is a JAK-STAT antagonist is expressed at high levels in the hub and at low levels in the CPCs. The JAK-STAT signaling in part drives the expression of position specific PS-integrin which is used by both the GSCs and the CPCs to bind and localize to the hub. The image to the right shows in F how typically the GSCs (yellow) have a large surface area integrin mediated connection with the hub, while CPCs (gray) only make small integrin mediated connections. As shown in G, when SOCS36E is inhibited in the CPCs, JAK-STAT signaling is downregulated resulting in an upregulation of PS-integrin which then allows the CPCs to bind more readily to the hub. This increased surface area of association between the hub and the CPCs allows the CPCs to outcompete the GSCs for binding spots, and eventually results in loss of GPCs (Issigonis Science 2009). Aberrant JAK-STAT signaling which includes loss of SOCS expression in mammals(Bowman Oncogene 2000, Pontier J Cell Sci 2009, Leeman Expert Opin Biol Ther 2006), and may play a role in stem cell misregulation driven cancers (Reya Nature 2001).

Similar to mammals, germline stem cell transplants in Drosophila are more efficient if the original GSCs are first depleted, supporting a space-filling model of GSC-hub binding (Bhattacharya Eur J Imm 2008, Oatley

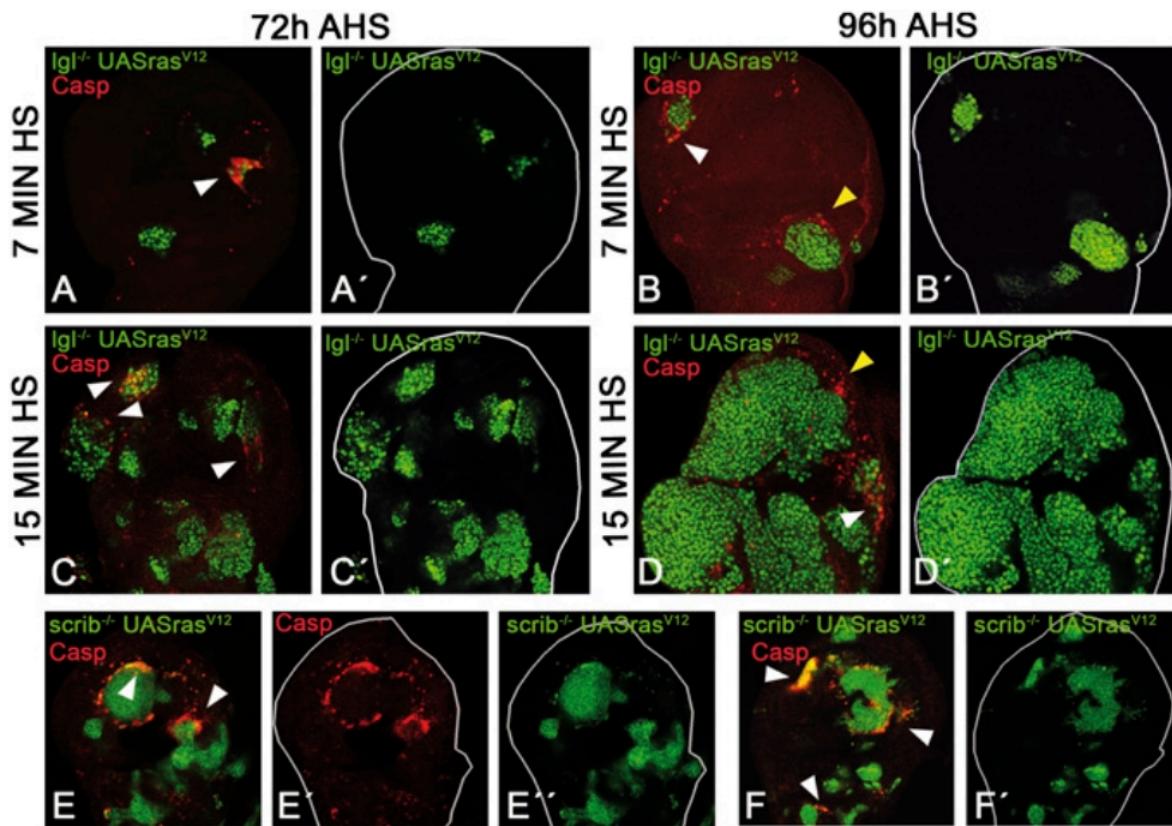
Ann Rev Cell Dev Bio 2008). Upon GSC loss, hub binding space is freed, which drives dedifferentiation of somatic stem cells that then fill the empty area adjacent to other GSCs (Sheng Cell Stem Cell 2009).

In the skin, collagen 17 (COL17A1), a component of the hemidesmosome, fluctuates in response to genomic and oxidative stress induced proteolysis. The stem cells that maintain high levels of COL17A1 are able to maintain contact with the niche and symmetrically divide, allowing them to outcompete neighbors that express low levels of COL17A1 as they will divide asymmetrically. With age it seems that all skin stem cells begin to lose their COL17A1 expression and eventually start to delaminate, and contributing to aging. Forced maintenance of COL17A1 however, seems to somewhat rescue skin aging (Liu et al., 2019).

5.5 Microenvironment

Lethal Giant Larvae (lgl) and scribble (scrib) are tumor suppressor genes in Drosophila that play necessary roles in establishing cell polarity and asymmetric cell divisions (Knoblich Cell 2008). Larvae that are constitutively mutant for lgl develop diffuse, ultimately lethal tumors, but clones of mutant cells surrounded by WT cells do not produce tumors (Froldi BMC Biol 2010, Igaki Dev Cell 2009).

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It appears that scrib mutant cells undergo JNK-driven apoptosis when surrounded by WT cells (Brumby EMBO 2003). This resembles minutes and Dpp cell competition (Moreno Nature 2002, Morata Dev Bio 1975). When lgl- cells are created using a heat shock method in Drosophila in order to affect only a small percentage of cells, the cells would still apoptose, and do so preferentially at the border of clones indicating a short-range apoptosis inducing mechanism originating from WT cells. Interestingly, when larvae were

heat shocked for different amounts of time, there was an exponential increase in surviving non-apoptosing lgl cells (figure) (Menéndez et al. 2010). The theory for why this occurs is that lgl- clones need to form a protective niche to survive, and merging clones can facilitate this. This may solve the riddle of how all oncogenic mutations could be present in a given tissue and not give rise to a cancer, it may be that a critical mass of oncogenically initiated cells is necessary before they can avoid WT cell outcompetition.

Chapter 6

Bioinformatics

6.1 Genome stuff

There are many instances of ‘NNN’ repeats within the human genome, because there are parts that are very challenging to sequence, including telomere and centromere regions. Lowercase letters in the genome specify things like repetitive sequences and introns. k-mers are fragments of DNA in the genome that are of a length k, so for the string ATGCA, the 2-mers are AT, TG, GC, and CA, and the 3-mers are ATG, TGC, and GCA k-mers can be useful for error correction because sequencing errors can bias towards producing k-mers, but they can also be used in alignment or in genome classification No free lunch theorem

6.2 Software

Google has designed a new variant caller called DeepVariant that uses deep neural networks to learn how best to call variants. This appears to provide a significant improvement to variant calling accuracy (Poplin et al., 2016).

A group put together well defined pipelines for common bioinfomatics analysis like RNASeq into bioconductor that can be easily used and then cited as a method of succinctly referring to the analysis process (<http://www.nature.com/authors/policies/license.html>).

A group came up with a deep machine learning algorithm that can be used to predict patient data and genomics patterns (Ching et al., 2017).

A group created a machine-learning algorithm for variant calling that seems to significantly outperform many common variant calling software like somatic sniper and mutect, though they do not compare against freebayes. Might be worth taking a look at (Wood et al., 2018)

Selene is a deep learning python library designed using PyTorch that is designed to ask questions using genomic and sequencing data (Chen et al., 2019). They also mention in their paper a number of other deep learning python libraries specifically designed to analyze genomics data, that may be worth checking out: DragoNN, pysster(Budach and Marsico, 2018), and Kipoi(Avsec et al., 2018).

Chapter 7

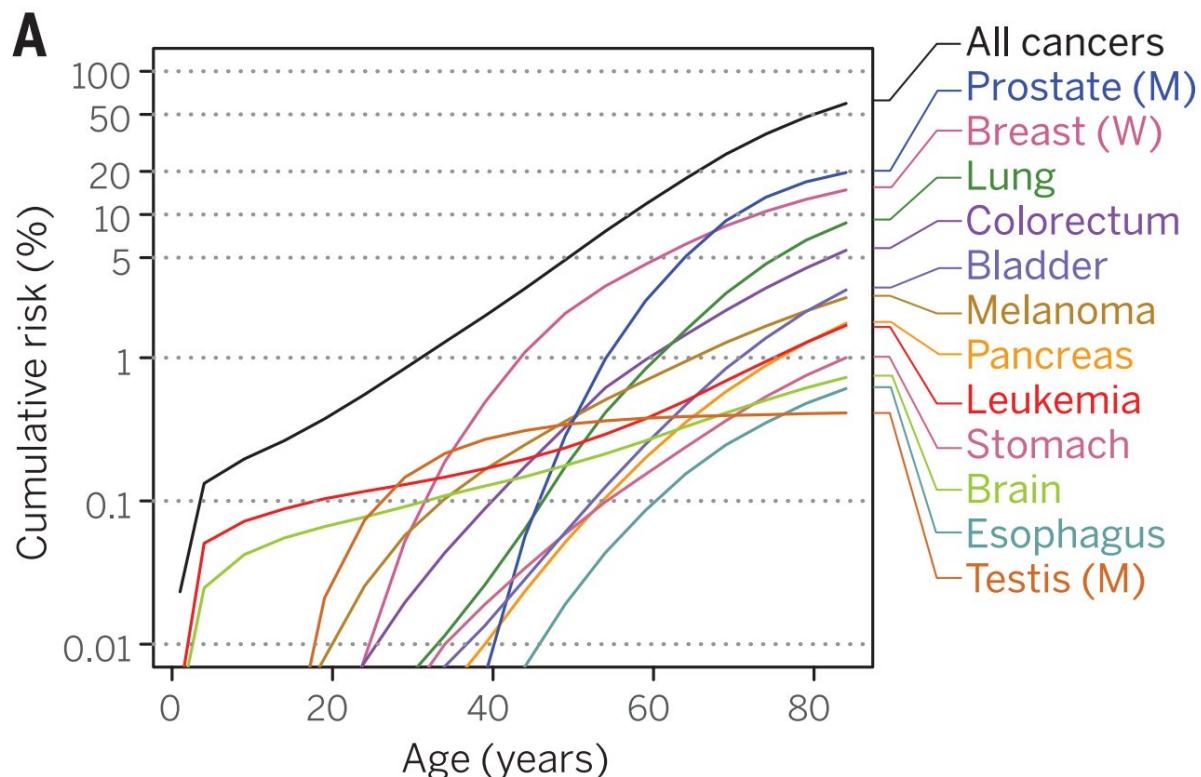
Cancer

7.1 Introduction

7.1.1 Incidence Rates

Time and age plays a major role in the occurrence of many cancers, where typically the risk of suffering most cancers is about 2% by the age of 40 in humans, while the risk increases to about 50% by the age of 80 (Martincorena and Campbell, 2015).

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7.2 Oncogenesis

Understanding the cell of origin for a cancer is difficult, but it appears that using ATAC-Seq to measure open chromatin regions within tumor cells can identify the hematopoietic cell of origin (George et al., 2016). This appears to be prognostically relevant as the more stemlike the cell of origin in AML, the worse the prognosis of the patient appears to be (Young and Trowbridge, 2016).

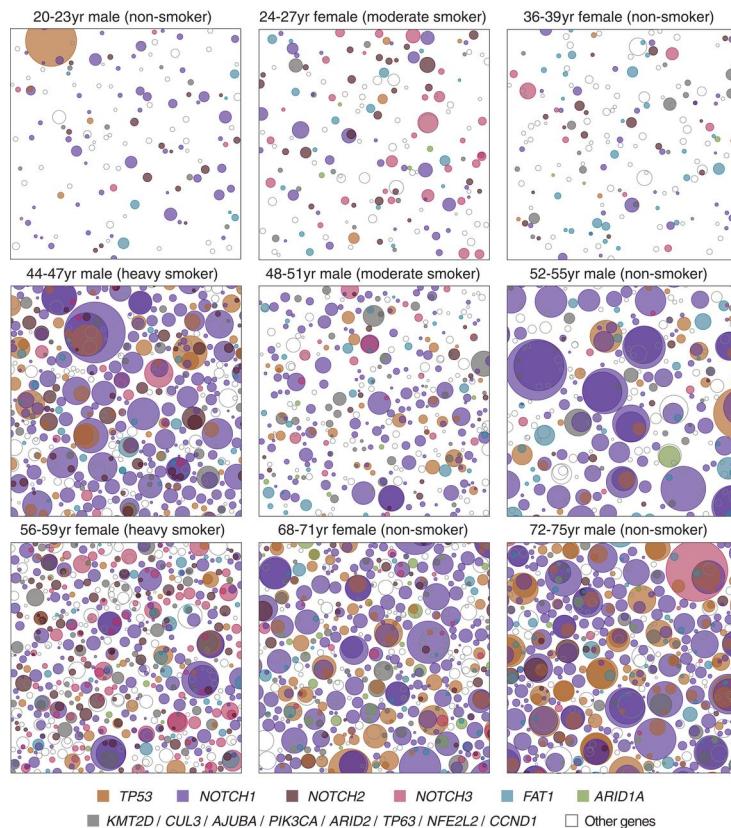
7.2.1 Mutation Order

While NPM1 and FLT3-ITD are commonly altered in AML, they appear to not be observed in CHIP, suggesting and consistent with other results that these changes occur late in the process of oncogenesis (McKerrell et al., 2015; Krönke et al., 2013; Abelson et al., 2018).

7.3 Aging Related Tissue Clonality

While the Martincorena group has shown that skin epithelium contains a significant number of cells that carry putatively oncogenic mutations, it is possible that this result may have been directly correlated with UV damage from sun exposure. Sequencing of esophageal endothelium revealed that NOTCH1 and TP53 mutations were widespread throughout the tissue (Yokoyama et al., 2019; Martincorena et al., 2018). The magnitude with which the tissue was covered by NOTCH1 mutated clones could be increased with chronic smoking and drinking. Furthermore, NOTCH1 mutant clones appeared to be less prevalent in esophageal cancers, and may be indicative of protective effects of the mutant clones.

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By classifying oncogenic mutations by the number of times they occurred in cosmic, and stratifying into low, intermediate, and high occurrence mutations, it appears that when more high risk mutations occur in CHIP, they are significantly predictive of progression to AML (Abelson et al., 2018).

Using a model that holds DFE constant of those mutations consistently observed in CHIP, a static mutation accumulation rate may be mathematically sufficient to explain CHIP incidence (Watson et al., 2019).

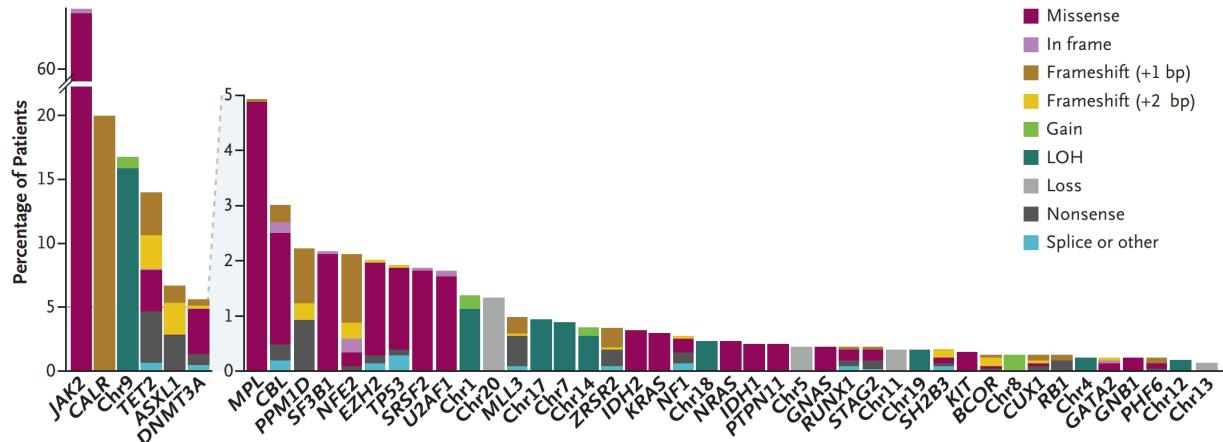
7.4 Myeloproliferative Neoplasms

7.4.1 Overview

The class of Myeloproliferative Neoplasms consists of a few different clonal hematopoietic disorders including polycythemia vera, which is characterized by red-cell overproduction; essential thrombocythemia, which involves elevated platelet counts; and myelofibrosis, which is defined by bone marrow fibrosis (Grinfeld et al., 2018). The myelofibrosis MPN subtype can follow and accompany the other subtypes. Myelofibrosis can also appear not in combination with the other two subtypes; termed secondary myelofibrosis (SMF) (Mesa et al., 2012). Using clinical and laboratory features, the three subtypes of MPN can be distinguished but the division of the three can often be quite unclear (Wilkins et al., 2008; Tefferi et al., 2014). The major driver mutations in MPNs are JAK2, CALR, and MPL, and are largely mutually exclusive, though other accompanying mutations are common (Tefferi and Pardanani, 2015). Diagnosis is currently performed using bone marrow morphology especially in distinguishing ET from prefibrotic PMF.

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A Recurrently Mutated Genes and Chromosomal Abnormalities



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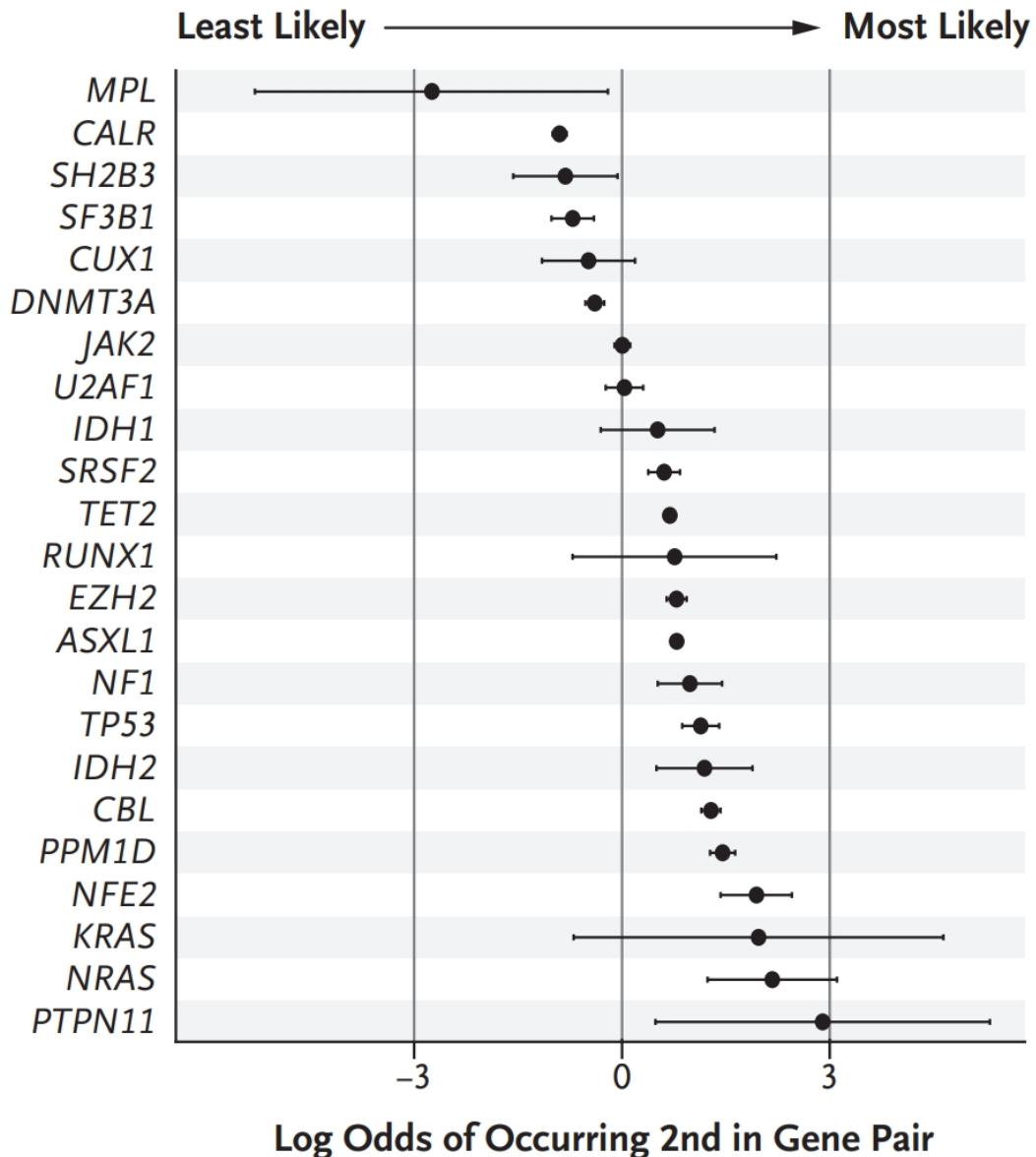
(Grinfeld et al., 2018)

In the above figure, the LOH occurring at chr9p JAK2 V617F homozygosity, or a high JAK2 V617F allele burden correlated with polycythemia vera.

While the identities of driver mutations can predict disease phenotype and prognosis (Vannucchi et al., 2013; Tefferi et al., 2016; Yogarajah and Tefferi, 2017) especially when accompanied by mutation order, it is unclear how the complex genetic landscape of MPNs contributes to the varied diagnostic features of the disease. SF3B1 and DNMT3a mutations commonly drive MPNs; as these appear to drive clonal hematopoiesis it may be possible that some MPNs are arising from asymptomatic clones that have come to dominate the hematopoietic system in a similar manner to CHIP.

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E Log Odds of Gene Occurring 2nd in Gene Pair



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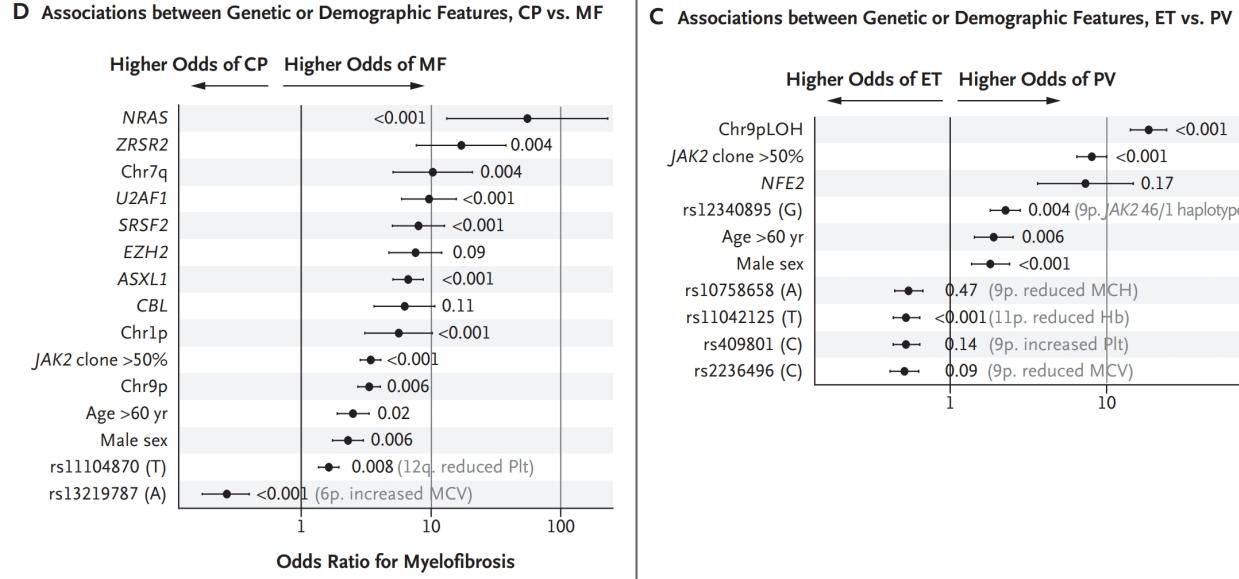
(Grinfeld et al., 2018)

It is interesting to note that the mutation order can influence the type of MPN (Ortmann et al., 2015; Nangalia et al., 2015). When JAK2 is the first mutation, it tends to produce PV, but when TET2 is the initiating mutation, it tends to produce ET (Ortmann et al., 2015). MPNs that begin with JAK2 mutations also appear to be more sensitive to the JAK2 inhibitor Ruxolitinib.

The concept of genetic canalization or functional buffering is one that describes the consequences of an early mutation, and how it influences the range of future compatible mutations (Ashworth et al., 2011; Hartman et al., 2001). Some mutations however, have been observed to occur both early and late during tumor

progression, perhaps suggesting that the final properties of a tumor are more reflective of the sum of the mutation effects rather than the evolutionary path taken. As an example, in NPM, when TET2 is mutated first, it appears to alter the transcriptional consequences of a subsequent JAK2 mutation.

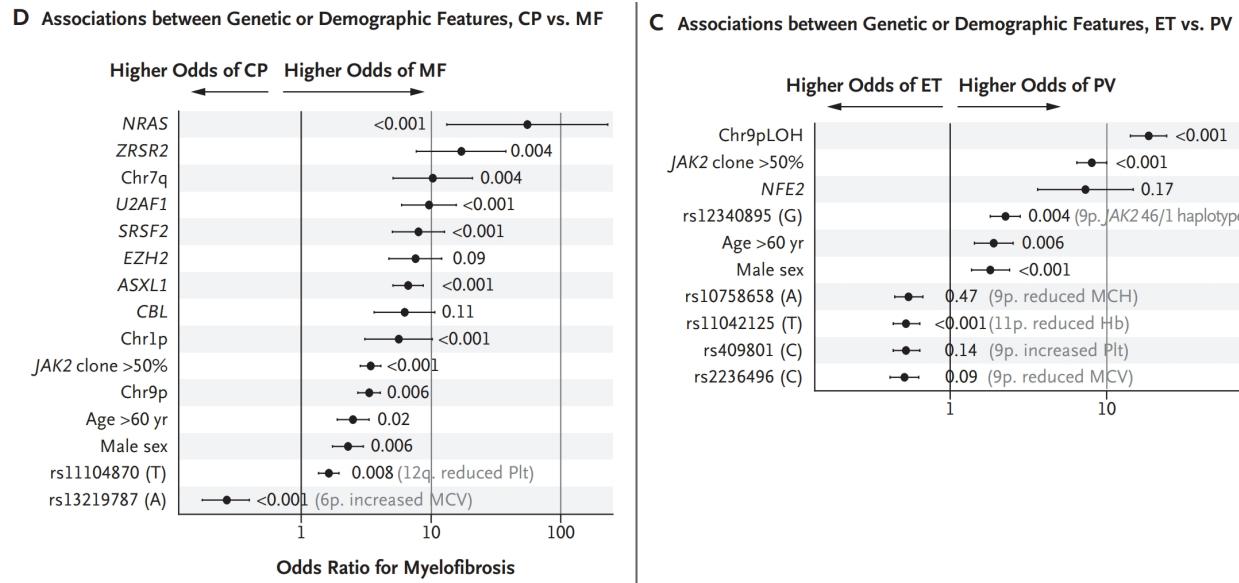
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In the above figure, HSPCs originating from a clone that first acquired either a JAK2 or TET2 mutation are expanded in culture to look for an effect of mutation order on the lineage generation (Ortmann et al., 2015). Each bar is a different set of clones coming from a particular MPN type as labeled along the x-axis, and shows an apparent transcriptional difference when the mutation acquisition order is changed. This is perhaps in part due to the epigenetic effects of TET2 mutation when it is the founder mutation.

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(Grinfeld et al., 2018)

Using Mayo Clinic patients as an approximation for overall MPN incidence, about 12% of all MPN incidence occurs within patients under 40 years of age, with the median age of incidence being 50 years (Szuber et al., 2018). With a median follow-up period of roughly 10 years, leukemia incidence is really not all that high, at about 5% on average. The probability of developing fibrosis is elevated in the younger individuals, which may be explained by a conspicuously longer expected survival time. Mean survival times in the Mayo Clinic data are 37, 35, 20 for under 40, 22, 22, 8 for 40-60, and 10, 11, 3 for over 60 for PV, ET, and PMF respectively (Szuber et al., 2018; Tefferi and Pardanani, 2015). The disease complications are typically thrombosis, leukemic transformation, or fibrotic transformation. In PV and ET, risk factors for survival include older age, leukocytosis, and thrombosis, whereas JAK2 mutation in ET is associated with increased risk of thrombosis. Thrombosis risk in PV is typically treated by phlebotomy to reduce haematocrit levels, or aspirin to reduce clotting potential in both PV and ET. Those individuals that are at a high risk of clotting may also be given hydroxyurea, interferon-alpha and busulfan as cytoreductive agents. Though the JAK2 inhibitor Ruxolitinib has been approved for use in treating hydroxyurea-resistant PV it is still unclear what the effects of chronic administration are.

7.4.2 Genetics

JAK2 is the most common of the mutations found within MPNs, occurring in about 98% of PV 55% in ET and 60% in PMF (Tefferi and Pardanani, 2015). JAK2 mutations also appear to be generally associated with old age, while CALR and PMF are more associated with young age. Below is a more in-depth understanding of the link between certain disease subtypes and the mutations associated with them. It is possible that JAK2 and MPL mutations directly activate JAK-STAT which allows cells to proliferate in a cytokine independent manner.

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Table. Mutations in Myeloproliferative Neoplasms (MPNs)

Mutation	Chromosome Location	Approximate Mutational Frequency, %			
		Polycythemia Vera	Essential Thrombocythemia	Primary Myelofibrosis	Blast-Phase MPN
Specific to MPN					
JAK2					
Exon 14 mutation; ie, JAK2V617F	9p24	95	55	60	40
Exon 12 mutations	9p24	3	Infrequent	Infrequent	Infrequent
CALR Exon 9 deletions and insertions	19p13.2	Infrequent	25	25	25
MPL Exon 10 mutations	1p34	Infrequent	3	7	8
LNK (as in Links; aka SH2B3) exon 2 mutations	12q24.12	Infrequent	Infrequent	Infrequent	10
Nonspecific to MPN					
TET2 Mutations involve several exons	4q24	16	5	17	17
ASXL1 Exon 12 mutations	20q11.1	7	4	20	18
IDH1/IDH2 Exon 4 mutations	2q33.3/15q26.1	2	1	4	22
EZH2 Mutations involve several exons	7q36.1	Infrequent	Infrequent	5	Infrequent
DNMT3A Most frequent mutations affect amino acid R882	2p23	7	3	7	17
CBL Exon 8/9 mutations	11q23.3	Infrequent	Infrequent	4	Infrequent
IKZF1 Mostly deletions including intragenic	7p12	Infrequent	Infrequent	Infrequent	21
TP53 Exons 4 through 9	17p13.1	Infrequent	Infrequent	4	11
SF3B1 Exons 14 and 15, mostly	2q33.1	Infrequent	Infrequent	7	4
SRSF2 Exon 2	17q25.1	Infrequent	Infrequent	17	19
U2AF1	21q22.3	Infrequent	Infrequent	16	6
SETBP1 Exon 4	18q21.1	Infrequent	Infrequent	2.5	7

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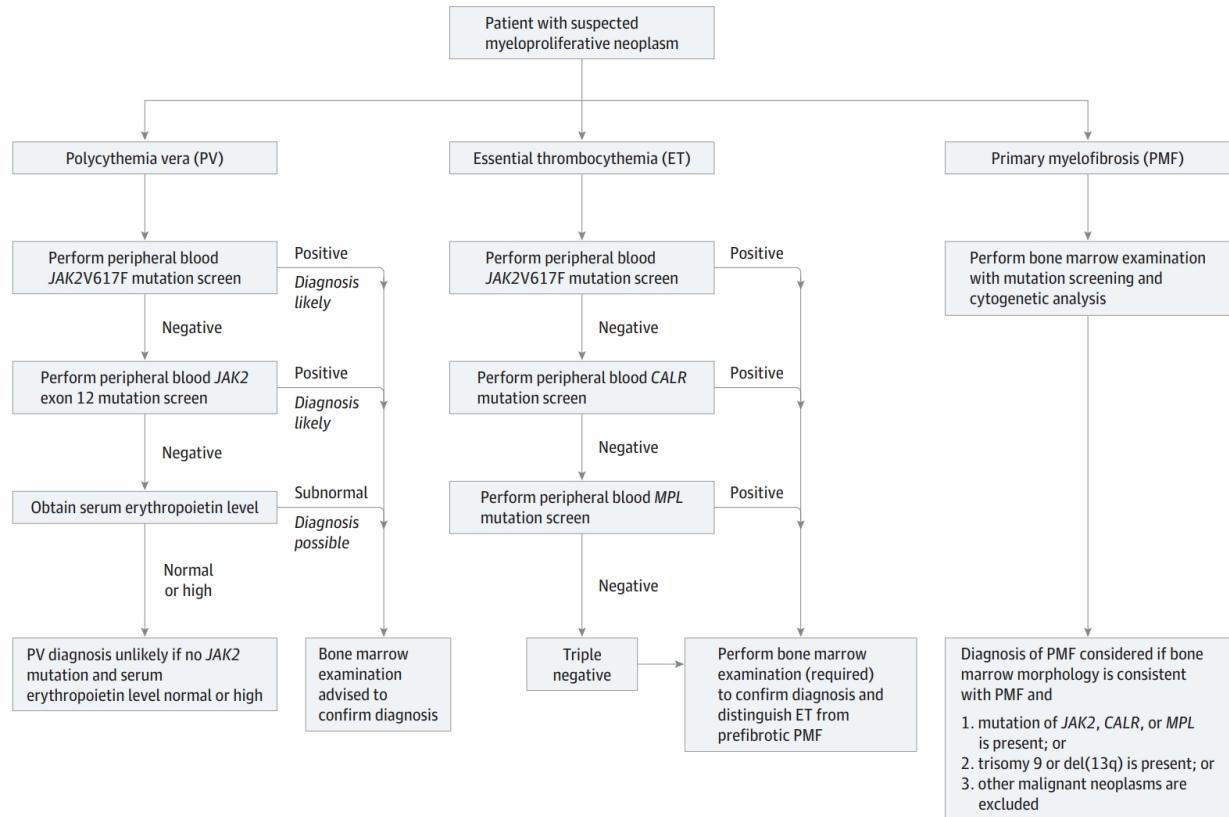
(Tefferi and Pardanani, 2015)

It is possible that JAK-STAT activation plays a key role in the development of MPNs, but it seems that people are confused why MPNs exist in an inflammatory state with altered cytokine signaling. I'm not sure I understand why the two understandings are inconsistent with each other (Rampal et al., 2014).

7.4.3 Disease Manifestations

Complete blood counts exceed the upper limit of the WHO reference range. Other characteristic features include palpable splenomegaly, anemia, aquagenic pruritus (itching when skin contacts water), unusual thrombosis such as portal or hepatic vein thrombosis, bone marrow fibrosis, and extramedullary hematopoiesis. A more complete explanation of diagnostics can be found in the figure below.

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(Tefferi and Pardanani, 2015).

Chapter 8

Microbiome

8.1 Relationship to Disease

Using germ-free mice, when gut microbiota were transplanted from either typical donors or donors with autism spectrum disorder, the brains of the mice that were injected with the microbiota from ASD donors exhibited predominant autistic behaviors (Sharon et al., 2019). Furthermore, microbiota from typical donors improved behavioral abnormalities and neuron function in ASD model mice.

8.2 Metabolism

Among 271 tested oral drugs, it appears that many are metabolized differently by different gut bacteria. It appears that of the 76 bacteria that were followed, they differentially modify the ingested drugs (Zimmermann et al., 2019). This may have important implications for personalized drug therapies.

Chapter 9

Methods

9.1 HSC Biology

Optimizations that include Polyvinyl alcohol (PVA), fibronectin, and high levels of TPO allow for the expansion of mouse HSCs in culture for at least a month. It seems that the PVA acts as a carrier molecule that may easily undergo oxidation or reduction within the culture in a manner that facilitates the maintenance of stem-like phenotype while allowing the cells to expand. This method allows for the expansion of mouse HSCs somewhere in the range of 250X-900X and thereby enabled successful transplantation into unconditioned mice (Wilkinson et al., 2019).

9.2 Microscopy

DNA microscopy employs a UMI system to label components of cells that can then be deconvolved into images that resemble fluorescent microscopy images (Weinstein et al., 2019). Using this system to understand tumor heterogeneity, immune cell heterogeneity, or nervous and gut system tissue architectures may be valuable approaches.

Bibliography

- Abelson, S., Collord, G., Ng, S. W., Weissbrod, O., Cohen, N. M., Niemeyer, E., Barda, N., Zuzarte, P. C., Heisler, L., Sundaravadanam, Y., et al. (2018). Prediction of acute myeloid leukaemia risk in healthy individuals. *Nature*, 559(7714):400.
- Aguilaniu, H. (2015). The mysterious relationship between reproduction and longevity. In *Worm*, volume 4, page e1020276. Taylor & Francis.
- Alcolea, M. P., Greulich, P., Wabik, A., Frede, J., Simons, B. D., and Jones, P. H. (2014). Differentiation imbalance in single oesophageal progenitor cells causes clonal immortalization and field change. *Nature cell biology*, 16(6):612.
- Alexandrov, L. B., Nik-Zainal, S., Wedge, D. C., Aparicio, S. A., Behjati, S., Biankin, A. V., Bignell, G. R., Bolli, N., Borg, A., Børresen-Dale, A.-L., et al. (2013). Signatures of mutational processes in human cancer. *Nature*, 500(7463):415.
- Altieri, F., Grillo, C., Maceroni, M., and Chichiarelli, S. (2008). Dna damage and repair: from molecular mechanisms to health implications. *Antioxidants & redox signaling*, 10(5):891–938.
- Armitage, P. and Doll, R. (1954). The age distribution of cancer and a multi-stage theory of carcinogenesis. *British journal of cancer*, 8(1):1.
- Ashworth, A., Lord, C. J., and Reis-Filho, J. S. (2011). Genetic interactions in cancer progression and treatment. *Cell*, 145(1):30–38.
- Avsec, Z., Kreuzhuber, R., Israeli, J., Xu, N., Cheng, J., Shrikumar, A., Banerjee, A., Kim, D. S., Urban, L., Kundaje, A., et al. (2018). Kipoi: accelerating the community exchange and reuse of predictive models for genomics. *BioRxiv*, page 375345.
- Baalsrud, H. T., Tørresen, O. K., Solbakken, M. H., Salzburger, W., Hanel, R., Jakobsen, K. S., and Jentoft, S. (2017). De novo gene evolution of antifreeze glycoproteins in codfishes revealed by whole genome sequence data. *Molecular biology and evolution*, 35(3):593–606.
- Behjati, S., Huch, M., van Boxtel, R., Karthaus, W., Wedge, D. C., Tamuri, A. U., Martincorena, I., Petljak, M., Alexandrov, L. B., Gundem, G., et al. (2014). Genome sequencing of normal cells reveals developmental lineages and mutational processes. *Nature*, 513(7518):422.
- Budach, S. and Marsico, A. (2018). pysster: classification of biological sequences by learning sequence and structure motifs with convolutional neural networks. *Bioinformatics*, 34(17):3035–3037.
- Campisi, J., Kapahi, P., Lithgow, G. J., Melov, S., Newman, J. C., and Verdin, E. (2019). From discoveries in ageing research to therapeutics for healthy ageing. *Nature*, 571(7764):183.
- Charlesworth, B. and Charlesworth, D. (2000). The degeneration of y chromosomes. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 355(1403):1563–1572.
- Chen, K. M., Cofer, E. M., Zhou, J., and Troyanskaya, O. G. (2019). Selene: a pytorch-based deep learning library for sequence data. *Nature Methods*, 16(4):315.

- Chen, X. J. (2013). Mechanism of homologous recombination and implications for aging-related deletions in mitochondrial dna. *Microbiol. Mol. Biol. Rev.*, 77(3):476–496.
- Cristiano, S., Leal, A., Phallen, J., Fiksel, J., Adleff, V., Bruhm, D. C., Jensen, S. Ø., Medina, J. E., Hruban, C., White, J. R., et al. (2019). Genome-wide cell-free dna fragmentation in patients with cancer. *Nature*, page 1.
- Cui, R., Medeiros, T., Willemse, D., Iasi, L. N., Collier, G. E., Graef, M., Reichard, M., and Valenzano, D. R. (2019). Relaxed selection limits lifespan by increasing mutation load. *Cell*.
- Dominy, S. S., Lynch, C., Ermini, F., Benedyk, M., Marczyk, A., Konradi, A., Nguyen, M., Haditsch, U., Raha, D., Griffin, C., et al. (2019). Porphyromonas gingivalis in alzheimer's disease brains: Evidence for disease causation and treatment with small-molecule inhibitors. *Science advances*, 5(1):eaau3333.
- George, J., Uyar, A., Young, K., Kuffler, L., Waldron-Francis, K., Marquez, E., Ucar, D., and Trowbridge, J. J. (2016). Leukaemia cell of origin identified by chromatin landscape of bulk tumour cells. *Nature communications*, 7:12166.
- Grinfeld, J., Nangalia, J., Baxter, E. J., Wedge, D. C., Angelopoulos, N., Cantrill, R., Godfrey, A. L., Papaemmanuil, E., Gundem, G., MacLean, C., et al. (2018). Classification and personalized prognosis in myeloproliferative neoplasms. *New England Journal of Medicine*, 379(15):1416–1430.
- Gusev, A., Lee, S. H., Trynka, G., Finucane, H., Vilhjálmsson, B. J., Xu, H., Zang, C., Ripke, S., Bulik-Sullivan, B., Stahl, E., et al. (2014). Partitioning heritability of regulatory and cell-type-specific variants across 11 common diseases. *The American Journal of Human Genetics*, 95(5):535–552.
- Harris, K. and Pritchard, J. K. (2017). Rapid evolution of the human mutation spectrum. *Elife*, 6:e24284.
- Harris, K., Zhang, Y., and Nielsen, R. (2019). Genetic rescue and the maintenance of native ancestry. *Conserv. Genet.*, 20(1):59–64.
- Hartman, J. L., Garvik, B., and Hartwell, L. (2001). Principles for the buffering of genetic variation. *Science*, 291(5506):1001–1004.
- Holth, J. K., Fritschi, S. K., Wang, C., Pedersen, N. P., Cirrito, J. R., Mahan, T. E., Finn, M. B., Manis, M., Geerling, J. C., Fuller, P. M., Lucey, B. P., and Holtzman, D. M. (2019). The sleep-wake cycle regulates brain interstitial fluid tau in mice and CSF tau in humans. *Science*, 363(6429):880–884.
- Imai, S.-I., Armstrong, C. M., Kaeberlein, M., and Guarente, L. (2000). Transcriptional silencing and longevity protein sir2 is an nad-dependent histone deacetylase. *Nature*, 403(6771):795.
- Ingvarsson, P. K. (2001). Restoration of genetic variation lost—the genetic rescue hypothesis. *Trends in Ecology & Evolution*, 16(2):62–63.
- Jones, O. R., Scheuerlein, A., Salguero-Gómez, R., Camarda, C. G., Schaible, R., Casper, B. B., Dahlgren, J. P., Ehrlén, J., García, M. B., Menges, E. S., et al. (2014). Diversity of ageing across the tree of life. *Nature*, 505(7482):169.
- Kandoth, C., McLellan, M. D., Vandin, F., Ye, K., Niu, B., Lu, C., Xie, M., Zhang, Q., McMichael, J. F., Wyczalkowski, M. A., et al. (2013). Mutational landscape and significance across 12 major cancer types. *Nature*, 502(7471):333.
- Kapahi, P., Chen, D., Rogers, A. N., Katewa, S. D., Li, P. W.-L., Thomas, E. L., and Kockel, L. (2010). With tor, less is more: a key role for the conserved nutrient-sensing tor pathway in aging. *Cell metabolism*, 11(6):453–465.
- Keller, L. F. and Waller, D. M. (2002). Inbreeding effects in wild populations. *Trends in ecology & evolution*, 17(5):230–241.

- Kennedy, B. K., Austriaco Jr, N. R., Zhang, J., and Guarente, L. (1995). Mutation in the silencing gene s/r4 can delay aging in *s. cerevisiae*. *Cell*, 80(3):485–496.
- Kenyon, C., Chang, J., Gensch, E., Rudner, A., and Tabtiang, R. (1993). A *C. elegans* mutant that lives twice as long as wild type. *Nature*, 366(6454):461.
- Kimura, M. et al. (1968). Evolutionary rate at the molecular level. *Nature*, 217(5129):624–626.
- Klein, A. M., Brash, D. E., Jones, P. H., and Simons, B. D. (2010). Stochastic fate of p53-mutant epidermal progenitor cells is tilted toward proliferation by UV B during preneoplasia. *Proceedings of the National Academy of Sciences*, 107(1):270–275.
- Kong, A., Frigge, M. L., Masson, G., Besenbacher, S., Sulem, P., Magnusson, G., Gudjonsson, S. A., Sigurdsson, A., Jonasdottir, A., Jonasdottir, A., et al. (2012). Rate of de novo mutations and the importance of father's age to disease risk. *Nature*, 488(7412):471.
- Kraytsberg, Y., Schwartz, M., Brown, T. A., Ebralidse, K., Kunz, W. S., Clayton, D. A., Vissing, J., and Khrapko, K. (2004). Recombination of human mitochondrial DNA. *Science*, 304(5673):981–981.
- Krönke, J., Bullinger, L., Teleanu, V., Tschürtz, F., Gaidzik, V. I., Kühn, M. W., Rücker, F. G., Holzmann, K., Paschka, P., Kapp-Schwörer, S., et al. (2013). Clonal evolution in relapsed NPM1-mutated acute myeloid leukemia. *Blood*, 122(1):100–108.
- Lawrence, M. S., Stojanov, P., Mermel, C. H., Robinson, J. T., Garraway, L. A., Golub, T. R., Meyerson, M., Gabriel, S. B., Lander, E. S., and Getz, G. (2014). Discovery and saturation analysis of cancer genes across 21 tumour types. *Nature*, 505(7484):495.
- Lawrence, M. S., Stojanov, P., Polak, P., Kryukov, G. V., Cibulskis, K., Sivachenko, A., Carter, S. L., Stewart, C., Mermel, C. H., Roberts, S. A., et al. (2013). Mutational heterogeneity in cancer and the search for new cancer-associated genes. *Nature*, 499(7457):214.
- Lee-Six, H., Øbro, N. F., Shepherd, M. S., Grossmann, S., Dawson, K., Belmonte, M., Osborne, R. J., Huntly, B. J., Martincorena, I., Anderson, E., et al. (2018). Population dynamics of normal human blood inferred from somatic mutations. *Nature*, 561(7724):473.
- Liu, N., Matsumura, H., Kato, T., Ichinose, S., Takada, A., Namiki, T., Asakawa, K., Morinaga, H., Mohri, Y., De Arcangelis, A., et al. (2019). Stem cell competition orchestrates skin homeostasis and ageing. *Nature*, page 1.
- Ludwig, L. S., Lareau, C. A., Ulirsch, J. C., Christian, E., Muus, C., Li, L. H., Pelka, K., Ge, W., Oren, Y., Brack, A., et al. (2019). Lineage tracing in humans enabled by mitochondrial mutations and single-cell genomics. *Cell*, 176(6):1325–1339.
- Lynch, M. (2010). Rate, molecular spectrum, and consequences of human mutation. *Proceedings of the National Academy of Sciences*, 107(3):961–968.
- Mamcarz, E., Zhou, S., Lockey, T., Abdelsamed, H., Cross, S. J., Kang, G., Ma, Z., Condori, J., Dowdy, J., Triplett, B., Li, C., Maron, G., Aldave Becerra, J. C., Church, J. A., Dokmeci, E., Love, J. T., da Matta Ain, A. C., van der Watt, H., Tang, X., Janssen, W., Ryu, B. Y., De Ravin, S. S., Weiss, M. J., Youngblood, B., Long-Boyle, J. R., Gottschalk, S., Meagher, M. M., Malech, H. L., Puck, J. M., Cowan, M. J., and Sorrentino, B. P. (2019). Lentiviral gene therapy combined with Low-Dose busulfan in infants with SCID-X1. *New England Journal of Medicine*, 380(16):1525–1534.
- Martincorena, I. and Campbell, P. J. (2015). Somatic mutation in cancer and normal cells. *Science*, 349(6255):1483–1489.
- Martincorena, I., Fowler, J. C., Wabik, A., Lawson, A. R., Abascal, F., Hall, M. W., Cagan, A., Murai, K., Mahbubani, K., Stratton, M. R., et al. (2018). Somatic mutant clones colonize the human esophagus with age. *Science*, 362(6417):911–917.

- Martincorena, I., Raine, K. M., Gerstung, M., Dawson, K. J., Haase, K., Van Loo, P., Davies, H., Stratton, M. R., and Campbell, P. J. (2017). Universal patterns of selection in cancer and somatic tissues. *Cell*, 171(5):1029–1041.
- Martincorena, I., Roshan, A., Gerstung, M., Ellis, P., Van Loo, P., McLaren, S., Wedge, D. C., Fullam, A., Alexandrov, L. B., Tubio, J. M., et al. (2015). High burden and pervasive positive selection of somatic mutations in normal human skin. *Science*, 348(6237):880–886.
- Matheoud, D., Cannon, T., Voisin, A., Penttinen, A.-M., Ramet, L., Fahmy, A. M., Ducrot, C., Laplante, A., Bourque, M.-J., Zhu, L., et al. (2019). Intestinal infection triggers parkinson's disease-like symptoms in pink1^{-/-} mice. *Nature*, page 1.
- Mattison, J. A., Colman, R. J., Beasley, T. M., Allison, D. B., Kemnitz, J. W., Roth, G. S., Ingram, D. K., Weindruch, R., De Cabo, R., and Anderson, R. M. (2017). Caloric restriction improves health and survival of rhesus monkeys. *Nature communications*, 8:14063.
- McCay, C. M., Crowell, M. F., and Maynard, L. A. (1935). The effect of retarded growth upon the length of life span and upon the ultimate body size: one figure. *The journal of Nutrition*, 10(1):63–79.
- McKerrell, T., Park, N., Moreno, T., Grove, C. S., Ponstingl, H., Stephens, J., Crawley, C., Craig, J., Scott, M. A., Hodkinson, C., et al. (2015). Leukemia-associated somatic mutations drive distinct patterns of age-related clonal hemopoiesis. *Cell reports*, 10(8):1239–1245.
- Medawar, P. B. (1952). *An unsolved problem of biology*. College.
- Merino, M. M., Rhiner, C., Lopez-Gay, J. M., Buechel, D., Hauert, B., and Moreno, E. (2015). Elimination of unfit cells maintains tissue health and prolongs lifespan. *Cell*, 160(3):461–476.
- Mesa, R. A., Mehta, J., Wang, H., Wang, Y., Iqbal, U., Neumann, F., Zhang, Y., and Colton, T. (2012). Epidemiology of myeloproliferative disorders in us-a real world analysis.
- Morley, A. A. (1995). The somatic mutation theory of ageing. *Mutation Research/DNAging*, 338(1-6):19–23.
- Mouchiroud, L., Houtkooper, R. H., Moullan, N., Katsyuba, E., Ryu, D., Cantó, C., Mottis, A., Jo, Y.-S., Viswanathan, M., Schoonjans, K., et al. (2013). The nad+/sirtuin pathway modulates longevity through activation of mitochondrial upr and foxo signaling. *Cell*, 154(2):430–441.
- Nangalia, J., Nice, F. L., Wedge, D. C., Godfrey, A. L., Grinfeld, J., Thakker, C., Massie, C. E., Baxter, J., Sewell, D., Silber, Y., et al. (2015). Dnmt3a mutations occur early or late in patients with myeloproliferative neoplasms and mutation order influences phenotype. *Haematologica*, pages haematol–2015.
- Newman, S. J. (2019). Supercentenarians and the oldest-old are concentrated into regions with no birth certificates and short lifespans.
- Nik-Zainal, S., Alexandrov, L. B., Wedge, D. C., Van Loo, P., Greenman, C. D., Raine, K., Jones, D., Hinton, J., Marshall, J., Stebbings, L. A., et al. (2012). Mutational processes molding the genomes of 21 breast cancers. *Cell*, 149(5):979–993.
- Ohta, T. and Kimura, M. (1973). A model of mutation appropriate to estimate the number of electrophoretically detectable alleles in a finite population. *Genetics Research*, 22(2):201–204.
- Ortmann, C. A., Kent, D. G., Nangalia, J., Silber, Y., Wedge, D. C., Grinfeld, J., Baxter, E. J., Massie, C. E., Papaemmanuil, E., Menon, S., et al. (2015). Effect of mutation order on myeloproliferative neoplasms. *New England Journal of Medicine*, 372(7):601–612.
- Petrova, E., Soldini, D., and Moreno, E. (2011). The expression of sparc in human tumors is consistent with its role during cell competition. *Communicative & integrative biology*, 4(2):171–174.
- Pifferi, F., Terrien, J., Marchal, J., Dal-Pan, A., Djelti, F., Hardy, I., Chahory, S., Cordonnier, N., Desquillet, L., Hurion, M., et al. (2018). Caloric restriction increases lifespan but affects brain integrity in grey mouse lemur primates. *Communications biology*, 1(1):30.

- Preston, S. L., Wong, W.-M., Chan, A. O.-O., Poulsom, R., Jeffery, R., Goodlad, R. A., Mandir, N., Elia, G., Novelli, M., Bodmer, W. F., et al. (2003). Bottom-up histogenesis of colorectal adenomas: origin in the monocryptal adenoma and initial expansion by crypt fission. *Cancer research*, 63(13):3819–3825.
- Rampal, R., Al-Shahrour, F., Abdel-Wahab, O., Patel, J. P., Brunel, J.-P., Mermel, C. H., Bass, A. J., Pretz, J., Ahn, J., Hricik, T., et al. (2014). Integrated genomic analysis illustrates the central role of jak-stat pathway activation in myeloproliferative neoplasm pathogenesis. *Blood*, 123(22):e123–e133.
- Rauch, S., He, E., Srienc, M., Zhou, H., Zhang, Z., and Dickinson, B. C. (2019). Programmable rna-guided rna effector proteins built from human parts. *Cell*.
- Rose, M. and Charlesworth, B. (1980). A test of evolutionary theories of senescence. *Nature*, 287(5778):141.
- Ségurel, L., Wyman, M. J., and Przeworski, M. (2014). Determinants of mutation rate variation in the human germline. *Annual review of genomics and human genetics*, 15:47–70.
- Sharon, G., Cruz, N. J., Kang, D.-W., Gandal, M. J., Wang, B., Kim, Y.-M., Zink, E. M., Casey, C. P., Taylor, B. C., Lane, C. J., et al. (2019). Human gut microbiota from autism spectrum disorder promote behavioral symptoms in mice. *Cell*, 177(6):1600–1618.
- Shendure, J., Findlay, G. M., and Snyder, M. W. (2019). Genomic medicine—progress, pitfalls, and promise. *Cell*, 177(1):45–57.
- Snippert, H. J., Schepers, A. G., van Es, J. H., Simons, B. D., and Clevers, H. (2014). Biased competition between lgr5 intestinal stem cells driven by oncogenic mutation induces clonal expansion. *EMBO reports*, 15(1):62–69.
- Stephens, P. J., McBride, D. J., Lin, M.-L., Varela, I., Pleasance, E. D., Simpson, J. T., Stebbings, L. A., Leroy, C., Edkins, S., Mudie, L. J., et al. (2009). Complex landscapes of somatic rearrangement in human breast cancer genomes. *Nature*, 462(7276):1005.
- Szuber, N., Vallapureddy, R. R., Penna, D., Lasho, T. L., Finke, C., Hanson, C. A., Ketterling, R. P., Pardanani, A., Gangat, N., and Tefferi, A. (2018). Myeloproliferative neoplasms in the young: Mayo clinic experience with 361 patients age 40 years or younger. *American journal of hematology*, 93(12):1474–1484.
- Tefferi, A., Lasho, T. L., Guglielmelli, P., Finke, C. M., Rotunno, G., Elala, Y., Pacilli, A., Hanson, C. A., Pancrazzi, A., Ketterling, R. P., et al. (2016). Targeted deep sequencing in polycythemia vera and essential thrombocythemia. *Blood advances*, 1(1):21–30.
- Tefferi, A. and Pardanani, A. (2015). Myeloproliferative neoplasms: a contemporary review. *JAMA oncology*, 1(1):97–105.
- Tefferi, A., Thiele, J., Vannucchi, A., and Barbui, T. (2014). An overview on calr and csf3r mutations and a proposal for revision of who diagnostic criteria for myeloproliferative neoplasms. *Leukemia*, 28(7):1407.
- Tomasetti, C. and Vogelstein, B. (2015). Variation in cancer risk among tissues can be explained by the number of stem cell divisions. *Science*, 347(6217):78–81.
- Vannucchi, A., Lasho, T., Guglielmelli, P., Biamonte, F., Pardanani, A., Pereira, A., Finke, C., Score, J., Gangat, N., Mannarelli, C., et al. (2013). Mutations and prognosis in primary myelofibrosis. *Leukemia*, 27(9):1861.
- Venn, O., Turner, I., Mathieson, I., de Groot, N., Bontrop, R., and McVean, G. (2014). Strong male bias drives germline mutation in chimpanzees. *Science*, 344(6189):1272–1275.
- Vila, C., Sundqvist, A.-K., Flagstad, Ø., Seddon, J., rnerfeldt, S. B., Kojola, I., Casulli, A., Sand, H., Wabakken, P., and Ellegren, H. (2003). Rescue of a severely bottlenecked wolf (*canis lupus*) population by a single immigrant. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1510):91–97.

- Vogelstein, B., Papadopoulos, N., Velculescu, V. E., Zhou, S., Diaz, L. A., and Kinzler, K. W. (2013). Cancer genome landscapes. *science*, 339(6127):1546–1558.
- Wang, Z., Ma, J., Miyoshi, C., Li, Y., Sato, M., Ogawa, Y., Lou, T., Ma, C., Gao, X., Lee, C., et al. (2018). Quantitative phosphoproteomic analysis of the molecular substrates of sleep need. *Nature*, 558(7710):435.
- Watson, C. J., Papula, A., Poon, Y. P. G., Wong, W. H., Young, A. L., Druley, T. E., Fisher, D. S., and Blundell, J. R. (2019). The evolutionary dynamics and fitness landscape of clonal haematopoiesis.
- Weinstein, J. A., Regev, A., and Zhang, F. (2019). Dna microscopy: Optics-free spatio-genetic imaging by a stand-alone chemical reaction. *Cell*.
- Wilkins, B. S., Erber, W. N., Bareford, D., Buck, G., Wheatley, K., East, C. L., Paul, B., Harrison, C. N., Green, A. R., and Campbell, P. J. (2008). Bone marrow pathology in essential thrombocythemia: interobserver reliability and utility for identifying disease subtypes. *Blood*, 111(1):60–70.
- Wilkinson, A. C., Ishida, R., Kikuchi, M., Sudo, K., Morita, M., Crisostomo, R. V., Yamamoto, R., Loh, K. M., Nakamura, Y., Watanabe, M., et al. (2019). Long-term ex vivo haematopoietic-stem-cell expansion allows nonconditioned transplantation. *Nature*, page 1.
- Williams, G. C. (1957). Pleiotropy, natural selection, and the evolution of senescence. *evolution*, pages 398–411.
- Yates, L. R., Gerstung, M., Knappskog, S., Desmedt, C., Gundem, G., Van Loo, P., Aas, T., Alexandrov, L. B., Larsimont, D., Davies, H., et al. (2015). Subclonal diversification of primary breast cancer revealed by multiregion sequencing. *Nature medicine*, 21(7):751.
- Yizhak, K., Aguet, F., Kim, J., Hess, J. M., Kübler, K., Grimsby, J., Frazer, R., Zhang, H., Haradhvala, N. J., Rosebrock, D., Livitz, D., Li, X., Arich-Landkof, E., Shores, N., Stewart, C., Segrè, A. V., Branton, P. A., Polak, P., Ardlie, K. G., and Getz, G. (2019). RNA sequence analysis reveals macroscopic somatic clonal expansion across normal tissues. *Science*, 364(6444).
- Yogarajah, M. and Tefferi, A. (2017). Leukemic transformation in myeloproliferative neoplasms: a literature review on risk, characteristics, and outcome. In *Mayo Clinic Proceedings*, volume 92, pages 1118–1128. Elsevier.
- Yokoyama, A., Kakiuchi, N., Yoshizato, T., Nannya, Y., Suzuki, H., Takeuchi, Y., Shiozawa, Y., Sato, Y., Aoki, K., Kim, S. K., et al. (2019). Age-related remodelling of oesophageal epithelia by mutated cancer drivers. *Nature*, 565(7739):312.
- Young, K. and Trowbridge, J. J. (2016). Open chromatin profiling as a novel strategy for identifying cancer cell of origin. *Molecular & cellular oncology*, 3(6):e1236770.
- Zimmermann, M., Zimmermann-Kogadeeva, M., Wegmann, R., and Goodman, A. L. (2019). Mapping human microbiome drug metabolism by gut bacteria and their genes. *Nature*, page 1.