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Med. Bio Lecture

An introduction to the immune system

Definition of the immune system: The immune system is a complex network of cells, tissues, and biochemical processes that protect the body against pathogenic microorganisms (e.g., viruses, bacteria, fungi, parasites) while maintaining tolerance to self-tissue.

Central concepts:

- ☐ **Pathogen Recognition:** The ability to detect foreign substances.
- ☐ **Effector Responses:** Mechanisms used to eliminate pathogens.
- ☐ **Immune Regulation:** Balancing attack against pathogens with prevention of self-damage.
- ☐ **Immunological Memory:** The capacity of the immune system to respond more rapidly and effectively to previously encountered pathogens.

1. Innate immunity

Definition and characteristics

Innate immunity is the body's immediate, non-specific defense system that relies on physical barriers (e.g., skin), chemical barriers (e.g., stomach acid), and specialized cells (e.g., macrophages, neutrophils) to recognize and eliminate a broad range of pathogens **without** the capacity for long-term immunological memory.

Characteristics of innate immunity

- **Speed:** Rapid response; first line of defense.
- **Specificity:** Broad, recognizes conserved pathogen-associated molecular patterns (PAMPs).
- **Memory:** No true memory; response is the same upon repeated exposures.

Key components of innate immunity

1. **Physical and chemical barriers**: Skin, mucous membranes, gastric acid, antimicrobial peptides.
2. **Cellular effectors**:
    - **Phagocytes** (e.g., macrophages, neutrophils): Engulf and degrade pathogens.
    - **Natural Killer (NK) Cells**: Target and kill virus-infected or tumor cells.
    - **Dendritic Cells**: Bridge innate and adaptive immunity via antigen presentation.
3. **Complement system**: A cascade of proteins that opsonize pathogens and form membrane attack complexes.

Mechanisms of recognition of innate immunity

1. **Detection of PAMPs and DAMPs**

   Pathogen-associated molecular patterns (PAMPs), molecular motifs common to many microbes, and damage-associated molecular patterns (DAMPs), signals from injured or dying cells, appear in tissues or circulation.

2. **Binding by Pattern Recognition Receptors (PRRs)**

   Innate immune cells (e.g., macrophages) carry specialized proteins called PRRs (such as Toll-like receptors, NOD-like receptors, RIG-I-like receptors). These receptors bind PAMPs and DAMPs, initiating intracellular signaling.

3. **Intracellular Signaling and Transcription Activation**

   Once activated, PRRs trigger signaling pathways (e.g., activation of NF-κB or interferon regulatory factors). These transcription factors move into the nucleus and induce the expression of pro-inflammatory cytokines, chemokines, and type I interferons.

4. **Effector Response and Recruitment of Immune Cells**

   Secreted cytokines and chemokines attract additional immune cells, like neutrophils and monocytes, to the site of infection or injury. This plans out inflammation and can also help prepare the adaptive immune system for a more precise response if needed.

5. **Resolution and Tissue Repair**

   As pathogens are cleared or damage is controlled, regulatory signals help resolve inflammation and foster tissue repair, restoring homeostasis.

2. Adaptive Immunity

Definition of adaptive immunity

Adaptive immunity is the highly specific arm of the immune system that develops after exposure to a particular pathogen or antigen, leading to long-lasting protection and immunological memory.

Characteristics of adaptive immunity

- **Speed:** Slower initial response compared to innate immunity.
- **Specificity:** High specificity for distinct antigens via antigen receptors on lymphocytes.
- **Memory:** Generates a faster and more robust response upon re-exposure to the same pathogen.

Lymphocytes: Central players in adaptive immunity

1. **B Lymphocytes (B Cells)**
    - **Function:** Produce antibodies (immunoglobulins); mediate humoral immunity.
    - **Location of Maturation:** Bone marrow.
    - **Plasma Cells and Memory B Cells:** Plasma cells secrete large quantities of antibodies, whereas memory B cells persist long-term for rapid future response.
2. **T Lymphocytes (T Cells)**
    - **Subtypes:**
        - **$CD4^+$ T Helper Cells:** Coordinate immune responses by producing cytokines; aid B cells in antibody production; help macrophages kill intracellular pathogens.
        - **$CD8^+$ Cytotoxic T Cells:** Recognize and kill cells harboring intracellular pathogens (e.g., virus-infected cells).
    - **Location of Maturation:** Thymus.
3. **Antigen Presenting Cells (APCs)**
    - **Types:** Dendritic cells, macrophages, and B cells.
    - **Role:** Process and present antigens to T cells via MHC molecules.

Mechanisms of adaptive immunity

I. Humoral immunity

Humoral immunity refers to the part of the adaptive immune system driven by antibodies produced by B cells. Below is a concise overview:

1. **Antigen Recognition**

   B cells detect specific antigens via their B-cell receptors. Some antigens can directly activate B cells (T-independent), while most require help from T helper cells (T-dependent).
2. **B-Cell Activation and Differentiation**

   Once activated, B cells multiply and transform into two main types of cells:
    - **Plasma Cells**: Produce and secrete large amounts of antibodies.
    - **Memory B Cells**: Persist long-term to enable a faster, stronger response if the antigen reappears.

3. **Antibody Functions**
    - **Neutralization**: Antibodies bind pathogens/toxins, blocking their harmful effects.
    - **Opsonization**: Coating pathogens to enhance their clearance by phagocytes.
    - **Complement Activation**: Triggering the complement cascade to destroy or tag microbes for elimination.

II. Cell-mediated immunity

Cell-mediated immunity is the branch of the adaptive immune system driven by T cells (T lymphocytes):

1. **Antigen Presentation and T-Cell Activation**
    - Antigen-presenting cells (APCs) capture pathogens, process their proteins into peptides, and present them on MHC molecules.
    - T cells recognize these peptide–MHC complexes through their receptors and receive additional stimulatory signals for full activation.
2. **T Helper Cells**
    - Once activated, T helper cells release cytokines that support and direct other immune cells, like B cells, macrophages, and cytotoxic T cells, in fighting infection.
    - They also aid in establishing and maintaining immune memory.
3. **Cytotoxic T Lymphocytes**
    - Cytotoxic T cells directly kill infected or abnormal cells (e.g., virus-infected cells or tumor cells) by inducing apoptosis.
    - This selective targeting helps contain and eliminate threats within cells.
4. **Memory T Cells**
    - After clearing the infection, some activated T cells persist as memory cells.
    - These respond more rapidly and robustly if the same antigen reappears.