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The Role of Immune Function in Longevity and Adaptation in Vertebrates

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Abstract Longevity and adaptation are critical aspects of vertebrate biology, where the immune system plays a central role in maintaining health and survival across diverse environments. This study explores the intricate relationships between immune function, lifespan, and environmental adaptation in vertebrates. It begins by providing an overview of vertebrate longevity and adaptation, followed by a detailed examination of the immune system's components and evolutionary mechanisms; then delves into the link between immune function and longevity, discussing key processes such as immunosenescence and inflammation, and highlights comparative studies across different vertebrate species. The role of immune function in adaptation, particularly in extreme environments, is also discussed, with a focus on genetic and physiological adaptations in Arctic vertebrates. A case study on the naked mole rat illustrates the unique immune characteristics that contribute to its exceptional lifespan. This study further explores the interplay between immune function, longevity, and disease resistance, emphasizing the trade-offs involved; finally, discusses the implications of immune function for conservation and wildlife management, and suggest future research directions, including the potential for translational applications in medicine and conservation. This study underscores the importance of integrating immune function studies into broader research on vertebrate longevity and adaptation.

Keywords Vertebrate longevity; Immune function; Adaptation; Immunosenescence; Environmental adaptation

1 Introduction

Longevity and adaptation are critical aspects of vertebrate biology, influencing survival and reproductive success across diverse environments. This process is driven by natural selection, where advantageous traits become more common in the population over successive generations (Li and Chen, 2024). Vertebrates exhibit a wide range of lifespans and adaptive strategies, from the short-lived and highly adaptable to the long-lived and specialized. The evolutionary emergence of vertebrates brought about significant innovations, including the development of complex immune systems that play a pivotal role in these processes (Boehm et al., 2012; Liu et al., 2019). The interplay between longevity and adaptation is evident in the physiological and genetic mechanisms that underpin these traits, with immune function being a central component (Omotoso et al., 2021).

The immune system is essential for maintaining homeostasis and defending against pathogens, which is crucial for the survival and longevity of vertebrates. Vertebrate immunity is characterized by both innate and adaptive components, each contributing to the organism's ability to respond to and remember pathogens (Romo et al., 2016; Boehm et al., 2018). Innate immunity provides the first line of defense and is present in all vertebrates, while adaptive immunity, which includes the development of immunological memory, is a hallmark of vertebrate evolution (Boehm, 2012). The adaptive immune system's ability to remember and respond more effectively to previously encountered pathogens is particularly important for long-lived species, as it enhances their ability to survive repeated exposures to infectious agents (Vinkler and Albrecht, 2011; Netea et al., 2016).

This study explores the role of immune function in the longevity and adaptation of vertebrates; examines the evolutionary history of vertebrate immune systems, highlighting key innovations and their impact on survival and adaptation; additionally, discusses the mechanisms by which immune function influences lifespan and how different vertebrate species have adapted their immune responses to their specific ecological niches. By integrating findings from various studies, this study seeks to provide a comprehensive understanding of the complex relationship between immune function, longevity, and adaptation in vertebrates.

2 Overview of the Immune System

The immune system is a complex network of cells, tissues, and organs that work together to defend the body against harmful pathogens and maintain homeostasis. It is broadly categorized into two main components: innate and adaptive immunity. Innate immunity provides the first line of defense and is characterized by its rapid response and broad specificity. Adaptive immunity, on the other hand, is highly specific and involves the generation of immunological memory, allowing for a more efficient response upon subsequent exposures to the same pathogen.

2.1 Components of the immune system

The immune system comprises various components that work in concert to protect the host. Innate immunity includes physical barriers like the skin and mucous membranes, chemical barriers such as antimicrobial peptides, and cellular components like macrophages, neutrophils, and natural killer cells. These elements recognize and respond to pathogen-associated molecular patterns (PAMPs) through pattern recognition receptors (PRRs) (Romo et al., 2016).

Adaptive immunity involves lymphocytes, including B cells and T cells. B cells are responsible for antibody production, which neutralizes and clears pathogens. T cells, particularly CD4+ T cells, play a crucial role in supporting B cell differentiation into memory and plasma cells, a process regulated by T follicular helper (TFH) cells (Tangye et al., 2013). The adaptive immune system's ability to remember past infections and respond more effectively upon re-exposure is a hallmark of its function.

2.2 Evolution of immune mechanisms in vertebrates

The evolution of the immune system in vertebrates has been marked by the development of both innate and adaptive immunity. Innate immunity is ancient and conserved across all animals, providing a rapid and generalized response to pathogens. Adaptive immunity, however, is a vertebrate-specific innovation that relies on somatically derived lymphocytes and exhibits near-limitless genetic diversity and long-term memory (Dishaw et al., 2012).

Studies on deuterostome invertebrates, such as amphioxus, have provided insights into the evolutionary origins of vertebrate immunity. Amphioxus possesses homologs of many innate immune receptors found in vertebrates, with significant expansions in gene families that enhance the innate immune repertoire. This suggests that the complexity of the vertebrate immune system arose from innovations in innate immune mechanisms, which later facilitated the development of adaptive immunity.

2.3 Key immune pathways and their roles in health and longevity

Several key immune pathways are integral to both health and longevity. The insulin/TOR network, MAPK pathways (ERK, p38, JNK), JAK/STAT, TGF-β, and NF-κB pathways are evolutionarily conserved and play pleiotropic roles in regulating immunity and lifespan (Fabian et al., 2021). These pathways are involved in various cellular processes, including stress response, inflammation, and cellular repair, which are crucial for maintaining health and extending lifespan.

For instance, the p38 MAPK pathway is essential for innate immune signaling and has been shown to enhance pathogen resistance and longevity in model organisms like Caenorhabditis elegans. Disruption of mitochondrial function can activate the mitochondrial unfolded protein response (mitoUPR) and p38 signaling, leading to increased innate immunity and extended lifespan (Campos et al., 2021). Similarly, the GABAergic transcription factor PITX/UNC-30 in C. elegans regulates a tradeoff between immunity and longevity, highlighting the interconnectedness of these pathways (Figure 1) (Otarigho and Aballay, 2021).

The study of Otarigho and Aballay (2021) presented in the image suggest that the *UNC-30* gene plays a significant role in regulating both immune responses and age determination pathways in *C. elegans*. The gene ontology and pathway analyses reveal that genes related to immune defense and aging are upregulated in UNC-30 mutants compared to wild-type (WT) animals. The qRT-PCR results further confirm the increased expression of specific

immune and age-related genes in the mutants, indicating that *UNC-30* may act as a critical regulator in these biological processes, influencing the organism's response to infection and lifespan.

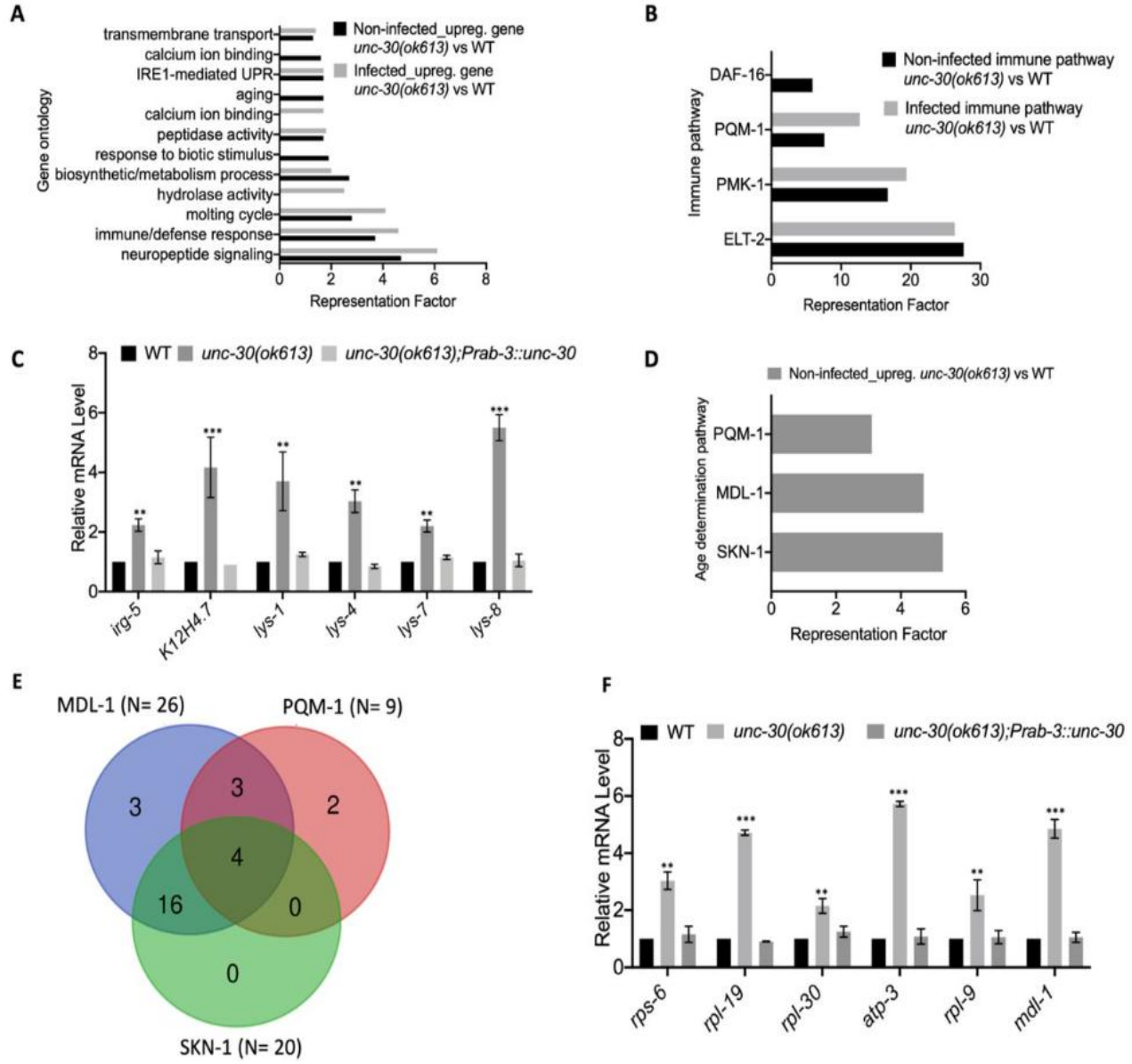

Figure 1 PITX1/UNC-30 regulates immune and age determination pathways (Adopted from Otarigho and Aballay, 2021)

Image caption: (A) Gene ontology analysis of upregulated genes in *unc-30(ok613)* vs WT in both non-infected and *P. aeruginosa*-infected animals. The cutoff is based on the filtering thresholds of $P < 0.05$ and arranged according to the representation factor. (B) Representation factors of immune pathways for the upregulated immune genes in *unc-30(ok613)* vs WT in both non-infected and *P. aeruginosa*-infected animals. (C) qRT-PCR analysis of immune gene expression in WT and *unc-30(ok613)* animals. Bars represent means while error bars indicate SD; $*p < 0.05$, $**p < 0.001$ and $***p < 0.0001$. (D) Representation factors of age determination pathways for the upregulated aging genes in *unc-30(ok613)* vs WT in non-infected animals. (E) Venn diagram showing the age determination genes in each pathway for the upregulated aging genes in *unc-30(ok613)* vs WT in non-infected animals. (F) qRT-PCR analysis of age determination genes expression in WT and *unc-30(ok613)* animals. Bars represent means while error bars indicate SD; $*p < 0.05$, $**p < 0.001$ and $***p < 0.0001$ (Adopted from Otarigho and Aballay, 2021)

Understanding the molecular mechanisms underlying these pathways can provide insights into the aging process and identify potential targets for interventions aimed at promoting healthy aging and longevity. The interplay between immune function and longevity underscores the importance of maintaining a balanced immune response to ensure both effective pathogen defense and prolonged lifespan.

3 Immune Function and Longevity

3.1 The link between immune function and lifespan

The relationship between immune function and lifespan is complex and multifaceted. Immunosenescence, the gradual deterioration of the immune system with age, plays a significant role in this dynamic. This process affects both innate and adaptive immunity, leading to increased susceptibility to infections, cancer, and autoimmune diseases in older individuals (Salminen, 2021). Interestingly, some studies suggest that immunosenescence may also have adaptive aspects, potentially contributing to longevity by triggering anti-inflammatory responses that counteract age-related pro-inflammatory environments (Santoro et al., 2021). This dual role of immunosenescence highlights the intricate balance between immune function and lifespan.

3.2 Mechanisms of immune-mediated longevity

3.2.1 Immunosenescence and its impact on aging

Immunosenescence is characterized by a decline in immune cell function, including reduced antibody responses and a decrease in the number of naive immune cells (Rodríguez et al., 2021). This decline is more pronounced in adaptive immunity compared to innate immunity. The accumulation of senescent immune cells and the associated chronic low-grade inflammation, termed "inflammaging," are hallmarks of this process. These changes contribute to the increased prevalence of age-related diseases and a general decline in health in the elderly.

3.2.2 Role of inflammation in aging

Inflammaging, the chronic, sterile inflammation associated with aging, is a significant factor in the aging process. It results from the accumulation of pro-inflammatory factors and the decline in the immune system's ability to regulate inflammation. This persistent inflammation can lead to tissue damage and the development of various age-related diseases, including cardiovascular diseases, neurodegenerative disorders, and cancers (Fulop et al., 2018). However, some researchers argue that inflammaging may also have adaptive benefits, such as promoting anti-inflammatory responses that help maintain homeostasis and support longevity.

3.3 Comparative studies of longevity in different vertebrate species

Comparative studies across different vertebrate species provide valuable insights into the relationship between immune function and longevity. For instance, research on wild animals has shown that immunosenescence is not unique to humans but is also observed in other species, including mammals, birds, and reptiles. These studies reveal that, similar to humans, age-related declines in immune function are more evident in adaptive immunity and are associated with increased inflammatory markers (Peters et al., 2019).

In long-lived species like the painted turtle (Chrysemys picta), evidence suggests that immunosenescence may not be as pronounced, and older individuals can maintain robust immune functions (Figure 2) (Judson et al., 2020). This finding contrasts with the typical pattern observed in mammals and highlights the variability in immune aging across species. Additionally, studies on Drosophila melanogaster have shown that evolutionary changes in immune function, particularly in the Toll pathway, can contribute to increased longevity and improved resistance to infections (Fabian et al., 2018). These comparative studies underscore the importance of immune function in determining lifespan and highlight the diverse strategies employed by different species to achieve longevity.

The study of Judson et al. (2020) illustrates a positive correlation between age and natural antibody titers in painted turtles, with older individuals exhibiting higher antibody levels than younger ones. This trend is consistent across both sexes and juveniles, indicating that immune function, as measured by natural antibodies, may enhance with age in this species. The equation and R^2 value suggest a modest yet significant relationship, emphasizing that age is a predictor of immune capability in painted turtles. The age scale bars highlight the distribution of ages among the studied groups, providing context for the observed correlation.

4 Immune Function and Adaptation

4.1 The Role of immune function in environmental adaptation

Immune function plays a critical role in the adaptation of vertebrates to diverse environmental conditions. The ability to mount an effective immune response is essential for survival in hostile environments, as it ensures

protection against pathogens and promotes longevity. For instance, the transcription factor SKN-1 in *Caenorhabditis elegans* is crucial for pathogen resistance and is activated in response to environmental stressors, highlighting the importance of immune regulation in adaptation (Papp et al., 2012). Additionally, the evolutionary history of the Toll-like receptor (TLR) gene family across vertebrates underscores the role of immune genes in adapting to various pathogenic environments, with specific adaptations observed in different vertebrate clades (Liu et al., 2019).

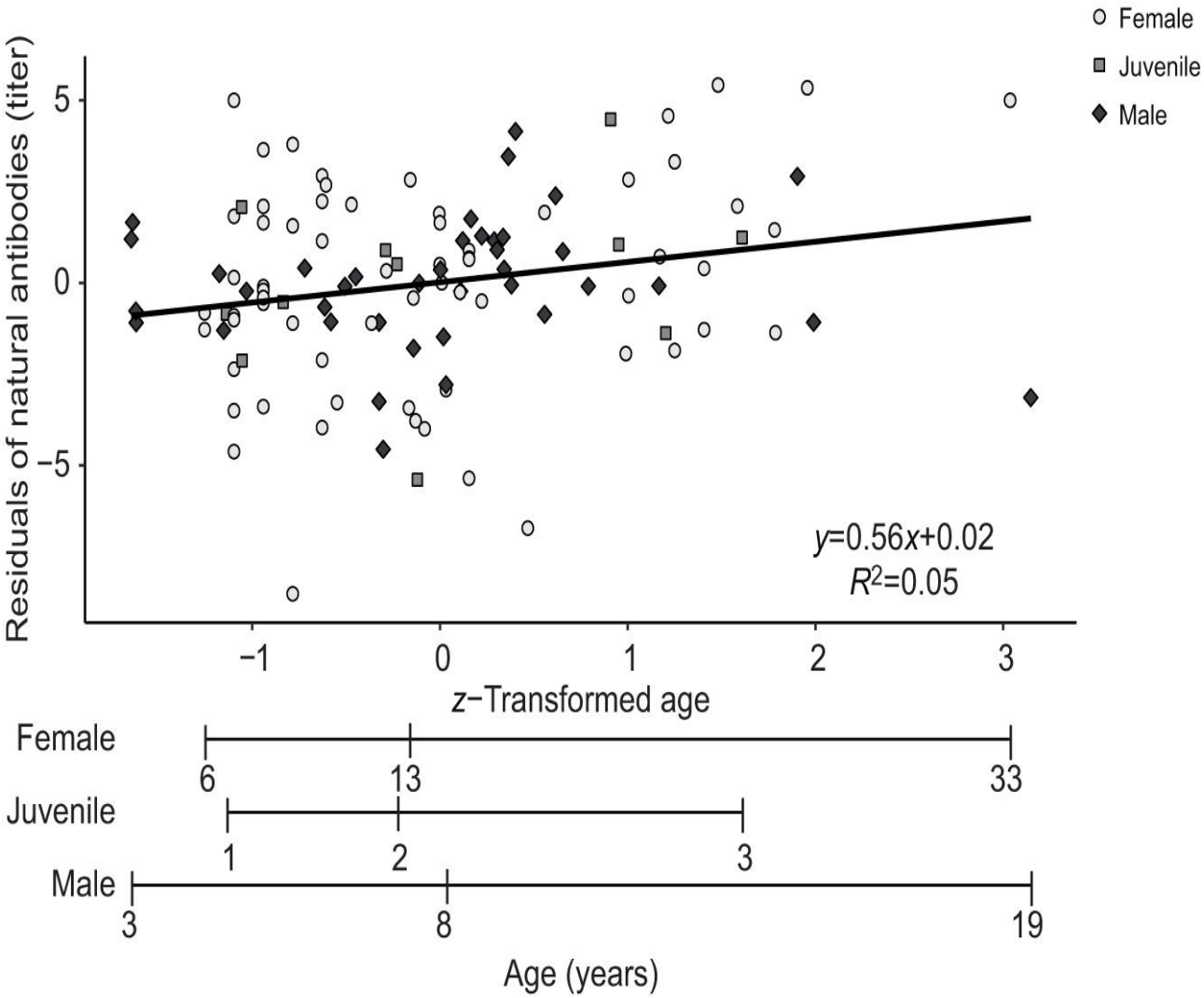

Figure 2 Older painted turtles exhibit greater levels of natural antibodies than do younger individuals across sexes (P=0.021) (Adopted from Judson et al., 2020)

Image caption: Relationship between z-transformed age (zAge) and the residuals of natural antibody titer in response to rabbit red blood cells across painted turtles measured in this study (N=115). Residuals were calculated from the model excluding zAge. The equation of the line of best fit and R^2 are shown on the plot. Scale bars beneath the x-axis represent the ages corresponding to the minimum, median and maximum zAge shown in the plot for females, juveniles and males (Adopted from Judson et al., 2020)

4.2 Genetic adaptations in immune function

Genetic adaptations in immune function are pivotal for the longevity and disease resistance observed in long-lived vertebrates. Comparative studies have shown that adaptive genetic factors control longevity and disease resistance, suggesting that these traits are maintained by natural selection (Omotoso et al., 2021). The evolution of the TLR gene family, which includes ancient membrane-bound sensors that detect and defend against pathogens, further illustrates the genetic basis of immune adaptations. Positive selection acting on specific codons within TLR genes indicates host-pathogen coevolutionary interactions, which are essential for the immune function of vertebrates.

4.3 Immune adaptations in Arctic vertebrates

4.3.1 Immune response to extreme cold

Arctic vertebrates, such as the Antarctic notothenioid fish, have evolved unique immune responses to survive in extreme cold environments. Transcriptome analyses of the Antarctic bullhead notothen *Notothenia coriiceps* revealed that exposure to bacterial and viral pathogens induces distinct immune responses, with antigen presentation mechanisms being up-regulated in response to bacterial infections and TNF-mediated apoptosis being prominent in viral infections (Ahn et al., 2016). These adaptations are crucial for maintaining immune function in the cold and thermally stable Antarctic sea.

4.3.2 Pathogen resistance in polar environments

Pathogen resistance in polar environments is facilitated by specific immune adaptations. For example, the *Cryonotothenioidea*, a group of Antarctic fish, exhibit unique genetic and molecular adaptations that enhance their immune responses. Comparative transcriptomics of these fish have identified several up-regulated genes involved in immune function, which are shared among different species within the group. These genetic adaptations likely contribute to their evolutionary success in the harsh Antarctic environment (Ansaloni et al., 2021). Additionally, the study of immune responses in Notothenia coriiceps provides insights into the specific defense strategies employed by Antarctic fish, such as the use of antigen presentation against bacterial infections and TNF-mediated apoptosis against viral infections.

In summary, the immune function of vertebrates is intricately linked to their ability to adapt to diverse and extreme environments. Genetic adaptations in immune genes, such as TLRs, and specific immune responses to environmental stressors, play a crucial role in ensuring survival and promoting longevity in these organisms.

5 Case Study: The Naked Mole Rat

5.1 Unique immune characteristics of the naked mole rat

The naked mole rat (Heterocephalus glaber) exhibits several unique immune characteristics that distinguish it from other mammals. Notably, its immune system features a higher myeloid-to-lymphoid cell ratio and lacks natural killer cells, which are typically present in other mammals (Figure 3) (Hilton et al., 2019). Additionally, naked mole rats have a novel subset of neutrophils that are highly responsive to lipopolysaccharides and express several antimicrobial peptides (Lin and Buffenstein, 2021). These immune traits suggest an atypical mode of immunosurveillance and a greater reliance on myeloid-biased innate immunity. Furthermore, the naked mole rat's immune system shows higher pro-inflammatory cytokine production in macrophages, which may contribute to its cancer resistance and longevity.

The study of Hilton et al. (2019) showcases a comparative single-cell RNA sequencing (scRNA-seq) analysis between mouse and naked mole-rat (NM-R) spleens, revealing significant differences in immune cell populations. The UMAP projections highlight the distinct clustering of immune cells in both species, with notable variations in the proportions and gene expression profiles of T cells, NK cells, and other immune cell types. The heatmaps provide a detailed comparison of gene expression levels across different cell clusters, emphasizing the unique immune cell landscape in the NM-R spleen compared to the mouse. This comparison underscores the potential evolutionary adaptations in immune function between these species.

5.2 Correlation between immune function and longevity

The unique immune characteristics of the naked mole rat are closely linked to its extraordinary longevity. Unlike other mammals, naked mole rats do not exhibit an age-related increase in mortality and maintain physiological functions well into old age (Oka et al., 2022). Their immune system's unusual features, such as the absence of natural killer cells and the presence of a novel neutrophil subset, may play a role in their resistance to cancer and other age-related diseases. Additionally, the naked mole rat's immune system appears to be adapted to its subterranean environment, which is low in oxygen and high in carbon dioxide, further contributing to its longevity (Kim et al., 2011). These adaptations may have evolved to protect the naked mole rat from the harsh conditions of its habitat, thereby enhancing its lifespan (Fang et al., 2014).

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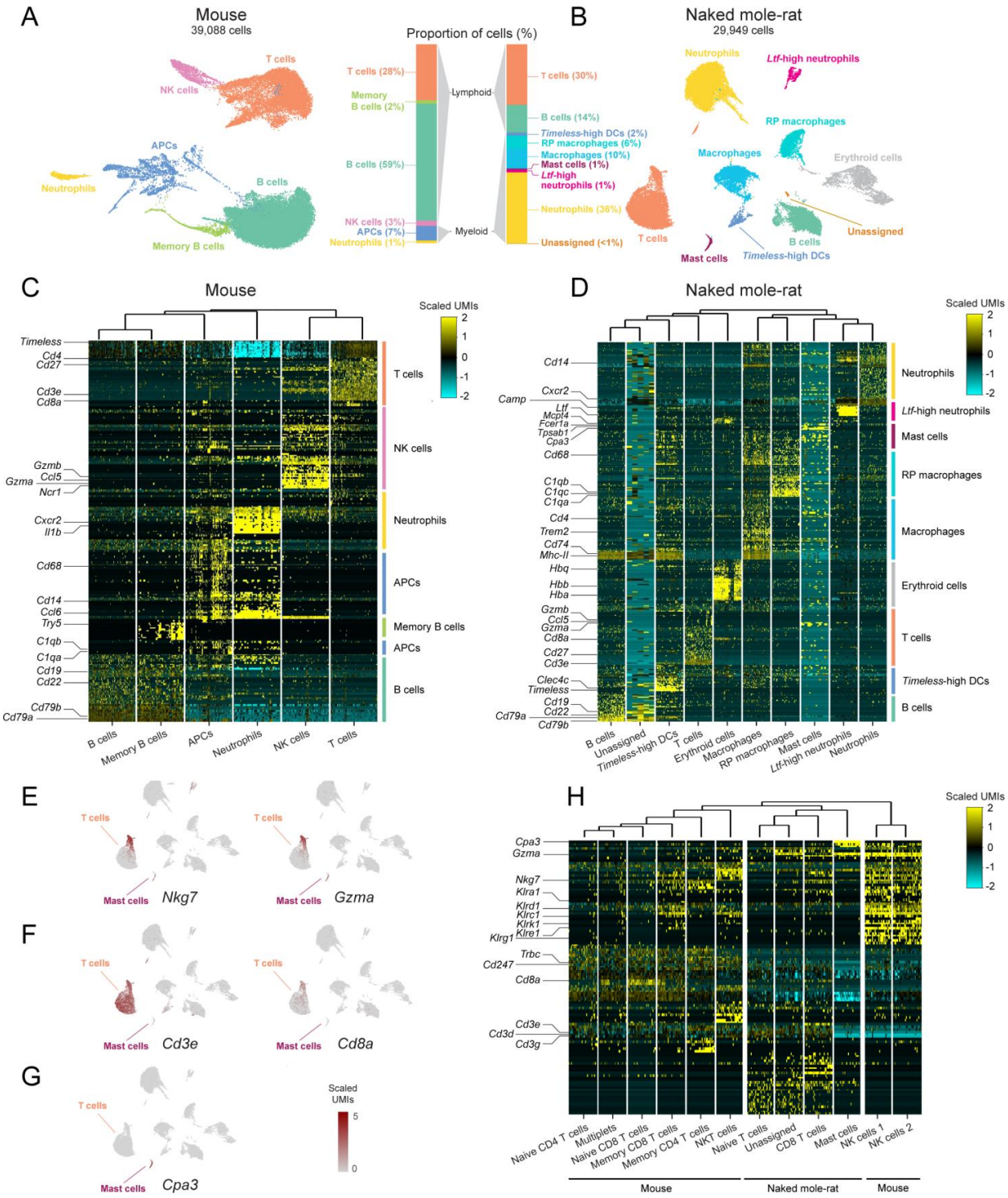

Figure 3 scRNA-seq of mouse and NM-R spleens reveals major differences in immune cell populations (Adopted from Hilton et al., 2019)

Image caption: UMAP projections of four mouse (A) and four NM-R (B) spleens. Each point is a cell color-coded by its cluster assignment and annotated cell type (Materials and methods). The proportions (%) of cells assigned to each cell type in each species (excluding NM-R clusters of erythroid cells) are shown in the stacked bar charts. Gene-by-cell expression-level heatmaps in the mouse (C) and NM-R (D) spleens. Selected marker genes are listed to the left and cells are faceted by their cluster assignment. UMAP projections of the NM-R spleens color-coded by the expression levels of *Nkg7* and *Gzma* (E), *Cd3e* and *Cd8a* (F), and *Cpa3* (G). Gene-by-cell expression-level heatmap of the mouse spleen T cells and NK cell clusters and NM-R spleen T cells and mast cell clusters (H). APC, antigen-presenting cell; DC, dendritic cell; NK, natural killer; NKT, natural killer T; NM-R, naked mole-rat; RP, red pulp; scRNA-seq, single-cell RNA-sequencing; UMAP, uniform manifold approximation and projection; UMI, unique molecular identifier (Adopted from Hilton et al., 2019)

5.3 Lessons from the naked mole rat for understanding vertebrate longevity

The study of the naked mole rat provides valuable insights into the mechanisms underlying vertebrate longevity. The naked mole rat's unique immune system, combined with its resistance to cancer and other age-related diseases, challenges traditional theories of aging and suggests that immune function plays a critical role in longevity. By understanding the molecular and genetic adaptations that contribute to the naked mole rat's long lifespan, researchers can identify potential targets for interventions aimed at extending human healthspan and lifespan (Heinze et al., 2017). For instance, the naked mole rat's low circulating levels of specific amino acids and its unique metabolomic profile resemble those observed in other long-lived species, indicating that metabolic pathways may be key determinants of longevity (Lewis et al., 2018). Additionally, the naked mole rat's ability to maintain physiological functions and resist age-related decline provides a model for studying successful aging and developing strategies to mitigate the effects of aging in humans (Edrey et al., 2011).

6 Interplay Between Immune Function, Longevity, and Disease Resistance

6.1 Immune function as a balancing act between longevity and disease resistance

The immune system plays a crucial role in maintaining health and longevity in vertebrates. However, the relationship between immune function and longevity is complex and often involves trade-offs. For instance, the splicing factor RNP-6/PUF60 has been shown to suppress immunity while promoting longevity in C. elegans, indicating a trade-off between these processes (Kew et al., 2020). Similarly, the transcription factor TCER-1 in C. elegans enhances longevity but represses immunity, suggesting that mechanisms promoting lifespan may concurrently suppress immune responses to balance energy expenditure and physiological demands (Ghazi et al., 2019). These findings highlight the intricate balancing act between maintaining robust immune defenses and promoting longevity.

6.2 Trade-offs between immune response and other physiological processes

Trade-offs between immune function and other physiological processes are well-documented across various vertebrate species. For example, in desert tortoises (*Gopherus agassizii*), a trade-off exists between natural antibodies (innate immunity) and acquired antibodies (adaptive immunity), with long-term elevations in acquired antibodies potentially compromising other physiological functions (Sandmeier et al., 2012). In loggerhead musk turtles (*Sternotherus minor*), sex-based differences in immune responses suggest that males with higher body condition indices exhibit more stressed phenotypes, indicating a trade-off between maintaining body condition and immune function. Additionally, in Drosophila Cytoraces, long-lived individuals exhibit reduced immune responses when challenged with pathogens, further supporting the existence of trade-offs between lifespan and immunity (Sinam et al., 2016).

6.3 Examples from vertebrate species: the cost of immunity

The cost of immunity is evident in various vertebrate species, where maintaining a robust immune system can come at the expense of other life history traits. For instance, in the study of loggerhead musk turtles, males with higher body condition indices showed more stressed phenotypes, suggesting that the energy allocated to maintaining body condition may detract from immune function (López-Pérez et al., 2020). In desert tortoises, the long-term elevation of acquired antibodies indicates a significant investment in adaptive immunity, which may impact other physiological processes. Furthermore, the study on *C. elegans* revealed that the splicing factor RNP-6/PUF60 and the transcription factor TCER-1 both promote longevity at the cost of immune suppression, illustrating the evolutionary trade-offs between immunity and lifespan. These examples underscore the complex interplay between immune function, longevity, and disease resistance in vertebrates, where the cost of immunity must be balanced against other physiological demands to optimize survival and reproductive success.

7 Implications for Conservation and Wildlife Management

7.1 The role of immune function in species survival

Immune function plays a critical role in the survival and longevity of vertebrate species. Studies have shown that body condition and immune responsiveness are significant predictors of long-term survival and reproductive success in wild populations. For instance, in a study on house wrens, neonates with higher immune responsiveness and intermediate hematocrit levels were found to have higher recruitment and longevity, indicating that robust

immune function is essential for individual fitness and species survival (Bowers et al., 2014). Additionally, the interplay between immune function and oxidative stress has been highlighted as a key factor in the adaptability of species to environmental changes, suggesting that immune function is a crucial determinant of species resilience (Costantini, 2022).

7.2 Impacts of environmental changes on immune function

Environmental changes, such as habitat degradation and the removal of large wildlife, have significant impacts on the immune function of vertebrates. A meta-analysis revealed that birds and mammals in degraded forests exhibit higher stress hormone levels and altered immune markers compared to those in undisturbed forests, indicating that habitat degradation can compromise immune function and, consequently, species adaptability (Messina et al., 2018). Similarly, the selective removal of large wildlife has been shown to drive increases in immune function in small rodents, likely due to increased pathogen pressure and changes in food resources, which underscores the complex relationship between environmental changes and immune health. These findings highlight the need to consider environmental factors when assessing the health and survival prospects of wildlife populations.

7.3 Conservation strategies incorporating immune function

Incorporating immune function into conservation strategies can enhance the effectiveness of wildlife management efforts. Understanding the physiological and immunological responses of species to environmental stressors can inform targeted interventions aimed at mitigating the impacts of habitat degradation and other anthropogenic disturbances. For example, conservation programs can benefit from monitoring oxidative stress markers and immune responses to better understand the health status and adaptability of species in changing environments. Additionally, recognizing the role of immune function in species survival can lead to the development of strategies that enhance immune health, such as habitat restoration and the protection of key resources that support robust immune responses (Young et al., 2016). By integrating immune function into conservation planning, we can improve the resilience of wildlife populations and support their long-term survival in the face of environmental challenges.

8 Future Directions

8.1 Emerging research areas

Recent studies have highlighted several emerging areas in the field of immune function and its role in longevity and adaptation in vertebrates. One promising area is the exploration of the metabolic pace-of-life model, which suggests that metabolic rate and pace of life can predict a species' investment in adaptive immune function. This model, particularly studied in reptiles, posits that animals with low metabolic rates invest more in innate immunity, while those with high metabolic rates optimize adaptive immune responses (Sandmeier and Tracy, 2014). Additionally, the concept of innate immune memory, or "trained immunity," is gaining traction. This paradigm shift suggests that innate immunity can adapt and build memory, similar to adaptive immunity, through mechanisms such as epigenetic reprogramming.

Another emerging area is the study of glial immunity in neuroprotection and lifespan determination. Research in Drosophila melanogaster has shown that glial cells play a crucial role in maintaining organismal health and longevity, with implications for understanding age-related pathologies in higher vertebrates (Kounatidis and Chtarbanova, 2018). Furthermore, the evolution of transgenerational immunity in invertebrates provides insights that could be applicable to vertebrates, particularly in understanding how long lifespan and low dispersal promote the evolution of immune traits (Pigeault et al., 2016).

8.2 Potential for translational research in medicine and conservation

The findings from these emerging research areas have significant potential for translational research in both medicine and conservation. For instance, understanding the metabolic pace-of-life model can inform medical strategies to enhance immune function in humans, particularly in managing diseases that involve immune dysregulation. The concept of trained immunity opens new avenues for developing therapies that harness the adaptive capabilities of the innate immune system to provide long-term protection against infections and possibly even cancer (Netea et al., 2016).

In conservation, insights into the immune function of reptiles and other understudied vertebrates can aid in the development of strategies to protect endangered species. By integrating ecoimmunological concepts with traditional immunological studies, researchers can better understand how environmental and life-history variables influence immune responses, leading to more effective conservation efforts (Field et al., 2022). Additionally, the study of glial immunity in model organisms like Drosophila can provide a basis for developing interventions to mitigate neurodegenerative diseases in wildlife, thereby enhancing their survival and longevity.

8.3 Integrating immune function studies into longevity and adaptation research

To fully understand the role of immune function in longevity and adaptation, it is crucial to integrate immune function studies into broader research on these topics. This involves examining the co-evolution of innate and adaptive immunity across different vertebrate lineages to identify conserved mechanisms that contribute to longevity (Boehm, 2012; Boehm et al., 2012). Comparative studies on B cell immunity in jawed and jawless vertebrates can also provide valuable insights into the evolution of immune strategies and their impact on lifespan (Parra et al., 2013).

Moreover, integrating ecological and evolutionary perspectives can help elucidate how adaptive genetic factors influence immune function and longevity. For example, the hitchhiking of adaptive genetic changes may play a significant role in lifespan extension, suggesting that natural selection indirectly favors genetic traits that enhance immune function and disease resistance (Omotoso et al., 2021). By combining these approaches, researchers can develop a more comprehensive understanding of how immune function contributes to the adaptive strategies that promote longevity in vertebrates.

In conclusion, the integration of immune function studies into longevity and adaptation research holds great promise for advancing our understanding of vertebrate biology. By exploring emerging research areas, leveraging translational potential, and adopting integrative approaches, we can uncover the complex interplay between immune function, longevity, and adaptation, ultimately leading to novel insights and applications in both medicine and conservation.

9 Concluding Remarks

The role of immune function in vertebrate longevity and adaptation is multifaceted and deeply interconnected with evolutionary processes. Adaptive immunity, traditionally considered a hallmark of vertebrates, has been shown to blur the lines with innate immunity, suggesting a more complex evolutionary history than previously thought. The emergence of adaptive immunity in vertebrates, occurring independently in jawless and jawed fishes, underscores its critical role in vertebrate evolution. Additionally, the trade-offs between immunity and longevity are evident, with neural and genetic mechanisms playing significant roles in balancing these traits. Studies in model organisms like Drosophila have highlighted that genetic changes in immune regulation can significantly impact longevity, suggesting that immune function is a key factor in the evolution of lifespan. Furthermore, ecological studies in wild populations, such as house wrens, have demonstrated that immune responsiveness and other health metrics are predictive of long-term survival and reproductive success.

The intricate relationship between immune function and longevity in vertebrates is a testament to the evolutionary pressures that shape these traits. The adaptive immune system, with its ability to remember and respond more effectively to pathogens, provides a significant survival advantage, particularly in long-lived species. However, this comes at a cost, as maintaining a robust immune system requires substantial energy investment, which can impact other life history traits such as reproduction and growth. The trade-offs between immunity and longevity are mediated by complex genetic and neural mechanisms, as seen in studies involving transcription factors and signaling pathways. These findings highlight the importance of immune function not only in immediate survival but also in the broader context of evolutionary fitness and adaptation. As we continue to unravel the genetic and ecological underpinnings of these relationships, it becomes clear that immune function is a cornerstone of vertebrate biology, influencing both the lifespan and the adaptive capabilities of species across diverse environments.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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