Nutrition and the Immune System: Dietary Strategies for Disease Defense

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Abstract

The immune system is the body's main line of defense against infectious agents, which is typically divided into two main types: innate and adaptive immunity. Innate immunity allows immediate, non-specific responses via physical barriers and immune cells; in contrast, adaptive immunity generates tailored responses to specific pathogens mediated by lymphocytes. The contents of this chapter deal with the more complicated parts of the immune system's recognition of pathogens, cytokines, antibodies, cellular cytotoxicity on the elimination of pathogens, and disruptions in the immune system. These disturbances, autoimmune diseases, and hypersensitivity reactions can greatly affect health and are best managed by specific therapies.' It also addresses the role of lifestyle in immunity, including dietary influences and physical activity, as well as recent developments in immunotherapy. New scientific data reveal that the microbiome plays an indispensable part in regulating immunity; therefore, it is crucial to maintain a healthy gut. Understanding these changes, we can see the importance of the immune system in disease prevention and face future research, which will allow the improvement of immune health and resilience.

Keywords: Immune response, Pathogen recognition, Adaptive immunity, Innate defense mechanisms, Immunological memory

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Introduction

Itroduction to Immune System Functions

The immune system is a set of interacting cells, tissues, and organs (Figure 1) that work as a team to protect the body from health-deteriorating pathogens such as bacteria, viruses, fungi, and parasites. The key function of the immune system is to recognize these foreign invaders, to react to them, to eliminate them, and to remember them for more effective defense (Figure 4, 5, 6) in the future. Moreover, besides controlling the crowd outside, the immune system also checks the premise for any intruders or abnormal cells that could later develop into cancer, thus being the main player in the whole body's well-being and homeostasis (Nicholson, 2016; McComb et al., 2019) .

Memory

The immune response's capacity to remember previous infections protects people from reinfection and inhibits disease transmission in groups. Immune memory may be extremely long-lasting; for example, studies demonstrate that memory for a measles infection decays so slowly that it would take over 3,000 years to diminish by half, offering lifelong protection.

Immune memory is dispersed throughout the body, with circulating antibodies in the blood and memory cells in tissues that are prepared to respond quickly if reinfection happens (Figure 3). Some illnesses can have a tremendous impact on a species, altering evolutionary pathways. Only those with efficient resistance genes survive and pass them down, revealing how host-pathogen co-evolution modifies immune systems and pathogen recognition mechanisms.

All immune systems address such challenges through an integrated variety of biological processes, uncovering techniques that continue to surprise researchers and enhance our understanding of immunology (Fig. 2) (Nicholson, 2016).

Detailed Mechanisms of Immune Recognition

The immune system employs highly specific mechanisms for identifying and reacting to infections, primarily through the actions of B cells and T cells. Specialized receptors called T cell receptors (TCRs) and B cell receptors (BCRs) are used by these lymphocytes—to identify antigens and initiate an immune response.

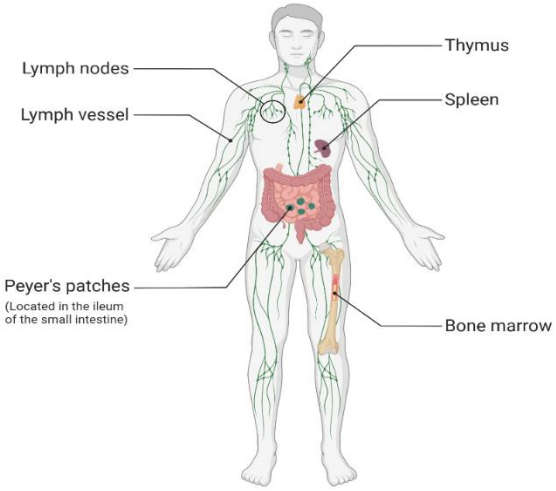

Fig. 1: Immune Organs in Human Body Created in BioRender. Noor, M. (2025)

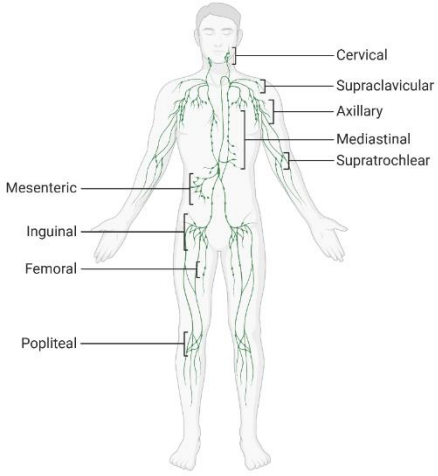

Fig. 2: Lymph Nodes Locations Created in BioRender. Noor, M. (2025)

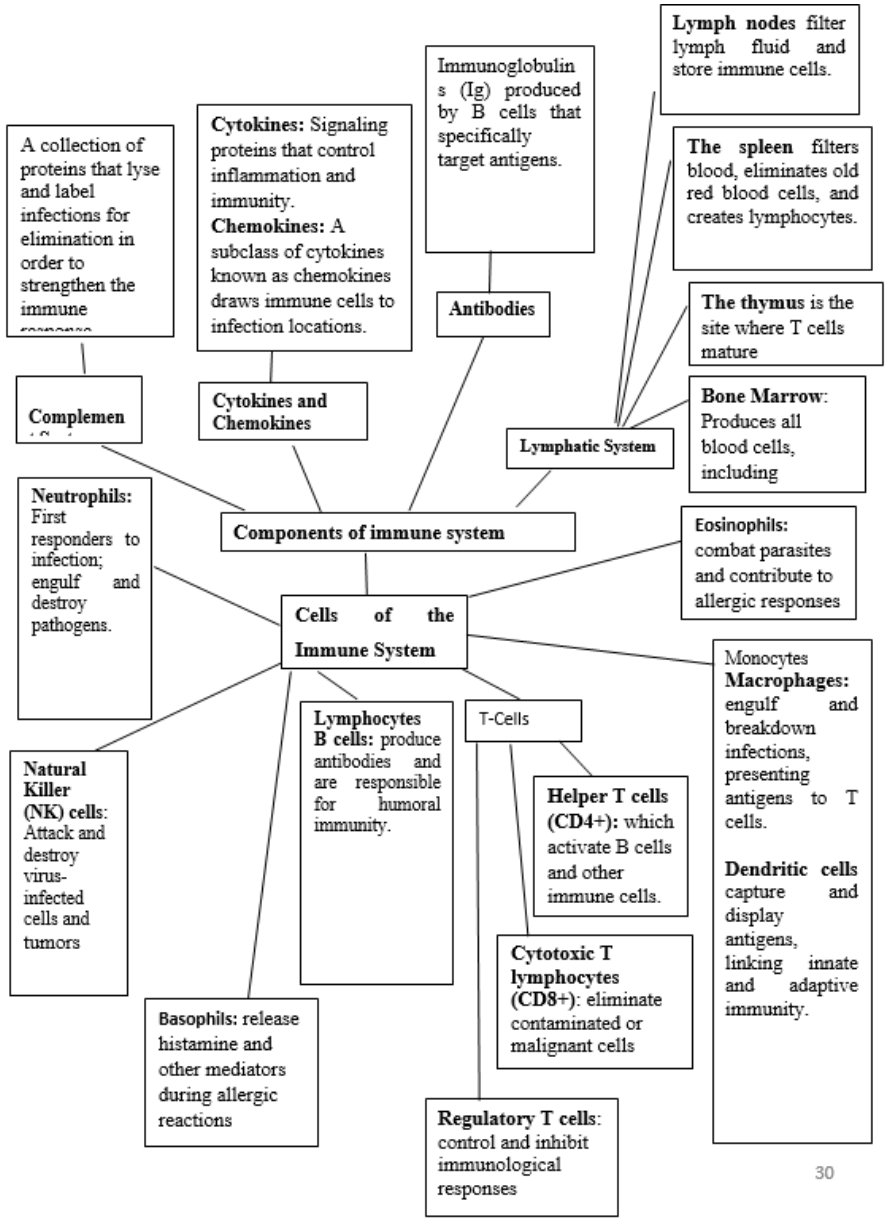

Fig. 3: Components of Immune System (Abbas et al., 2015a; Liao & von der Weid, 2015; Lubbers et al., 2017; Marshall et al., 2018).

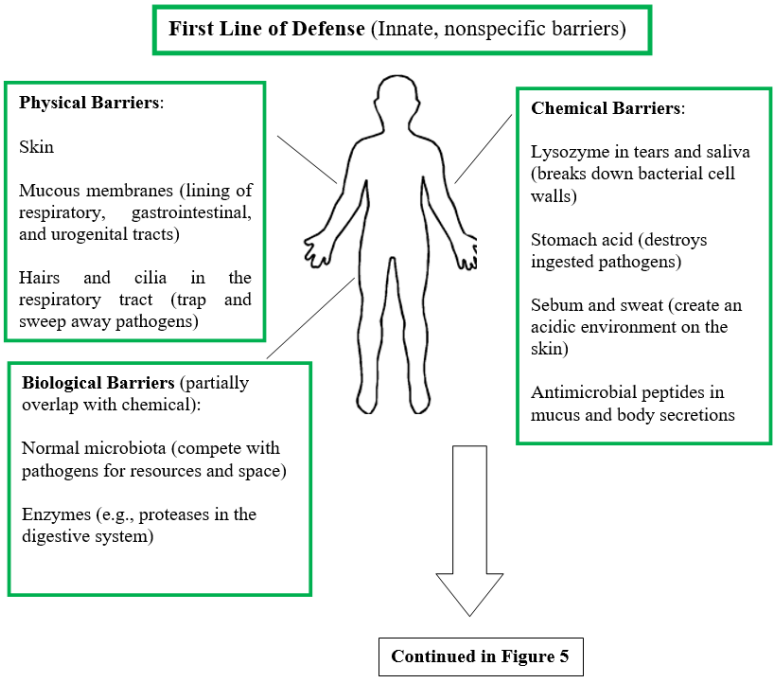

Fig. 4: First Line of Defense.

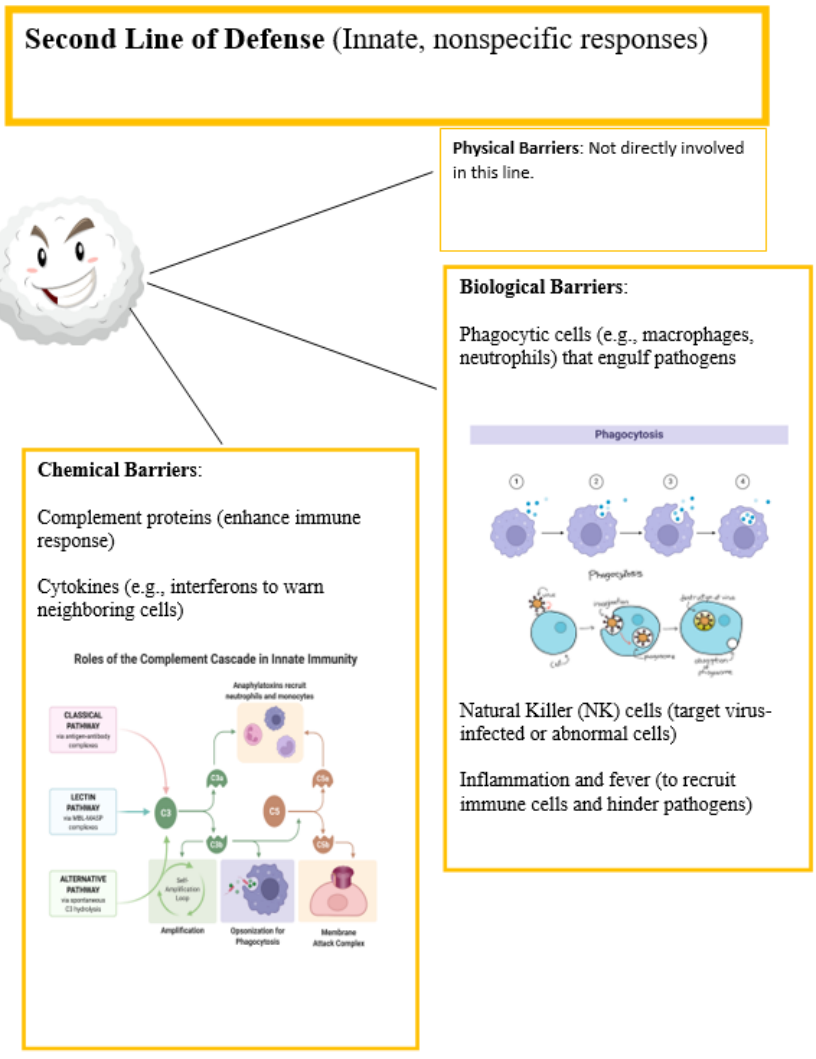

Fig. 5: Second Line of Defense

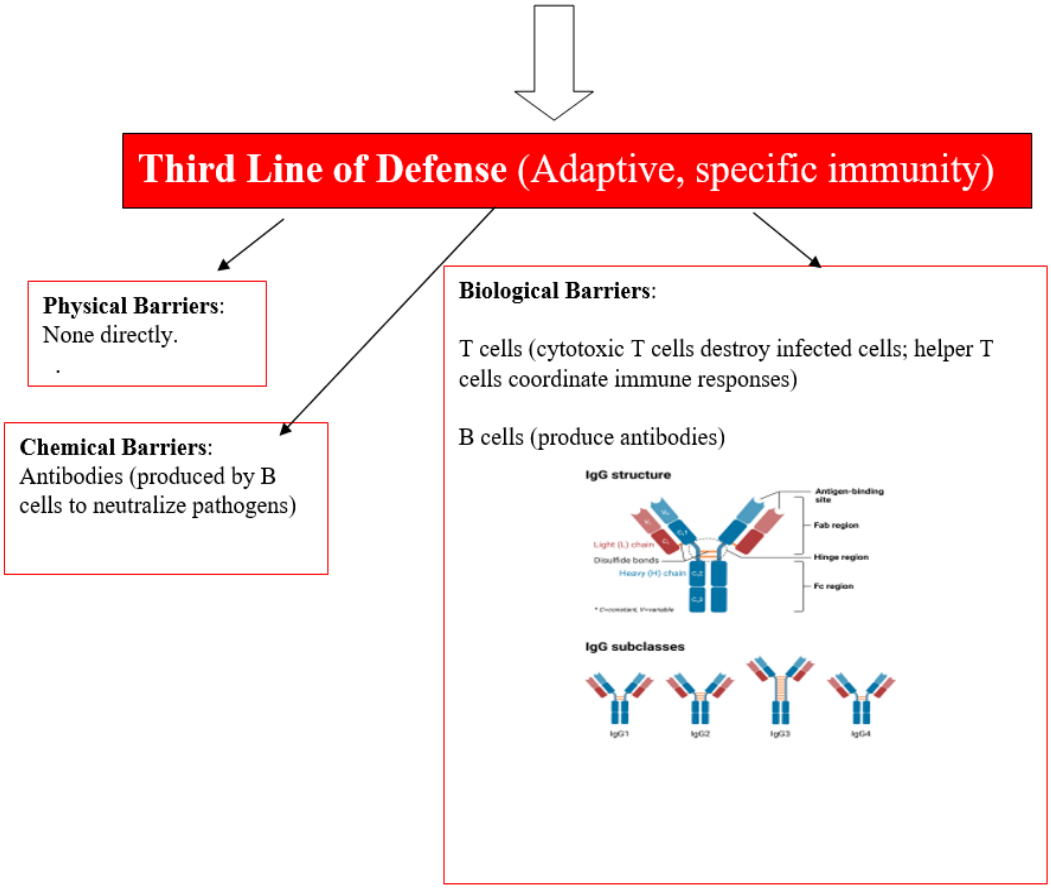

Fig. 6: Third Lines of Defense in the Immune System and Associated Barriers (Takiishi et al., 2017; Okumura & Takeda, 2018; Nguyen & Soulika, 2019; Yoo et al., 2020).

B Cell Recognition of Antigens

B cells recognize antigens through their B cell receptors (BCRs), which are membrane-bound immunoglobulins specific to particular antigens. Each B cell is programmed to recognize a unique antigen. The BCR structure is Y-shaped, consisting of two heavy and two light chains, with antigen-binding sites at the tips of the Y that provide specificity. B cells can bind directly to native antigens, such as whole pathogens or soluble antigens. Upon binding, the B cell becomes activated, leading to processes like class switching (producing different antibody types, e.g., IgM, IgG) and affinity maturation (enhancing antigen-binding strength). Although B cells can recognize native antigens independently, full activation often requires interaction with helper T cells (CD4+ T cells) through the presentation of processed antigens.

T Cell Recognition of Antigens

T cells recognize antigens via their T cell receptors (TCRs)**,** which bind to peptide fragments presented by Major Histocompatibility Complex (MHC) molecules (Figure 7). Unlike BCRs, TCRs consist of two chains (alpha and beta) and cannot bind free antigens. MHC molecules are classified into two types: MHC Class I, present on nearly all nucleated cells, which display endogenous peptides to CD8+ cytotoxic T cells, enabling them to identify and destroy infected or abnormal cells; and MHC Class II, expressed on professional antigen-presenting cells (APCs) like dendritic cells, macrophages, and B cells, which present exogenous peptides to CD4+ helper T cells. T-cell activation requires the peptide-MHC complex to bind the TCR and additional co-stimulatory signals. These signals typically involve CD28 on T cells interacting with CD80/CD86 on APCs. Once activated, CD8+ T cells directly kill infected cells, while CD4+ T cells differentiate into subtypes (e.g., Th1, Th2, Th17) that orchestrate the immune response.

The intricate mechanisms of immune recognition through BCRs and TCRs are fundamental to the adaptive immune response. B cells primarily recognize intact antigens, while T cells require processed peptides presented by MHC molecules. This specificity ensures a tailored immune response to various pathogens, allowing for effective defense and long-term immunity through memory formation. Understanding these mechanisms is crucial for developing vaccines and immunotherapies which harness the power of the immune system (Figure 8, 9) (Shevyrev et al., 2021; Rappazzo et al., 2023).

Importance in Disease Prevention and Control

The immune system's capacity to recognize, respond to, and recall pathogens is critical for avoiding diseases. By detecting and eliminating harmful invaders, it protects against serious illnesses. Adaptive immunity (Figure 10), with its memory cells, provides long-term protection and helps control disease spread. A robust immune system helps keep the severity of infections and recovery from diseases in check, whereas

a weak immune system makes the body more susceptible to disease — therefore maintaining an efficient immune system is essential for disease prevention and improved health (Sompayrac, 2022).

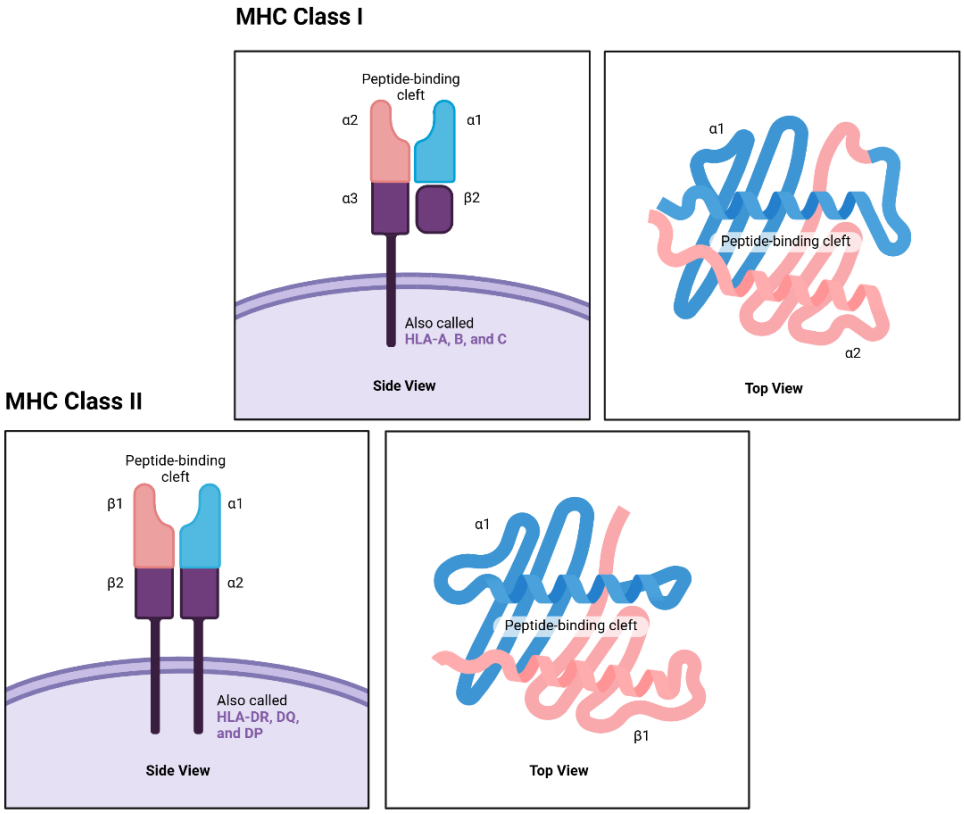

Fig. 7: Major Histocompatibility Complex. Created in https://BioRender.com

Types of Immunity

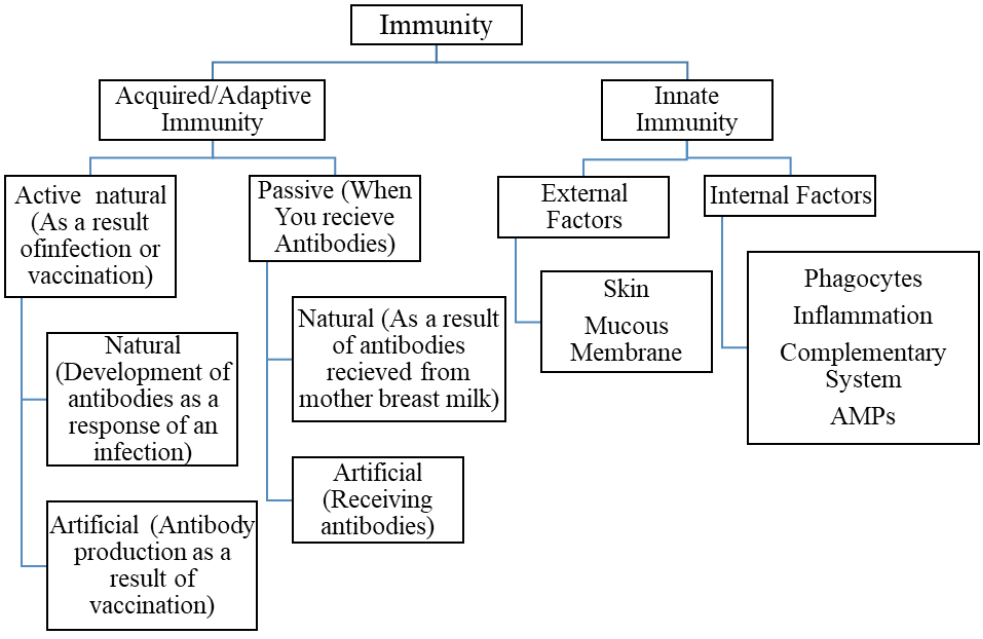

Fig. 8: Types of Immunity (Abbas et al., 2015; Mishra et al., 2017; DuBourdieu, 2019)

Recognition of Pathogens

Mechanisms of Antigen Recognition

Specific molecules called antigens tell the immune system that something belongs to a pathogen. Most antigens are surface proteins or polysaccharides of pathogens. immune cells, such as B and T lymphocytes, recognize these antigens through specialized receptors on which they bind and then an immune response is initiated (Sela-Culang et al., 2013; Rossjohn et al., 2015).

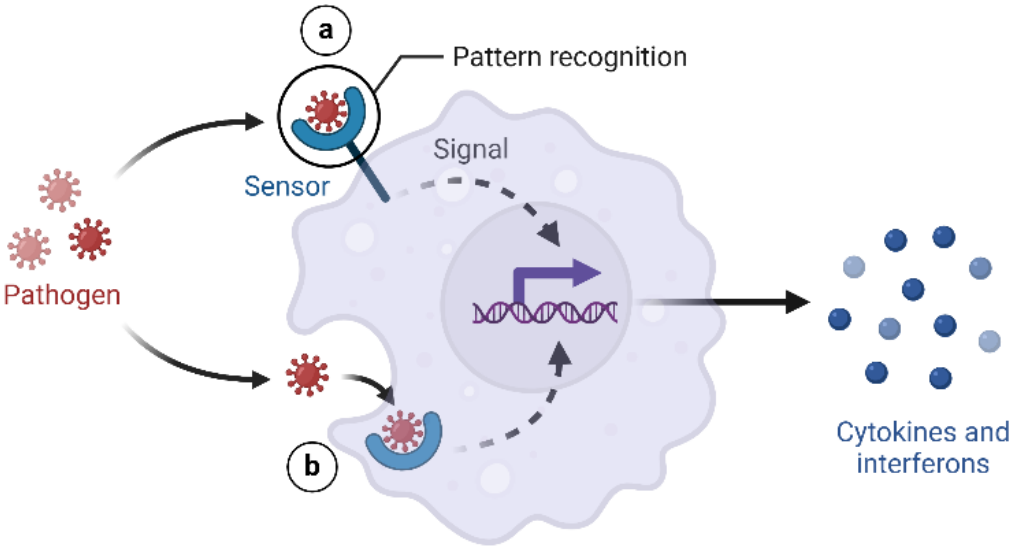

Fig. 9: Innate Immunity. Created in BioRender. Noor, M. (2025) https://BioRender.com/x25d468

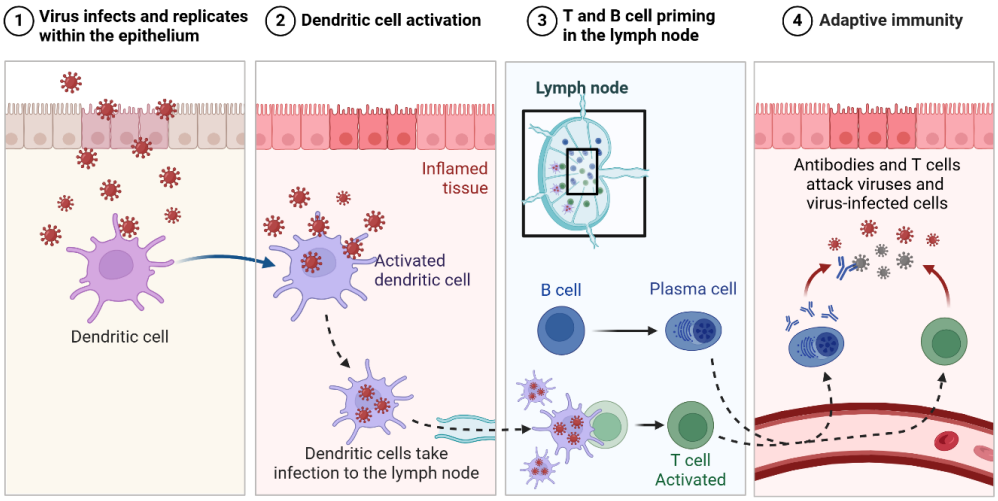

Fig. 10: Adaptive Immunity Created in BioRender. Noor, M. (2025) https://BioRender.com/n19r533

Pathogen-Associated Molecular Patterns (PAMPs) and Pattern Recognition Receptors (PRRs)

Unique molecular signatures on the pathogen known as pathogen-associated molecular patterns (PAMPs) on the pathogen differentiate it from host cells. Pattern recognition receptors (PRRs) identify patterns (PAMPS) and a subsequent innate immune response is triggered. One type of PRR that is very prevalent is toll-like receptors (TLRs) which detect a variety of PAMPs resulting in the activation of macrophages and dendritic cells (Kaczmarek et al., 2013; Huang et al., 2015).

Response to Pathogens

Cytokine Production and Signaling Pathways

When pathogens are recognized, immune cells produce cytokines, molecules that signal immunity and inflammation. The cytokines of interest are the interleukins and tumor necrosis factor-alpha (TNF-α) which orchestrate the immune response by bringing more immune cells to the site of infection and enhancing their functionality (Figure 11) (Reddick & Alto, 2014; Turner et al., 2014).

Phagocytosis and Cellular Killing Mechanisms

Phagocytosis is a very critical innate immune mechanism used by macrophages and neutrophil cells. During this process, phagosomes are formed to wall off the pathogen, and they fuse with lysosomes containing digestive enzymes, which digest the pathogen. Furthermore, many immune cells directly kill pathogens by releasing, for example, reactive oxygen species (ROS) (Lu et al., 2014; Gordon, 2016).

Antibody Production and Neutralization

B lymphocytes are part of the adaptive immune system that generates an antibody. These antibodies only bind to antigens on pathogens, and block them or mark them for destruction by other immune cells. Targeting specific infections and providing long-term immunity are all part of this process (Forthal, 2014; Klasse, 2014).

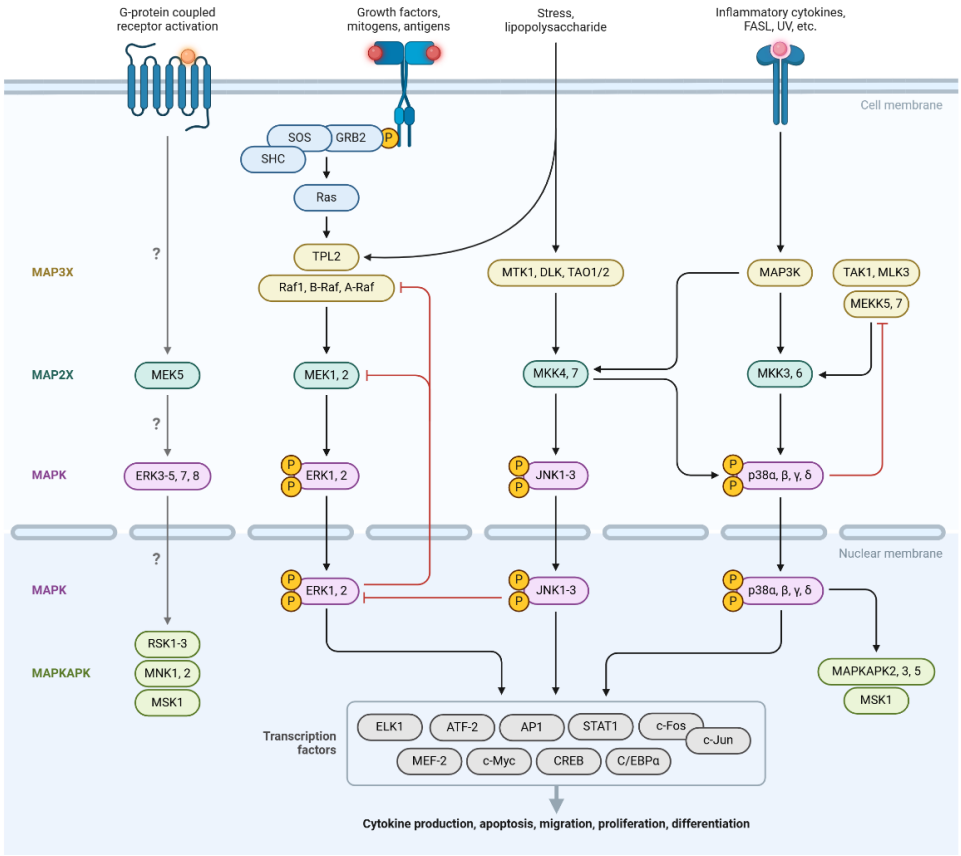

Fig. 11: MAPK Signaling Pathway. Created in BioRender. Noor, M. (2025) https://BioRender.com/d55n271

Elimination of Pathogens

Role of Complement System

In the complement system, protein series exist that increase the ability of antibodies and phagocytic cells to clear pathogens. Opsonization (marking pathogens for destruction), the recruitment of inflammatory cells, and the formation of the membrane attack complex, the MAC, which can lyse pathogen cell membranes directly, are pathogen-specific functions that result from the activation of the complement cascade (Figure 12) **(**Merle, et al., 2015**;** Merle, et al., 2015).

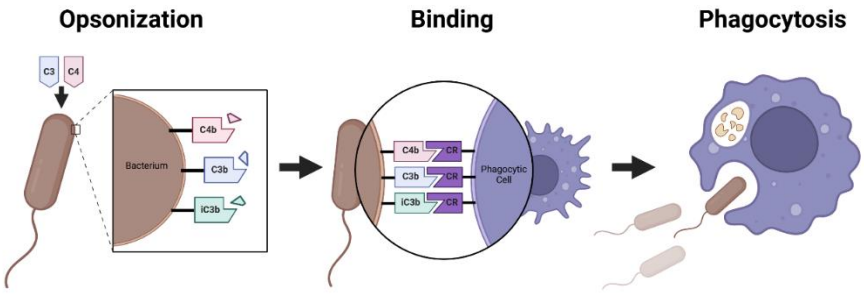

Fig. 12: Role of Complement System in Opsonization and Phagocytosis. Created in BioRender. Noor, M. (2025) https://BioRender.com/b45a569

Cellular Cytotoxicity (Natural Killer Cells, Cytotoxic T Cells)

Natural killer (NK) cells and cytotoxic T lymphocytes (CTLs) are important cells to kill infected or cancerous cells. Consequently, NK cells specifically recognize stressed or infected cells without previous sensitization, while CTLs depend on antigen presentation by major histocompatibility complex (MHC) molecules. For both cell types, cytotoxic granules containing perforin and granzyme induce target cell apoptosis (Kumar, 2018; Prager & Watzl, 2019)

Apoptosis and Clearance of Infected Cells

Programmed cell death (apoptosis) is a mechanism that exists in order to remove infected or damaged cells without causing subsequent inflammation. This is an important process to maintain tissue homeostasis and to stop spread of infection. After apoptosis, phagocytic cells get rid of the remnants of dead cells to prevent further danger of provoking inflammation or a secondary infection. Together, these defense mechanisms comprise a strong system that defenses the body against a vast number of infectious agents, avoiding damage to self-tissues (Figure 13) (Poon et al., 2014; Nagata, 2018).

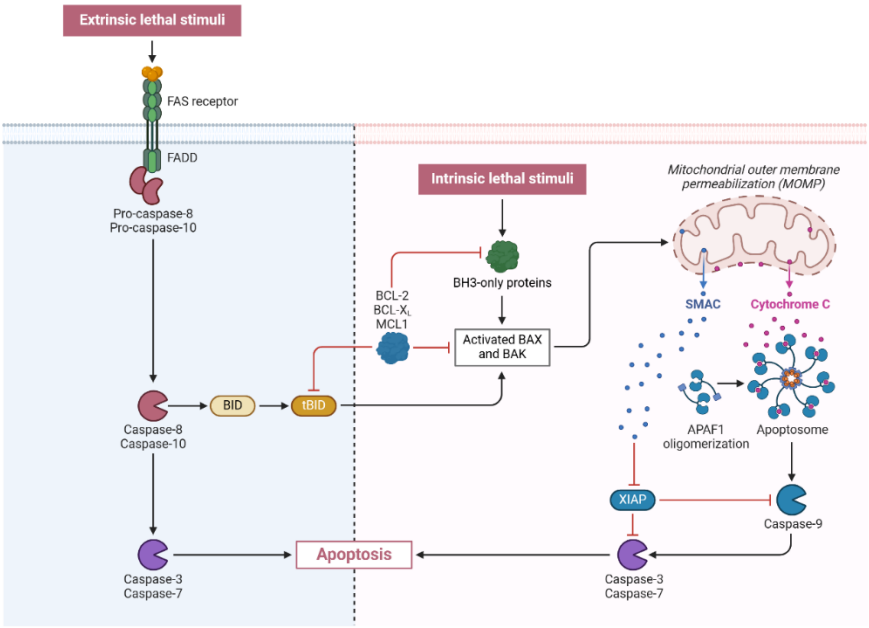

Fig. 13: Apoptosis (Extrinsic vs Intrinsic Pathway). Created in https://BioRender.com

Immune System Disorders

In general, immune system disorders are classified into immunodeficiency diseases, autoimmune diseases, and hypersensitivity reactions. There are a variety of conditions within each category that affect the immune system's ability to work correctly.

Immunodeficiency Diseases

Primary (Congenital) Immunodeficiencies

Primary immunodeficiencies are usually genetic disorders visible at birth early infancy, or early childhood. Severe Combined Immunodeficiency (SCID) is one of the most severe forms and here cells of both the T and B lymphocyte groups are severely deficient, which in turn predisposes the patient to increased infection. Several different genes can be mutated causing SCID, with the most common type being X-linked SCID (McCusker et al., 2018).Often these disorders cause recurring infections and if not treated appropriately can cause chronic health issues.

Secondary (Acquired) Immunodeficiencies

Secondary immunodeficiencies appear later in life and are usually due to exposure to infection, medication, or other disease. A secondary immunodeficiency such as HIV/AIDS is a great example of HIV (a virus) attacking the CD4+ T cells component of the immune system, preventing the immune response, leaving the host open to opportunistic infections, and cancer (Figure 14) (Tuano et al., 2021). This may also be caused by other illnesses such as diabetes or cancer that weaken immune function.

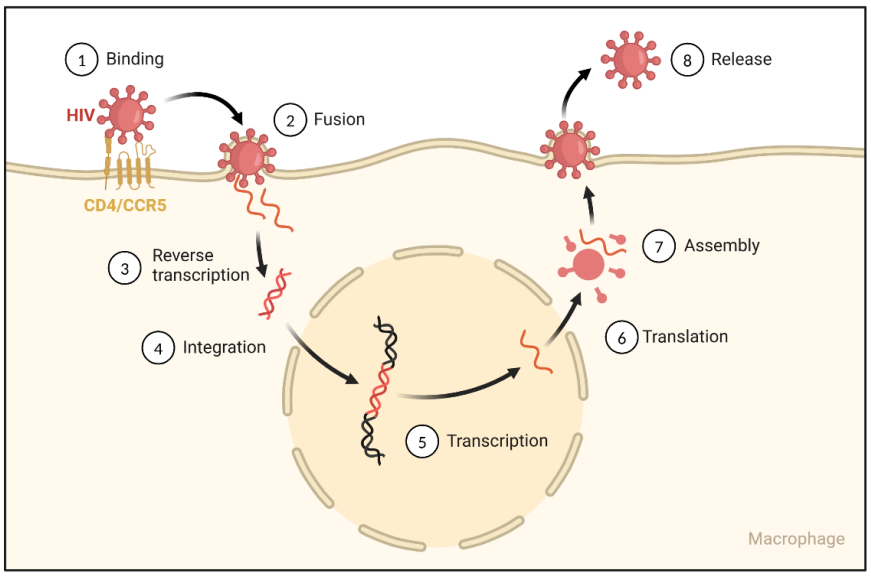

Fig. 14: HIV Mechanism of Action. Created in BioRender. Noor, M. (2025) https://BioRender.com/m31f133

Autoimmune Diseases

In autoimmune diseases, the immune system attacks the body's own tissues. Their dysregulation may be a result of a genetic predisposition along with environmental triggers.

Mechanisms of Autoimmunity

Autoimmunity often is the complex interaction between genetic factors, epigenetic addition, and environmental influences. More specifically, some genes involved in the regulation of the immune system, while properly regulated, may become dysregulated and result in an inappropriate immune response to self-antigens.

Examples: Rheumatoid Arthritis, Type 1 Diabetes, Lupus

- **Rheumatoid Arthritis (RA):** A disease in which the body's own immune system destroys healthy body tissue, causing inflammation and pain in joints (Figure 15).

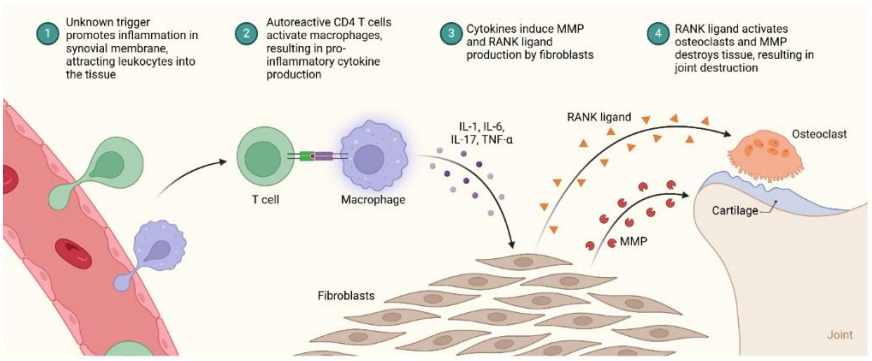

Fig. 15: Pathogenesis of Rheumatoid Arthritis. Created in https://BioRender.com

- **Type 1 Diabetes:** In this condition, the body's immune system attacks insulin-producing beta cells in the pancreas, causing high blood sugar levels to result.
- **Systemic Lupus Erythematosus (SLE):** An autoimmune illness that affects several organ systems and can cause a variety of symptoms (Figure 16) (Wang et al., 2015).

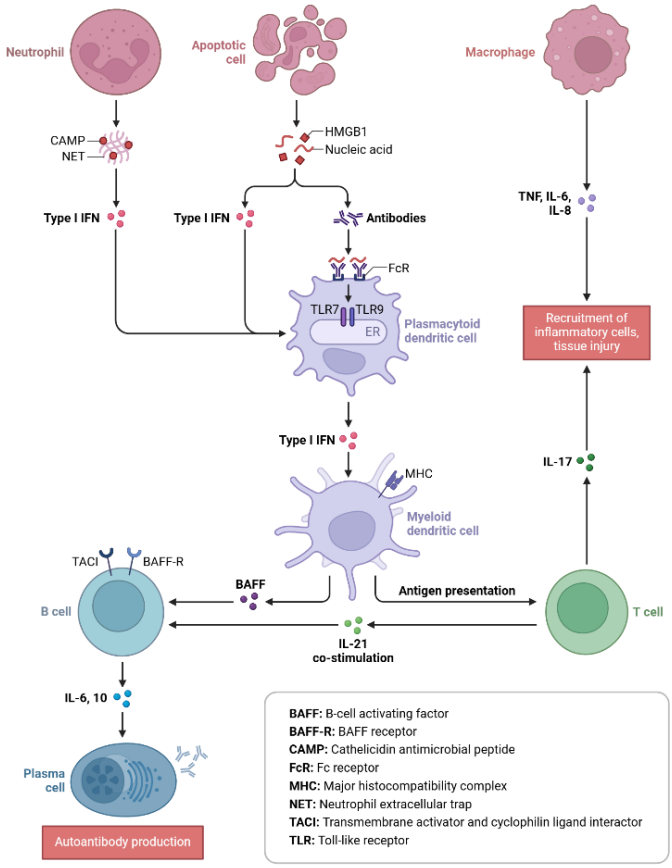

Fig. 16: Immunopathogenesis of Systemic Lupus Erythematosus Created in BioRender. Noor, M. (2025) https://BioRender.com/jo1m831

Hypersensitivity Reactions

Exaggerated immune responses that might harm tissue are known as hypersensitivity reactions. According to their mechanisms, they are divided into four categories.

Types I–IV Hypersensitivity

Type I: Anaphylaxis and allergies are instances of immediate hypersensitivity caused by IgE antibodies.

Type II: Hemolytic anemia is an example of type II cytotoxic responses, which are mediated by IgG or IgM antibodies.

Type III: Reactions mediated by the immune complex; seen in diseases such as SLE and RA.

Type IV: T cell-mediated delayed-type hypersensitivity; contact dermatitis is one example (Dispenza, 2019).

Allergies and Anaphylaxis

Type I hypersensitivity frequently manifests as allergies, symptoms including swelling, itching, and respiratory distress when exposed to allergens. Severe allergic reactions like anaphylaxis can be fatal if epinephrine is not administered right away (Cardona et al., 2020; Shaker, 2024). These disorders highlight the complexity of the immune system and its critical role in maintaining health while also posing risks when dysregulated. Understanding these conditions is essential for developing effective treatments and management strategies.

Viral Infections and Immune Response

The immune system responds to viral infections by detecting viral particles and initiating both innate and adaptive immune responses. The innate response is the first to activate, with natural killer cells targeting virus-infected cells (Koyama et al., 2008). Adaptive immunity follows, with T cells recognizing and attacking cells presenting viral antigens, and B cells producing antibodies to neutralize the virus. Together, these responses help clear the infection and create memory cells to prevent future infections by the same virus (Muhammad et al., 2024).

Mechanisms of Viral Evasion

Viruses have evolved various mechanisms to evade immune detection and response. Some viruses, like HIV, hide within host cells to avoid immune surveillance. Others mutate rapidly, as seen with influenza, altering surface proteins to avoid antibody recognition. Some viruses, such as herpes simplex, can enter latency, remaining dormant in cells and reactivating later, thus evading long-term immune responss (Bertoletti & Ferrari, 2013; Chen et al., 2018).

Role of Interferons and Cellular Immunity

Interferons are critical cytokines in antiviral defense, signaling nearby cells to heighten their antiviral defenses and inhibit viral replication. These proteins activate immune cells like macrophages and natural killer cells to clear infected cells, while also enhancing the antigen presentation needed for adaptive immunity. Interferons bridge the innate and adaptive responses, coordinating a strong cellular immunity that includes cytotoxic T cells, which specifically target infected cells (Crouse et al., 2015: Zhou et al., 2018).

Bacterial Infections and Immunity

The immune system combats bacterial infections through various mechanisms, including antibody production and phagocytosis. Neutrophils and macrophages play key roles in engulfing and digesting bacteria, while antibodies tag bacteria for destruction. Moreover, complement cells form membrane attack complexes that puncture bacterial cell walls causing loss of cell viability (Figure 17).

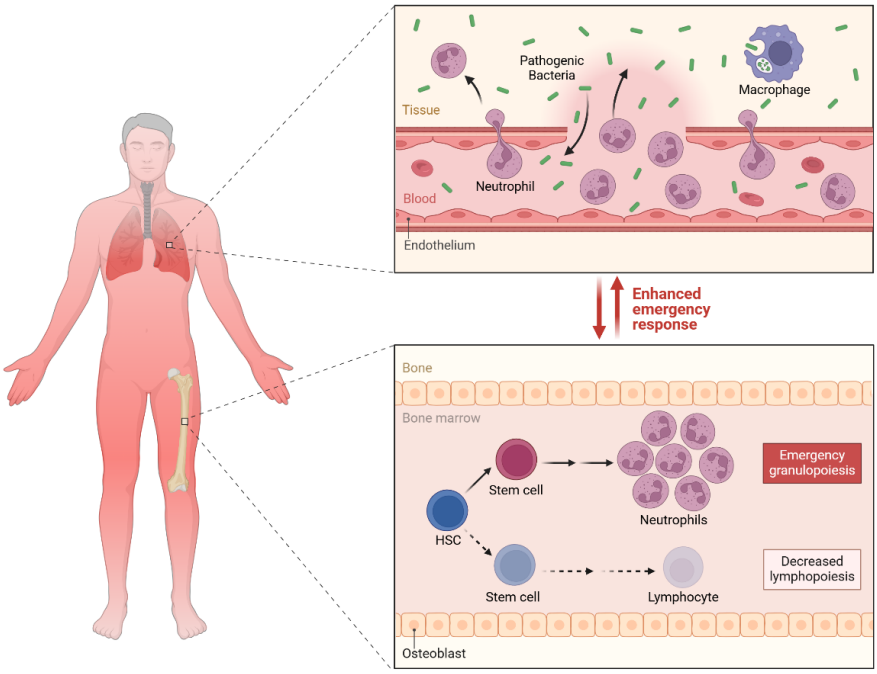

Fig. 17: Systemic Bacterial Infection and Immune Response. Created in https://BioRender.com

Mechanisms of Bacterial Defense and Immune Evasion

There are also many ways bacteria have learned to avoid the immune system. One group produces capsules that prevent phagocytosis; another, such as *Mycobacterium tuberculosis*, survives intracellularly in human macrophages by preventing lysosomal fusion (Figure 18) (Aleem et al., 2022). Bacteria may make toxins that interfere with immune cell function or enzymes that break down antibodies so that they remain alive in their host (Flannagan et al., 2015; Kobayashi et al., 2018).

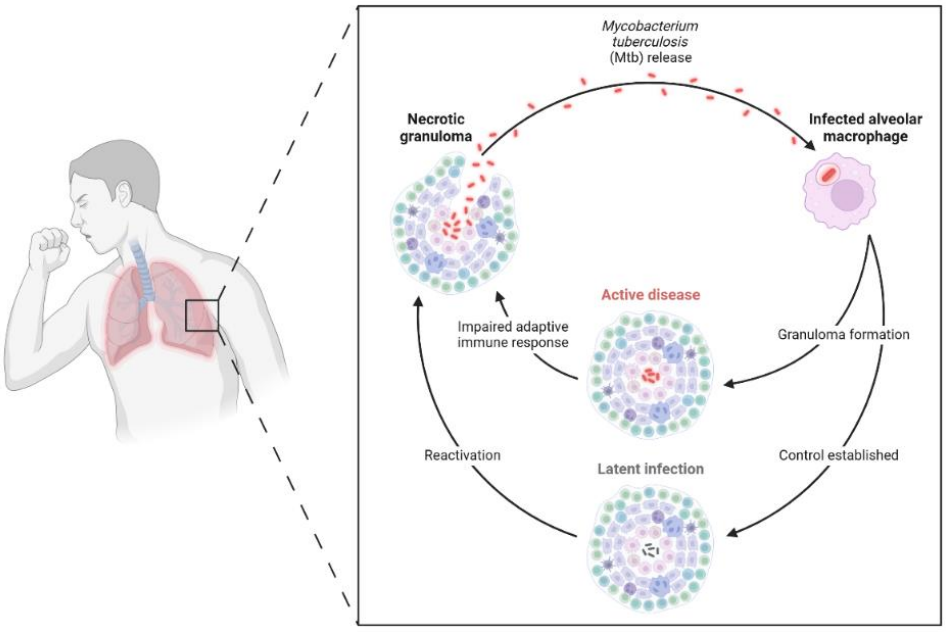

Fig. 18: Mechanism of *Mycobacterium Tuberculosis*. Created in https://BioRender.com

Antibody and Phagocyte Interactions

Antibodies are essential for detection and the immune elimination of bacterial pathogens. Bacterial antigens to which they bind enable opsonization, or the coating of the bacteria so it can be marked by macrophages and neutrophils for phagocytosis and destruction. The cooperation between antibodies and phagocytes is an important defense mechanism, particularly for encapsulated bacteria, which are usually phagocytosis-resistant directly (Ko et al., 2013; Vandendriessche et al., 2021).

Parasitic and Fungal Infections

The life cycles of many parasitic and fungal infections are very complex and present unique challenges due to the ability of some species to change form(s) within the host. Parasites can avoid the immune system and they also elicit chronic immune responses because parasites also have mechanisms to avoid the immune system. Finding immune differences against fungal infections is challenging as fungal and host cell structures are similar.

Challenges in Immune Response to Parasites

parasites can keep immune detection at bay by mimicking host molecules or by changing their surface proteins. For example, the antigens of the malaria-causing Plasmodium vary their expression at different life stages so that the parasite can evade immune responses. Over time the immune system can become worn out from chronic infections such that the immune system becomes exhausted, immune suppression occurs, and parasites cannot be completely cleared (Gomes et al., 2016; Belachew, 2018).

Immune Evasion Mechanisms in Fungi

Fungi evade immune responses through various mechanisms, such as hiding within macrophages, altering surface antigens, and producing immunosuppressive molecules. For example, polysaccharide capsules produced by Cryptococcus neoformans prevent its phagocytosis. In addition, some fungi can also adapt to the acidic environment within macrophages, survive and replicate intracellularly (König et al., 2021).

Nutrition and Immune Function

A well-functioning immune system requires proper nutrition. Immune cells need a variety of key nutrients — like vitamins A, C, D, and E, plus zinc and selenium — to develop and perform their activation functions well. Vitamin C, for instance, promotes immune cell function and helps protect against oxidative stress and vitamin D helps to modulate immune responses. Amino acids are the building blocks for immune cells and antibodies, and so protein also plays a key role (Childs et al., 2019).

Essential Nutrients for Immune System Support

Specific immune functions require specific nutrients. Altogether, vitamin C improves the action of immune cells, vitamin D helps regulate

immune responses, and zinc helps regulate the signaling between immune cells. Nourishing these nutrients in a balanced way helps the body fight infection and stresses (Calder et al., 2020; Calder, 2020).

Effects of Malnutrition on Immunity

Immune defense weakens with malnutrition and the body becomes more vulnerable to infection. A lack of nutrients makes it impossible for the body to produce active immune cells, thus making it vulnerable to pathogens. Chronic malnutrition is also associated with higher-risk infections, slower recovery, and increased severity of disease (Rytter et al., 2014).

Exercise and Immunity

The relationship between exercise and immune health is complex. Excess blood flow associated with moderate physical activity increases circulation and powers immune cell activity, while extreme or long workouts prompt temporary immune suppression.

Benefits of Moderate Exercise

Regular moderate exercise helps to keep immune health regular by reducing inflammation, improving the flow of immune cells, and supporting the body's defenses to fighting infections. It also directly helps to lower the risk of chronic diseases and indirectly benefits immune function (Scheffer & Latini, 2020; Wang et al., 2020).

Effects of Overtraining and Immunosuppression

Exercise that's too much or too hard without rest can also reduce the immune responses in athletes, making them more susceptible to infection. All this overload increases your stress hormones, namely cortisol, which acts to decrease immune defenses and make you more susceptible to respiratory infections (Guimarães et al., 2017).

Stress, Sleep, and Immune Health

Chronic stress and poor sleep can weaken immune defenses, putting one at risk of illness. Lack of quality rest and prolonged stress decreases the immune efficiency of the body and it can't fight infection.

Role of Chronic Stress on Immune Function

On a larger scale when people are chronically stressed, cortisol gets elevated which can suppress some immune responses over time. This hormonal effect has an effect on the immune cells and makes the body less able to fight infections. Chronic stress is also linked with greater inflammation and a poorer ability to fight off infection (Dhabhar, 2014; Hannibal & Bishop, 2014).

Importance of Sleep for Immune Recovery

Immune repair and recovery depend on sleep. When the body is sleeping deeply, the body releases cytokines, which regulate the immune responses and reduce inflammation. Quality, consistent sleep is a key component to supporting immune memory—your body's ability to react faster to pathogens you've responded to in the past (Ibarra-Coronado et al., 2015; Besedovsky et al., 2019).

Future Directions in Immune System Research

Advances in Immunogenetics and Personalized Medicine

The revolution of personalized medicine is immunogenetics — the study of how genetic variation affects immune responses. Discovering what genetic factors lead to an individual immune response allows them to develop therapies directed specifically to patients' unique genetic profiles. The promise of this approach is in treating conditions that include autoimmune diseases in part because they involve genetic predisposition. Moreover, personalized medicine enables increased efficacy of cancer immunotherapy through matching patients to therapies based on immune-related genetic markers, improved outcomes, and less toxic side effects (Tarabayeva et al., 2015; Servushan, 2023).

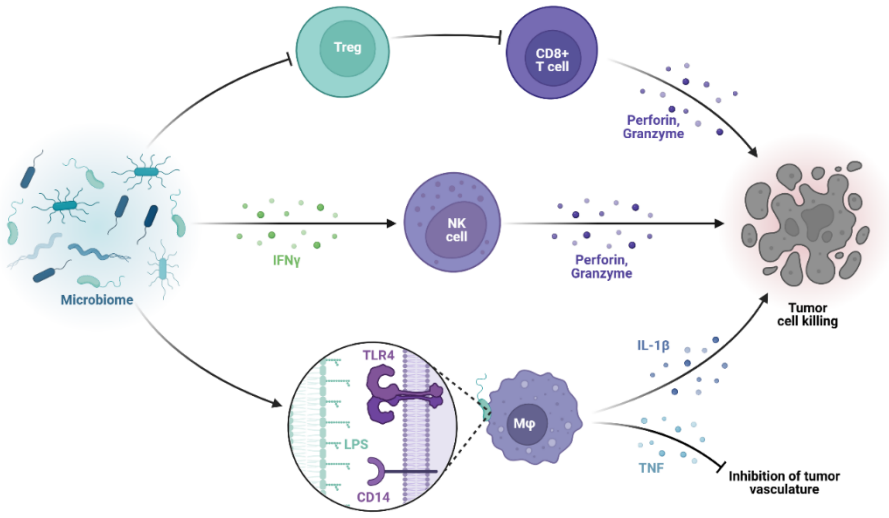

Fig. 19: Microbiome and Anti-Tumor Response

The Role of the Microbiome in Immunity

The human microbiome, trillions of microorganisms in the human body, are critical to the regulation of immune function. They interact with immune cells to promote immune tolerance and protect from pathogens. Disruptions to the microbiome — including from a poor diet, antibiotics, or infections — can impair immune function and lead to diseases such as inflammatory bowel disease (IBD) or allergies. If we reach a point where we understand the microbiome–immune system connection, such therapies could then restore or even promote immune function by modifying the microbiome, creating new avenues of treatment for immune-related diseases (Figure 19) (McDermott & Huffnagle, 2014; Thaiss et al., 2016).

Conclusion

The immune system is a complicated and active network that is required for good health and for preventing diseases. Understanding the balance between inherent and acquired immunity, the mechanisms of pathogen recognition, and the various immune disorders opens the doors for immune function analysis. Additionally, the behavioral aspects related to this domain are largely involved, which highlights good diet, physical activity, and relaxation in the long run for the immune system. Also, as the research develops, especially in immunotherapy and personalized medicine, we have the potential to create new methods that will help the immune system and conquer diseases. The diligence of research in this field is a must for the betterment of global health and for the world to be resilient against the infectious diseases.

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