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Biomaterials

Stage : fourth

LEC (4)

Biocompatibility

BY

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1. Definition of Biocompatibility

Biocompatibility is one of the fundamental concepts in biomaterials science. It refers to the ability of a material to function within a biological environment while producing an appropriate and controlled response from the host tissue.

Importantly, biocompatibility is not considered an intrinsic property of a material alone. Instead, it results from the interaction between the material and the biological system under specific physiological and clinical conditions. When a material is implanted in the body, it becomes exposed to complex biological environments containing water, proteins, electrolytes, enzymes, and living cells. These components may influence the material's stability and performance.

A biocompatible material must therefore maintain **chemical stability, structural integrity, and resistance to corrosion or degradation** during its service life inside the body.

2. Functional Performance of Biomaterials

In addition to chemical stability, a biomaterial must successfully perform its intended medical function. This includes maintaining appropriate mechanical, structural, and physical properties throughout the duration of implantation.

For example, load-bearing implants such as orthopedic devices must possess adequate **elastic modulus, yield strength, fracture toughness, and fatigue resistance** to withstand mechanical stresses in the body. Similarly, materials used in cardiovascular devices must have surface characteristics that minimize blood clot formation.

A material that fails mechanically or loses its functional properties cannot be considered biocompatible, even if it does not cause toxic effects.

3. Host Response to Biomaterials

When a biomaterial is implanted, the body initiates a series of biological reactions known as the **host response**. These reactions occur in a sequential and time-dependent manner and involve molecular, cellular, and tissue-level processes.

The purpose of these responses is to recognize and react to the foreign material. The magnitude and duration of the host response strongly influence the long-term success of the implanted device.

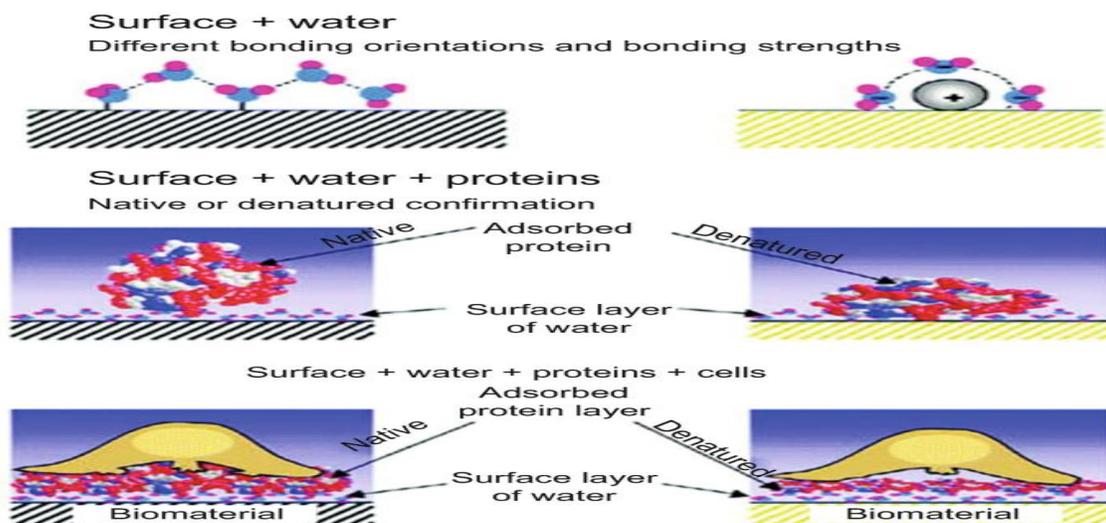
3.1 Protein Adsorption

The first event that occurs after implantation is **protein adsorption**, which typically happens within seconds. Blood plasma proteins rapidly attach to the surface of the biomaterial, forming a thin protein layer.

This adsorption process depends on several surface characteristics of the material, including **surface energy, wettability, electrical charge, and surface roughness**.

Common proteins involved include **albumin, fibrinogen, fibronectin, and immunoglobulins**. These proteins may undergo structural changes after adsorption, exposing new molecular sites that influence cell attachment and recognition.

Therefore, cells interact not with the original material surface but with the **adsorbed protein layer**, which essentially defines the biological identity of the implant.



3.2 Acute Inflammation

Acute inflammation is the next stage of the host response and typically occurs within hours or days after implantation.

This phase is characterized by **vasodilation, increased blood vessel permeability, and migration of immune cells**, particularly neutrophils, toward the implant site. These cells release enzymes and reactive molecules that attempt to degrade foreign substances and remove damaged tissue.

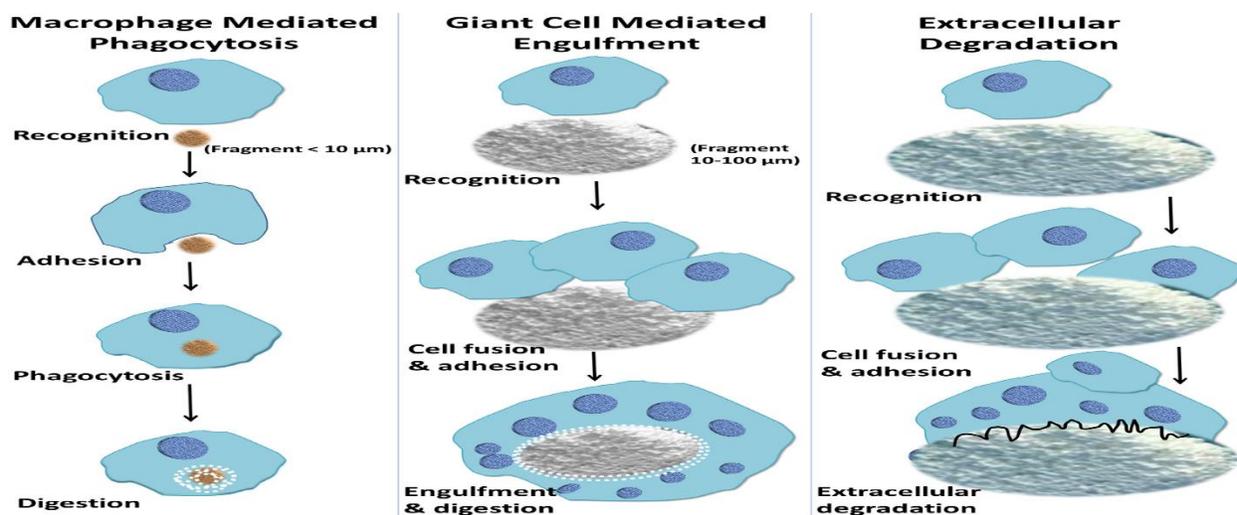
If the biomaterial is stable and non-toxic, acute inflammation gradually subsides as the tissue begins the healing process.

3.3 Chronic Inflammation

If the acute inflammatory phase does not resolve, the reaction may progress to chronic inflammation. This stage is dominated by immune cells such as **macrophages and lymphocytes**.

Macrophages attempt to engulf and digest foreign materials through a process known as **phagocytosis**. However, when the implanted material is too large to be internalized, macrophages may fuse together to form **multinucleated foreign body giant cells**.

These cells remain attached to the material surface and release enzymes and reactive molecules that attempt to degrade the implant.



3.4 Fibrous Capsule Formation

In the final stage of the host response, fibroblast cells begin to proliferate around the implanted material. These cells produce extracellular matrix components, particularly **collagen fibers**, resulting in the formation of a **fibrous capsule** surrounding the implant.

The thickness and structure of this capsule depend on the material properties and the severity of the inflammatory response.

In some medical devices, moderate fibrous encapsulation may not significantly affect performance. However, in sensitive devices such as biosensors or drug delivery systems, the capsule may interfere with molecular transport and reduce device functionality.

4. Toxicity of Biomaterials

Toxicity refers to the potential of a material or its degradation products to cause harmful biological effects. Toxic reactions may occur locally at the implantation site or systemically throughout the body.

Understanding the toxic potential of biomaterials is essential to ensure patient safety and long-term implant success.

4.1 Local Toxicity

Local toxicity affects the tissues surrounding the implanted material. It may occur due to corrosion products, degradation products, or particles generated from wear and mechanical damage.

These substances may cause **cell death, tissue necrosis, or intensified inflammation** at the implantation site.

4.2 Systemic Toxicity

Systemic toxicity occurs when harmful substances released from the implant enter the bloodstream and travel to distant organs such as the **liver, kidneys, or spleen**.

Accumulation of these substances may disrupt normal physiological functions depending on their concentration and duration of exposure.

4.3 Cellular Mechanisms of Toxicity

At the cellular level, toxicity may occur through several mechanisms, including:

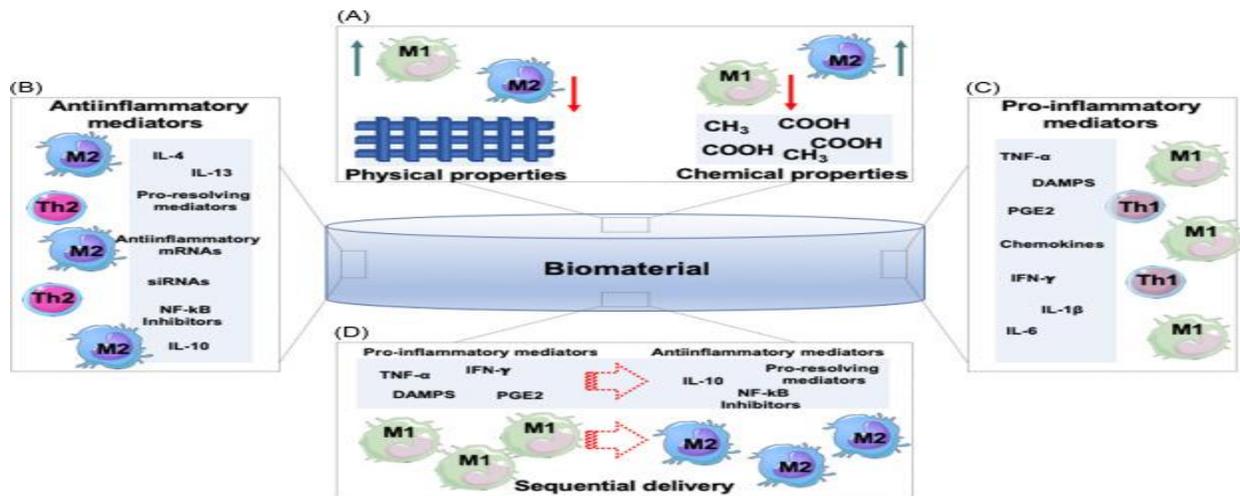
- Damage to the cell membrane
- Inhibition of enzyme activity
- Mitochondrial dysfunction and reduced energy production. **الميتوكوندريا**
- Generation of reactive oxygen species
- DNA damage and genetic mutations

Evaluation of biomaterial toxicity usually begins with **in vitro cytotoxicity tests** using cultured cells, followed by **in vivo animal studies** to assess tissue responses.

5. Immune Response to Biomaterials

The immune system responds to implanted materials through two main defense mechanisms: **innate immunity** and **adaptive immunity**.

These responses are part of the body's natural defense system against foreign substances.



5.1 Innate Immune Response

Innate immunity is the first and immediate defense mechanism activated after implantation. It involves immune cells such as **neutrophils, macrophages, and components of the complement system**.

Macrophages play a central role by secreting cytokines, growth factors, and enzymes that regulate inflammation and tissue repair.

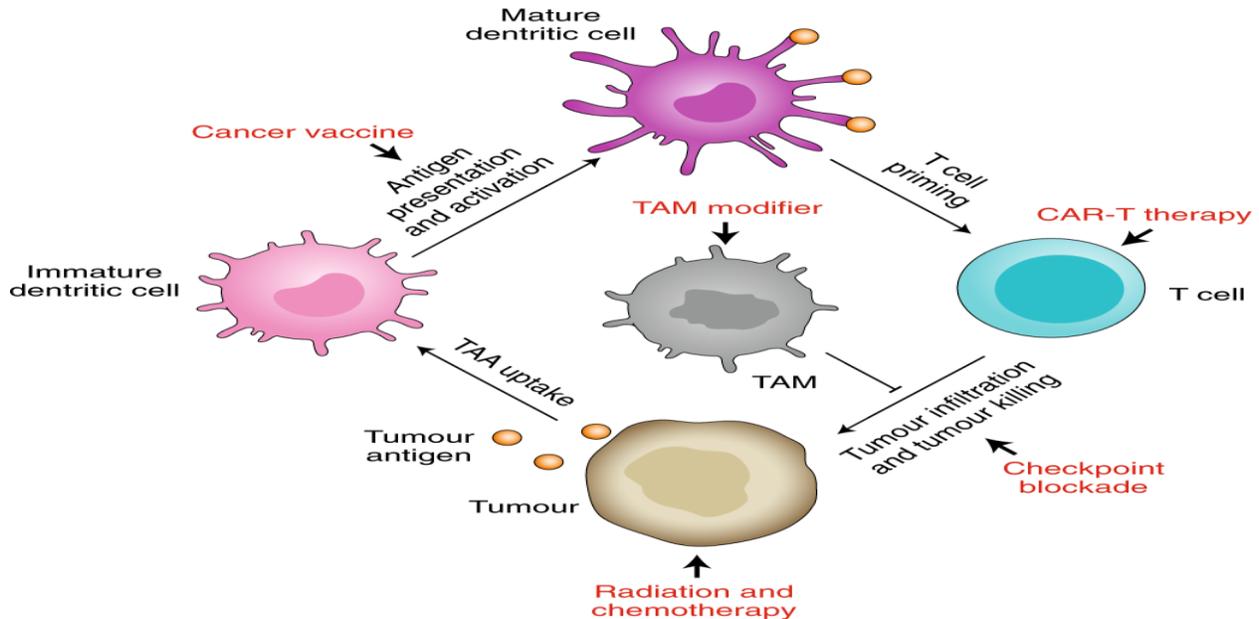
Persistent macrophage activity at the implant interface is a hallmark of the **foreign body reaction**.

5.2 Adaptive Immune Response

Adaptive immunity involves highly specific responses mediated by **T lymphocytes and B lymphocytes**. In most cases, inert biomaterials do not strongly activate adaptive immune responses.

However, certain materials may cause **hypersensitivity reactions**, especially when metal ions such as nickel are released. These reactions are typically **Type IV delayed hypersensitivity responses** mediated by T cells.

Such immune reactions may lead to persistent inflammation and possible implant failure.



T-cell-mediated immune response is a type of immune response that depends on **T lymphocytes** rather than antibodies. This process begins when **antigen-presenting cells (APCs)**, such as **dendritic cells** or **macrophages**, display antigens on their surface, which leads to the activation of T cells. After activation, T cells proliferate and differentiate into different types, including **helper T cells** and **cytotoxic T cells**, which destroy infected or foreign cells within the body.

In the case of **biomaterials**, T-cell activation may occur as a result of the interaction between the immune system and the implanted material or with the proteins adsorbed on its surface. This interaction can lead to the release of **cytokines** and the regulation of the **inflammatory response** around the implant.

6. Foreign Body Reacti

The **foreign body reaction** represents the typical biological response to implanted biomaterials. It consists of a sequence of biological events that occur after implantation.

These stages include:

1. Protein adsorption
2. Acute inflammation
3. Chronic inflammation
4. Formation of foreign body giant cells
5. Development of a fibrous capsule

The severity and duration of each stage determine the long-term success of the implanted material.