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HIGH-PERFORMANCE BIOCOMPATIBLE HOLLOW FIBERS FOR LOCALIZED SKIN CANCER THERAPY: A TEXTILE-BASED APPROACH

ВЫСОКОЭФФЕКТИВНЫЕ БИОСОВМЕСТИМЫЕ ПОЛЫЕ ВОЛОКНА ДЛЯ ЛЕЧЕНИЯ ЛОКАЛИЗОВАННОГО РАКА КОЖИ: ПОДХОД НА ОСНОВЕ ТЕКСТИЛЯ

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Skin cancer has become a major public health issue worldwide, with incidence rates steadily increasing due to factors such as prolonged exposure to ultraviolet (UV) radiation, aging populations, and environmental pollution. According to the World Health Organization, skin cancer ranks as the 17th most common cancer globally, and is particularly prevalent in countries with high UV exposure like Australia, the United States, and parts of Europe. In 2022 alone, over 330,000 new cases were diagnosed worldwide. The most frequent forms – basal cell carcinoma, squamous cell carcinoma, and melanoma – not only pose serious health threats but also impact quality of life due to disfigurement and aggressive treatment protocols. While current treatments – such as surgical excision, radiotherapy, and systemic chemotherapy – can be effective, they often come with significant drawbacks. Surgical approaches can lead to visible scarring and prolonged recovery; chemotherapy affects both healthy and cancerous tissues, leading to systemic toxicity; and radiotherapy may damage surrounding healthy skin. Moreover, these approaches frequently cause patient discomfort and increase the risk of recurrence. To address these limitations, this study explores the use of high-performance hollow textile fibers as a localized drug delivery system for skin cancer treatment. These fibers, created using advanced fabrication techniques such as electrospinning and microfluidic spinning, allow for targeted, sustained release of therapeutic agents – including chemotherapeutics, immunomodulators, or gene-editing molecules – directly at the tumor site.

Keywords: Skin cancer, hollow fiber, injections, biocompatibility, immunotherapy, chemotherapy

Recent advancements in material science have significantly expanded the field of textile materials. Innovations in advanced material technologies have facilitated the development of medical textiles capable of enhancing both the efficiency and responsiveness of healthcare systems. Historically, natural fibrous materials were among the earliest used in medical applications, including wound closures, dressings, and surgical sutures, with evidence of such usage dating back to approximately 5000 BCE in ancient Egypt [1, 2, 3]. The field of textile materials science has experienced substantial growth in recent years. Advanced material technologies have enabled the development of novel applications, particularly in the area of medical textiles, which contribute to improved efficiency and responsiveness of healthcare delivery systems [1, 2, 3]. The biological properties of various textile materials were systematically explored beginning in the 1950s [4]. Since 1952, textiles have been employed in the fabrication of vascular implants. The first textile-based vascular graft was developed by Voorhees and collaborators, who successfully replaced infected aortic vessels in a canine model using woven polyvinyl chloride (PVC) tubes. Subsequent developments in vascular grafts and heart valve cuffs incorporated

polyester due to its superior tensile strength, structural stability, and long-term biocompatibility [4, 5, 6]. Biomedical textiles incorporating drug delivery functionalities via hollow fiber technology have been extensively investigated. These systems enable controlled release of therapeutic agents directly to target sites through dermal or tissue interfaces [7, 8]. Hollow fibers have also been proposed for integration into artificial bioactive scaffolds, facilitating localized drug delivery [6, 9]. Moreover, porous hollow fiber membranes have been considered for incorporation into three-dimensional scaffolds to enhance the delivery of nutrients and culture media in tissue engineering applications [10].

In addition to drug delivery, hollow fiber-based biomedical textiles have been implemented to improve the efficiency of dialysis procedures, to evaluate antibiotic efficacy through hollow fiber cell-culture cartridges, and to screen anticancer compounds using cell-loaded hollow fiber implants in mammalian models [11]. Although the volume of current research on hollow fibers in medical applications may be less extensive compared to other material systems, they continue to represent essential components within the value-added domain of commercial medical textiles [11]. Skin cancer, including basal cell carcinoma, squamous cell carcinoma, and melanoma, constitutes an escalating global health challenge. Conventional treatment approaches – such as surgical excision, radiotherapy, and chemotherapy – are generally effective but often associated with significant limitations, including systemic toxicity, patient discomfort, and the potential for tumor recurrence. Localized drug delivery systems, particularly those utilizing hollow fiber-based injections, present a promising therapeutic alternative by facilitating site-specific administration of anticancer agents directly to the tumor or affected dermal regions. The biocompatibility of these hollow fiber systems is of paramount importance, as the materials employed must interact safely with human tissue, avoiding immunogenic responses [12, 13], inflammation, or cytotoxicity. This study aims to evaluate the biocompatibility of hollow fiber injection systems fabricated from high-performance materials and to assess their therapeutic potential in the management of skin cancer. According to data from the World Health Organization, skin cancer ranks as the 17th most prevalent cancer globally, and is the 14th most commonly diagnosed malignancy among both men and women. Epidemiological statistics from 2022 indicate that the United States, Germany, and the United Kingdom reported the highest numbers of skin cancer cases. A comparative analysis of global incidence rates reveals the ten countries with the highest reported skin cancer incidences for both sexes combined, as well as separately for males and females. Age-standardized incidence rates (ASRs) for each of these countries are also included to provide a normalized comparison across populations [14].

Table / Таблица 1

10 countries with the highest skin cancer incidence in 2022
10 стран с самым высоким уровнем заболеваемости раком кожи в 2022 году

Rank Ранг	Country Страна	Number Число	ASR/100,000 На 100 тысяч	New cases in men Новые случаи у мужчин	ASR/100,000 На 100 тысяч
	World / В мире	331,722	3.2	179,953	3.7
1	US / США	101,388	16.5	60,762	19.3
2	Germany / Германия	21,976	16.5	11,667	13.4
3	UK / Великобритания	19,712	15.3	10,170	15.1
4	Australia / Австралия	16,819	37.0	10,902	45.9
5	France (metropolitan) Франция	15,729	13.5	7,880	14.5
6	Italy / Италия	13,769	12.7	7.325	13.3
7	Russia / Россия	12,903	5.3	5,223	5.2
8	Canada / Канада	11,383	14.5	6.434	15.9
9	Brazil / Бразилия	9,676	3.3	4,958	3.6
10	China / Китай	8,789	0.37	4,402	0.37

Etiological Factors of Skin Cancer:

Skin cancer is associated with a range of environmental, genetic, and physiological risk factors, including:

1. Ultraviolet (UV) Radiation – Prolonged and unprotected exposure to ultraviolet radiation remains the primary risk factor.

2. Fair Skin Phenotype – Individuals with lighter skin tones possess reduced levels of melanin, decreasing natural protection against UV damage.

3. Genetic Predisposition and Family History – A hereditary component is evident, with increased risk observed in individuals with a familial history of skin malignancies.

4. Immunosuppression – Patients with compromised immune systems, such as organ transplant recipients, exhibit heightened susceptibility.

5. Exposure to Carcinogenic Substances – Contact with hazardous chemicals, including arsenic and industrial compounds, may increase risk.

6. Ionizing Radiation – Previous therapeutic or environmental exposure to ionizing radiation is a recognized contributing factor.

7. Chronic Skin Trauma or Inflammation – Persistent skin injuries or inflammatory conditions can predispose tissue to malignant transformation.

Emerging Risk Consideration:

An underrecognized but potentially significant contributor to dermal pathology is the residual presence of systemic pesticides in conventionally harvested cotton fibers. This is particularly relevant to textiles in direct contact with the skin, such as undergarments and medical cotton fabrics used in wound care. These chemical residues may pose a risk of dermal irritation, sensitization, or systemic absorption, thereby contributing to chronic skin damage. A proposed mitigation strategy involves the use of certified organic cotton, which is cultivated without the application of such agrochemicals. Skin Cancer and Limitations of Conventional Therapies, Skin cancer represents one of the most prevalent malignancies globally, with millions of new cases diagnosed annually. Although advancements in early detection and standard treatment modalities have improved patient outcomes, several challenges persist in conventional therapeutic approaches:

– Surgical excision, while effective in tumor removal, is inherently invasive and frequently results in postoperative scarring.

– Chemotherapy exerts non-selective cytotoxic effects, often leading to systemic side effects due to the destruction of both malignant and healthy cells.

– Radiation therapy may inadvertently damage adjacent non-cancerous tissues, contributing to adverse effects and complicating recovery.

– To address these limitations, targeted drug delivery systems, such as hollow fiber technologies, offer a promising alternative by enabling localized administration of therapeutic agents. This approach enhances treatment specificity, reduces systemic toxicity, and improves patient compliance by delivering drugs directly to the affected site.

Hollow Fibers: Selection of Materials and Methods

Hollow fibers are tubular filamentous structures characterized by one or more longitudinal internal cavities (cores). Due to their unique architecture and functional versatility, they have attracted considerable attention as drug delivery systems (DDS). The inherent flexibility of hollow fibers can be precisely modulated during synthesis or fabrication, allowing control over key structural parameters. The morphology typically exhibits a distinct separation between the dense outer wall and the porous internal core (Fig. 1) [15]. These fibers have been extensively utilized across various biomedical and biotechnological applications, including tissue culture, bioreactor systems, biosensing technologies, micro-level substance extraction, and gas separation processes [13]. Key physical properties – such as fiber diameter, wall thickness, pore size, and mechanical elasticity – can be tailored using fabrication and spinning techniques [16]. Compared to conventional solid fibers, hollow fibers are approximately 20% lighter by volume, offering enhanced performance in weight-sensitive applications [17]. One of the earliest hollow fiber systems was developed by DuPont, utilizing polyamide-based materials. These fibers were fabricated through the electrospinning process, where they were deposited and aligned between two electrodes to form ordered arrays [13, 18].

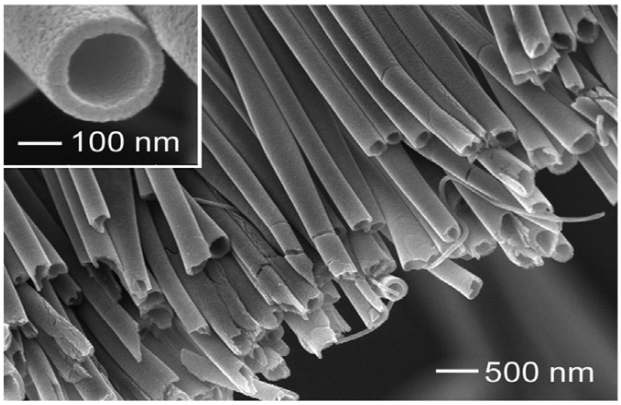

Fig. / Рис. 1. Scanning Electron Microscopy (SEM) images depicting the uniaxial alignment and surface morphology of ceramic hollow fibers / Изображения с помощью сканирующей электронной микроскопии (СЭМ), отображающие одноосное расположение и морфологию поверхности керамических полых волокон [19].

Hollow Fibers for Drug Delivery:

Pharmaceutical agents, commonly referred to as drugs, are substances employed in the diagnosis, prognosis, and prevention of diseases. Pharmacology is the branch of science that studies these substances and their effects on the body. According to the U.S. Food and Drug Administration (FDA), a "drug" is defined as any substance that produces a therapeutic effect by inducing a biological response in the body and influencing the function of biological systems, including biological products such as proteins and hormones. The field of pharmacodynamics focuses on the study of a drug's molecular properties, its biochemical interactions, and its physiological effects within the body [20]. Upon administration into a biological system, drugs exert specific biological effects by interacting with target sites within the body. These effects arise from binding interactions between the drug and its biological targets, which induce molecular alterations through intramolecular and intermolecular interactions. Common drug targets in biological systems include G-protein coupled receptors (GPCRs), ion channels, enzymes, and nuclear receptors. The mechanisms of drug action can be classified into three categories: receptor binding, chemical interactions between the drug and its target, and post-binding interactions [21].

Microfluidic Spinning:

Microfluidic spinning is a precise technique capable of generating hollow fibers with high accuracy, utilizing minimal quantities of polymeric liquids. This process employs capillary-based microfluidic devices, which can incorporate varying numbers of capillaries, typically two or more. These capillaries are arranged in such a way that, with the assistance of a micro-pipette-based puller, the devices enable controlled injection at the orifice. The capillaries are aligned on a glass slide, with syringes connected to them, and arranged in a coaxial configuration. This assembly is commonly referred to as a microfluidic chip [22] (Fig. 2). Using this setup, hollow calcium alginate microfibers have been successfully generated.

To fabricate these fibers, four distinct solutions are prepared: Solution 1 consists of distilled water and sodium carboxymethyl cellulose, Solution 2 contains sodium alginate and bromeosin, Solution 3 includes water and polyethylene glycol, and Solution 4 is composed of anhydrous calcium chloride. The microfluidic device assembly includes three cylindrical glass capillaries, with two additional glass tubes fixed on a glass slide. Two capillaries are utilized as injectors, while a capillary puller ensures that one injector capillary is securely fixed into the orifice. The other two capillaries serve as outlet tubes and are affixed to the setup using epoxy resin, leaving their inlet ends open for the continuous flow of the solutions.

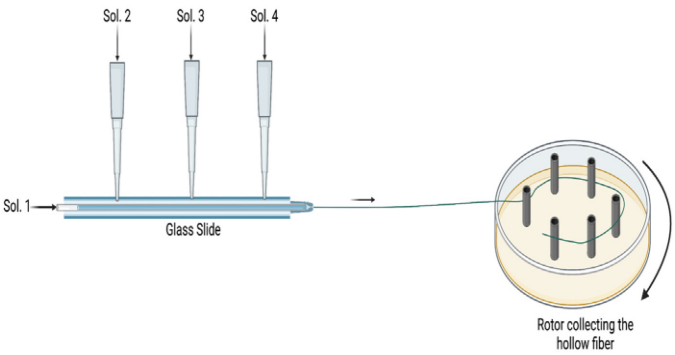

Fig. / Рис. 2: Experimental setup for the production of hollow fibers via microfluidic spinning. This configuration utilizes four distinct solutions to enable the precise and continuous fabrication of hollow fibers, which are subsequently collected on a rotor plate with capillary tubes / Экспериментальная установка для производства полых волокон методом микрожидкостного прядения. В этой конфигурации используются четыре различных решения, обеспечивающих точное и непрерывное изготовление полых волокон, которые затем собираются на роторной плите с капиллярными трубками [19].

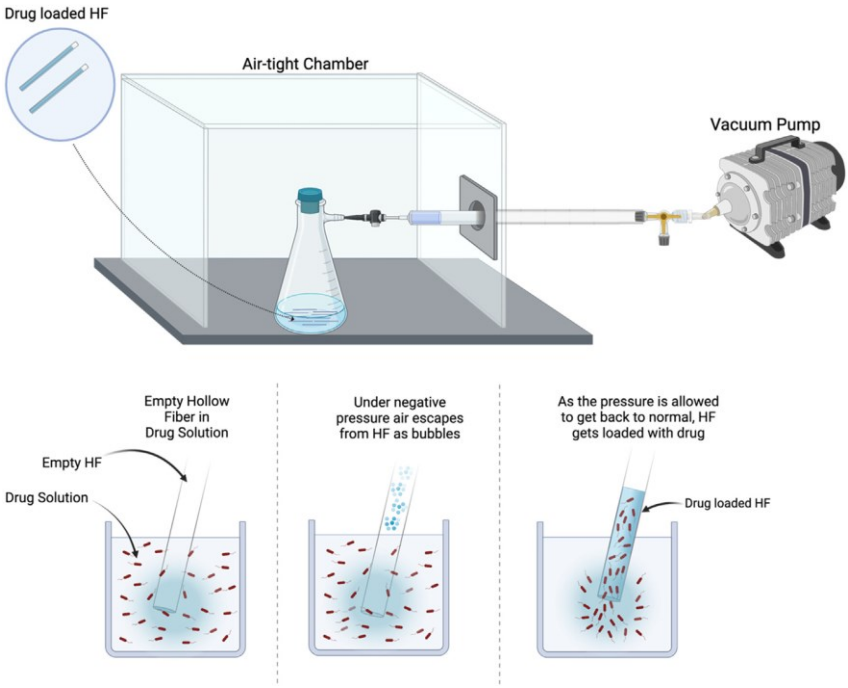

Fig. / Рис. 3.
Drug loading in hollow fibers / Загрузка лекарственного средства в полые волокна [19].

Drug-loading in hollow fiber: Drug loading into hollow fibers can be effectively achieved using a vacuum-assisted infusion method. Here, hollow fibers are immersed in a drug-containing solution inside a vacuum chamber. Negative pressure evacuates the internal air from the fibers, allowing the surrounding liquid to enter the hollow core once pressure is normalized. This simple yet effective technique ensures efficient encapsulation of therapeutic agents within the fiber structure.

Mechanism of Drug Release via Hollow Fibers:

A significant advantage of fiber-based drug delivery systems (DDS) is their ability to efficiently deliver therapeutic agents with targeted precision over a defined period. The process by which the drug is released or transported from the delivery system is referred to as the drug release mechanism [23]. In the case of hollow fibers, the release profile is heavily influenced by the fiber's morphology, including factors such as fiber length, release duration, hydrophobicity of the drug, the chemical properties of the drug, and the specific characteristics of the fiber material used.

Conventional Methods for Fabricating Hollow Fibers:

Hollow Fiber Production Technologies: The fabrication of hollow fiber membranes involves various spinning techniques, each optimized for specific polymers and the desired properties for targeted applications. These techniques, depicted in Figure 4, include wet spinning, dry-jet-wet spinning, dry spinning, melt spinning, and electrospinning [19, 24, 25].

Influence of Spinning Parameters: Operating conditions such as extrusion rate, air gap humidity, coagulation bath temperature, and spinneret design play a crucial role in determining the final morphology of the fibers (e.g., wall thickness, internal diameter, and pore distribution). Accurate control of these parameters enables the optimization of mechanical strength, permeability, and separation efficiency [26].

Hollow Fiber Injections for Targeted Therapy

Hollow fibers represent a promising platform for localized therapy, offering the ability to encapsulate and gradually release therapeutic agents such as chemotherapeutics or cytokines. Their design enables controlled release directly to the tumor, minimizing systemic side effects. The use of biocompatible and biodegradable polymers ensures safe interaction with tissues and gradual decomposition, preventing chronic inflammation or accumulation [27].

Method for Drug Incorporation Using Electrospinning:

Electrospinning employs an electric field to generate nanofibers from a conductive polymer or composite solution [15, 30, 31].

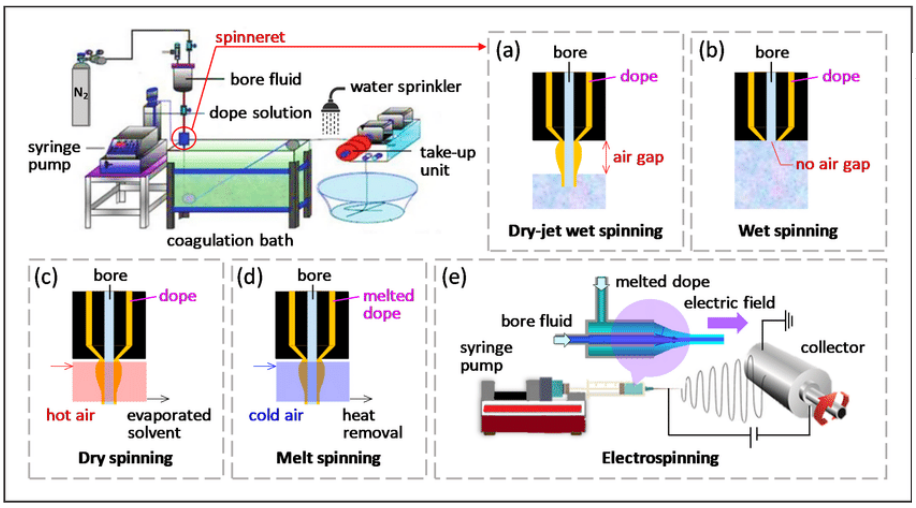

Fig. / Рис. 4.
Diagram illustrating the primary spinning techniques for hollow fibers: a) Dry-jet-wet spinning, b) Wet spinning, c) Dry spinning, d) Melt spinning, e) Electrospinning / Схема, иллюстрирующая основные технологии изготовления полых волокон: а) сухоструйно-мокрое прядение, б) Влажное прядение, в) Сухое прядение, г) Прядение из расплава, д) Электроформование [28, 29].

Recent advancements in the medical field have led to the increased application of this technique in drug delivery systems (DDS), facilitating the administration of multiple therapeutics with enhanced properties, improved efficiency, reliability, and reduced cytotoxicity [32, 33]. Over the past 15 years, research on electrospinning (ES) has grown exponentially, driven by its ability to provide better control and predictability in drug delivery compared to traditional methods. Electrospinning devices utilize electro-hydrodynamic techniques to load bioactive drugs onto nanofibers, composites, and polymers for DDS applications. Various methods, including blending, coaxial electrospinning, electrospray, surface modification electrospinning, emulsion electrospinning, and coaxial electrospray, are employed to incorporate drugs while preserving their therapeutic efficacy.

Blending Electrospinning:

In this method, a solution is prepared by dissolving and dispersing a drug within a polymer prior to the electrospinning process, resulting in the formation of nanofibers with encapsulated drugs that exhibit a prolonged-release profile. This technique also enhances the mechanical and physicochemical properties of drug-loaded nanofibers [34]. The physicochemical properties of the polymer influence the interactions between the polymer and the encapsulated drug, thereby improving drug encapsulation efficiency, drug dispersion within the fibers, and the release rate. Blending electrospinning has been employed to incorporate a variety of therapeutics, including antibiotics, cytostatic agents, and anti-inflammatory drugs. Recent studies indicate that this method facilitates the efficient incorporation and delivery of small molecules, and it has also been successfully utilized to encapsulate antimicrobial peptides [34, 35].

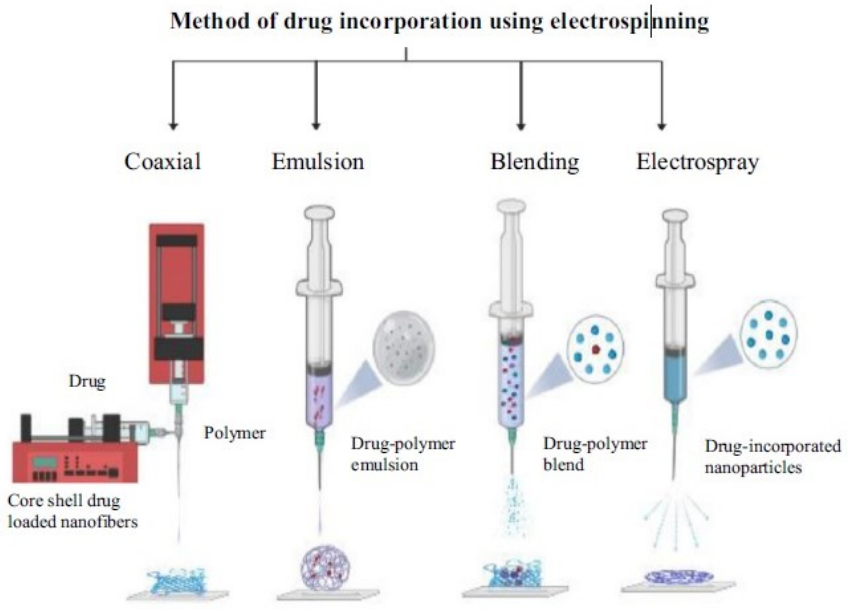

Fig. / Рис. 5.
Methods of drug incorporation in electrospun nanofibers
Способы введения лекарственных средств в электроспряденые нановолокна [19].

Biocompatibility Considerations for Hollow Fiber Injections: To enhance the biocompatibility of hollow fiber injections, surface modifications are frequently employed. These modifications improve the interaction between the fibers and adjacent tissues, thereby minimizing the risk of inflammation and immune system activation.

Bioconjugation Techniques:

Bioconjugation techniques involve anchoring bioactive substances to the surface of textile materials or polymers through chemical and physical conjugation methods, allowing the drug-polymer system to achieve controlled release and site-specific delivery. To facilitate this process, the required functional groups must be present in sufficient quantity on the surface of the textile material. If these groups are not naturally available, they can be introduced using various methods, including chemical linkage, plasma treatment, grafting, and co-spinning. In plasma treatment, functional groups are incorporated onto the fabric surface through plasma exposure, followed by radiation-induced graft polymerization and a subsequent ring-opening reaction with sodium sulfide. The sulfonic group-functionalized fabric can then be conjugated with silver ions to impart antibacterial activity. Co-spinning is another method used to attach functional groups to the fiber surface, employing pre-functionalized polymers [19, 24, 36, 37].

Material Selection: The materials utilized in the construction of hollow fibers are crucial in determining their biocompatibility. Several synthetic and natural polymers are considered for medical applications [19, 38]:

– Polyurethane (PU): A flexible, durable material with established biocompatibility, commonly used in medical devices due to its mechanical strength and comfort.

– Polycaprolactone (PCL): Known for its slow degradation rate, PCL is ideal for sustained drug release and induces minimal inflammatory responses in the body.

– Polymeric Materials: High-performance hollow textile fibers are typically made from synthetic polymers such as polyurethane (PU), polylactic acid (PLA), polyglycolic acid (PGA), or silicone. These polymers are selected for their durability, flexibility, and biodegradability, ensuring no harm to the body. They are widely used in medical devices, sutures, and drug delivery systems due to their favorable biocompatibility profiles.

– PLGA (Polylactic-co-glycolic acid): Particularly relevant due to its biodegradability, PLGA is extensively used in medical textiles, enabling gradual drug release and supporting tissue regeneration without long-term accumulation in the body.

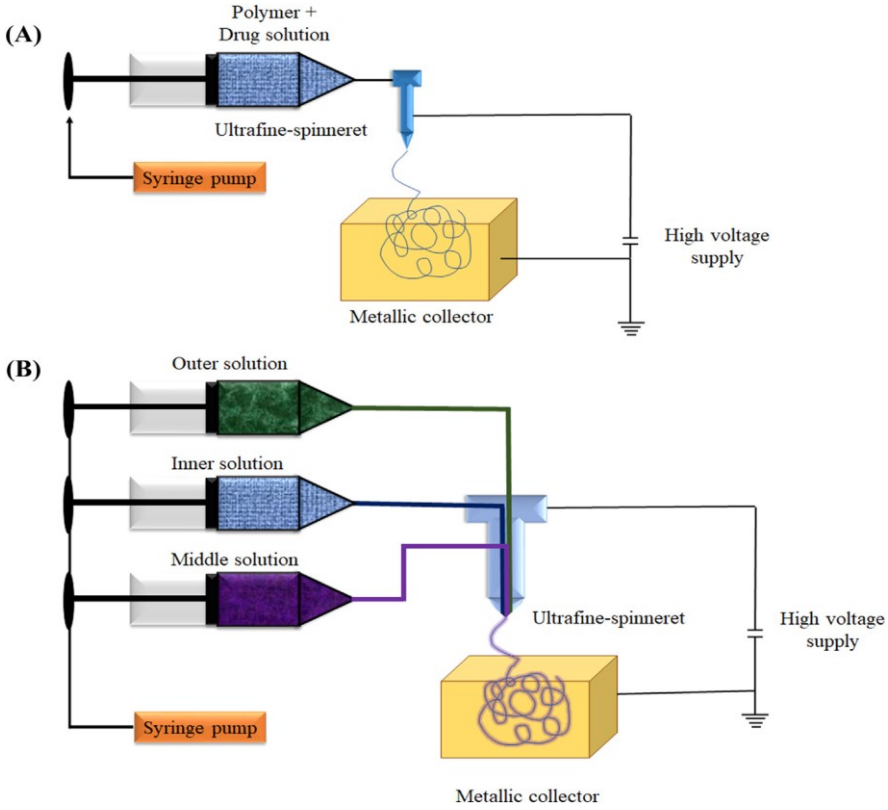

Fig. / Рис. 6.
Preparation of nanofibers via (A) electrospinning and (B) coaxial electrospinning techniques /
Получение нановолокон с помощью (А) методов электроспиннинга и (Б) методов коаксиального электроспиннинга [30].

– Incorporation of Smart Polymers into Fibers: Certain high-performance fibers integrate smart polymers that respond to environmental stimuli (e.g., pH, temperature, light). These materials can alter their properties based on the skin's environment, allowing for targeted drug delivery or modifications in fiber mechanical properties to aid in healing [10]. They provide advanced functionality while maintaining biocompatibility [19, 38].

– Bioactive Molecule Incorporation: Molecules like collagen, fibronectin, or peptides are incorporated to promote cell growth and wound healing, enhancing tissue regeneration at the application site.

– Antimicrobial Injections [35]: Silver nanoparticles or chitosan coatings are employed to mitigate infection risks, which are a significant concern for skin cancer patients with compromised immune systems.

– Anti-inflammatory Injections: Incorporating corticosteroids or NSAIDs can reduce inflammation and improve patient comfort.

Immune and Inflammatory Response: To ensure medical safety, hollow fibers must exhibit high biocompatibility. This includes surface modifications to limit inflammatory responses, the use of inert polymers like PU or silicone, and rigorous biological testing (cytotoxicity, genotoxicity, immunogenicity) following ISO 10993 standards. These strategies minimize risks of immune rejection, inflammation, or long-term tissue irritation.

Therapeutic Application in Skin Cancer Treatment:

1. Localized Drug Delivery for Chemotherapy: Hollow fiber injections can deliver chemotherapeutic agents directly to the site of skin cancer, thereby reducing systemic side effects and enabling higher localized drug concentrations. The controlled release of drugs such as 5-fluorouracil (5-FU), methotrexate, or doxorubicin can enhance treatment efficacy while minimizing damage to healthy tissues.

2. Immunotherapy and Gene Therapy:

Hollow fibers can function as delivery systems for immunotherapeutic agents, such as immune checkpoint inhibitors (e.g., nivolumab) or cytokines (e.g., interferon-gamma). These therapies are especially promising for melanoma and other aggressive skin cancers, where immune evasion represents a significant challenge. Gene therapy could also benefit from hollow fiber injections, enabling the direct delivery of DNA or RNA-based therapies to skin cancer cells, thereby enhancing tumor-specific responses and addressing issues associated with systemic delivery.

3. Controlled Degradation and Biodegradability:

Gradual Degradation: A critical factor in the biocompatibility of high-performance hollow fibers is their ability to degrade in a controlled manner. Fibers that persist too long may result in chronic inflammation, while those that degrade too rapidly may fail to deliver their therapeutic payload or provide insufficient time for healing.

Biodegradable Polymers: High-performance hollow fibers frequently incorporate biodegradable polymers such as polycaprolactone (PCL) or PLGA. These materials undergo controlled degradation over time, breaking down into non-toxic metabolites that can be absorbed by the body, preventing harmful material accumulation. In the context of skin cancer treatments, gradual degradation is essential for maintaining a consistent release of therapeutic agents, such as chemotherapy drugs, growth factors, or immunomodulatory agents, over an extended period. This ensures sustained therapeutic efficacy while minimizing unwanted side effects.

Tuning Degradation Rate: The degradation rate of fibers can be modulated depending on their intended use. For instance, fibers intended for drug delivery or wound healing may require a different degradation rate compared to those providing physical support. By adjusting polymer compositions and the molecular weight of the materials, the fibers can be tailored to degrade appropriately without causing tissue damage.

4. Inflammation and Immune Response:

– Minimizing Inflammation: High - performance hollow fibers must be engineered to induce minimal inflammatory responses upon contact with skin or injured tissues. Skin cancer patients often experience inflammation due to treatments such as radiation or surgery, and additional inflammation from the fiber material could hinder healing and increase the risk of infection.

– Polymeric Materials with Low Inflammatory Potential: Polymers such as silicone and

polyurethane (PU) are well-documented for their low immunogenicity and minimal risk of causing inflammation in medical applications. Materials used for hollow fibers must undergo testing for cytotoxicity (cell toxicity) and genotoxicity (DNA damage) to ensure they do not provoke harmful immune reactions.

– Avoiding Immune Activation: Any component incorporated into the fibers should be carefully chosen to prevent triggering an immune response that could result in chronic irritation or rejection. Biodegradable polymers are generally better tolerated by the body over time compared to non-degradable materials, which may persist in tissue and heighten the likelihood of inflammation.

5. Cellular Interactions and Tissue Regeneration:

– Supporting Skin Regeneration: For post-treatment skin cancer wounds, hollow fibers must facilitate tissue regeneration and cell proliferation at the wound site. These fibers can be engineered to enhance the regenerative capacity of the skin, promoting faster recovery and minimizing scarring. Collagen-based fibers, or those incorporating growth factors such as epidermal growth factor (EGF) or vascular endothelial growth factor (VEGF), are especially effective in supporting skin cell migration and the formation of new tissue.

– Promoting Keratinocyte and Fibroblast Growth: The surface of hollow fibers can be modified to stimulate the growth of keratinocytes (skin cells) and fibroblasts (cells responsible for forming connective tissue). This is essential for promoting the restoration of a healthy skin barrier following cancer treatment, ensuring the skin regains its normal function and appearance.

6. Long-Term Safety and Monitoring:

– Chronic Exposure Testing: Due to the potential for prolonged use, hollow fibers must undergo rigorous long-term safety testing. This involves evaluating their effects over extended periods to ensure they do not induce chronic irritation, infection, or systemic toxicity. The fibers should maintain stability throughout the treatment duration and degrade in a manner that is safe for the body.

– Biological Evaluation: Continuous evaluation using both in vivo (animal) models and in vitro (cell culture) models is essential to assess chronic toxicity and genotoxicity. The fibers must undergo various biocompatibility tests as outlined in ISO 10993, which provides standards for the biological evaluation of medical devices, ensuring their safety for extended contact with human tissues.

7. Injection of Hollow Canals into Fibers with Enhanced Biocompatibility: Surface Modification for Enhanced Biocompatibility:

– Hydrophilic Injection: Incorporating hydrophilic (water-attracting) layers into the fibers reduces friction, improving patient comfort. This modification also enhances the interaction between the fibers and the skin, facilitating better absorption of therapeutic agents (e.g., drugs, growth factors) and promoting faster healing.

– Bioactive Functional Groups: Injection of bioactive molecules such as fibronectin, collagen, or gelatin into the fibers can improve cell adhesion and stimulate tissue regeneration. This modification is particularly beneficial for skin cancer patients requiring wound healing after treatment or surgery.

– Antimicrobial and Anti-inflammatory Injection: Hollow fibers used in cancer treatment may be coated with antimicrobial agents like silver nanoparticles [2, 35, 39], chitosan, or honey, which help prevent infection, a critical concern for patients with weakened skin due to cancer treatments. Additionally, injection with anti-inflammatory agents (e.g., corticosteroids or nonsteroidal anti-inflammatory drugs) can help reduce inflammation at the treatment site [19].

Case study:

The hollow fiber assay, initially developed by Hollingshead and colleagues, was designed to provide an efficient method for prioritizing compounds exhibiting activity in the 60-cell line panel for subsequent evaluation in the human tumor xenograft assay [25]. This assay has effectively achieved its intended purpose. In 2001, the National Cancer Institute (NCI) published a study assessing the predictive value of both the hollow fiber and xenograft assays for identifying potential clinical agents [40]. The study evaluated thirty-nine agents that had progressed to phase II trials and had been tested in the tumor xenograft assay [40]. Compounds demonstrating in vivo activity in at least one-third of the xenograft models also exhibited efficacy in cer-

tain phase II trials, highlighting the utility of the xenograft assay in forecasting clinical activity [41].

The investigators also compared the activity of 564 compounds in both the hollow fiber assay and tumor xenograft models. The results demonstrated that the probability of detecting xenograft activity in at least one-third of the models increased with higher intraperitoneal (ip) hollow fiber activity, rising from 8% for all compounds tested to 20% for agents active in more than six fibers implanted ip. Moreover, intraperitoneal hollow fiber activity was found to be a more reliable predictor of xenograft activity than subcutaneous (sc) hollow fiber activity. These findings were further validated and expanded upon in a subsequent analysis of 690 compounds tested across both models [42]. The authors concluded that activity in ip-implanted hollow fibers serves as a useful predictor of subsequent activity in the xenograft assay. A similar conclusion was reached by Voskoglou-Nomikos et al. in their review of the xenograft model's predictive utility for clinical efficacy in the Canadian NCI study [43]. Additionally, as previously discussed, the hollow fiber assay is relatively simple, rapid, and enables researchers to advance compounds through the drug discovery process while minimizing animal use, representing a significant advancement in terms of animal welfare [44]. Thus, the assay has effectively fulfilled its original purpose [41].

Results and Discussions:

The integration of hollow fiber technology into textile-based platforms presents a compelling opportunity to transform skin cancer therapy. By enabling localized delivery of drugs, light, or heat, such systems can enhance therapeutic efficacy while reducing patient discomfort and systemic side effects.:

1. Localized Drug Delivery Systems: Controlled Release of Chemotherapy or Immunotherapy Drugs. Hollow fibers incorporated into fabrics are engineered to transport and release chemotherapy or immunotherapy agents directly at the skin cancer site. This system facilitates localized and sustained drug delivery, minimizing systemic side effects. For instance, a fabric could be designed as a bandage or dressing containing hollow fibers loaded with drugs such as 5-fluorouracil (5-FU), a widely used treatment for superficial skin cancers. This setup would enable prolonged, targeted drug delivery directly to the tumor site. Additionally, hollow fibers can be employed to deliver immune-modulating agents, such as cytokines or checkpoint inhibitors, directly to the tumor, enhancing the body's immune response to the cancer cells [30].

2. Photodynamic Therapy (PDT) Enhancement: Fiber-Based Light Conduits for PDT Photodynamic therapy (PDT) utilizes a photosensitizer drug that becomes activated upon light exposure, leading to the destruction of cancer cells. Hollow fibers can function as light guides embedded within fabrics, directing light precisely to the cancerous regions. These fibers can be integrated into a fabric designed to deliver a photosensitizing agent to the tumor site. Subsequently, an external light source can activate the drug via the hollow fibers, enhancing the effectiveness of PDT while minimizing damage to surrounding healthy tissue.

3. Thermal Ablation via Hyperthermia: Localized Heat Treatment Thermal ablation through localized hyperthermia is an effective treatment strategy for superficial skin cancers. Hollow fiber-based fabrics can be engineered to transport heated fluids or conduct thermal energy from external sources directly to the tumor site. These fibers may serve as conduits for microwave or radiofrequency-induced hyperthermia, enabling precise temperature elevation at the cancerous region. This targeted thermal treatment induces cancer cell death while preserving adjacent healthy tissue integrity.

4. Wound Healing and Skin Regeneration: Accelerating Post-Surgical Recovery. Following surgical excision of skin cancer, efficient wound healing is essential. Hollow fiber-integrated fabrics can function as advanced dressings, promoting tissue regeneration by delivering therapeutic agents directly to the wound site. These fibers may be engineered to release bioactive molecules such as epidermal growth factor (EGF), which facilitates epidermal regeneration and minimizes scarring. Additionally, hollow fibers can be utilized for the localized delivery of anti-inflammatory agents to reduce edema and accelerate the healing process.

5. Oxygen Delivery to Tumor Sites: Enhancing Treatment Efficacy via Localized Oxygenation Tumor hypoxia, characterized by reduced oxygen levels, is a common condition that diminishes the effectiveness of therapies such as

radiation and chemotherapy. Hollow fiber-based fabrics can be engineered to deliver molecular oxygen directly to hypoxic tumor regions in the skin. These fibers may be designed for controlled oxygen release at the tumor site, thereby increasing cellular oxygenation and sensitizing cancer cells to therapeutic interventions, including radiotherapy.

6. Gene Therapy Delivery: Direct Genetic Modification via Hollow Fiber Systems. Hollow fiber fabrics present a novel platform for the localized delivery of gene therapy in the treatment of skin cancer. These fibers can be engineered to transport gene-editing agents such as CRISPR-Cas9 or RNA-based therapeutics directly to malignant cells. The fabric may be designed to facilitate the controlled release of targeted DNA or RNA sequences aimed at correcting oncogenic mutations or silencing genes implicated in tumor proliferation. This approach offers a promising alternative to conventional modalities such as chemotherapy and radiation therapy [19].

7. Immunotherapy Enhancement: Localized Stimulation of Immune Response. Hollow fiber systems offer a targeted approach to enhance immunotherapy efficacy in skin cancer treatment. These fibers can be engineered to deliver immune-modulating agents, including checkpoint inhibitors or cytokines, directly to the tumor microenvironment. By releasing compounds that activate T-cells or other immune effector cells locally, the fibers can potentiate the immune response against malignant cells, thereby improving therapeutic outcomes while minimizing systemic immune-related side effects.

8. UV Protection for Prevention: Prophylactic Application of Hollow Fiber Fabrics. Hollow fiber-based textiles can be engineered as a preventive strategy against ultraviolet (UV)-induced skin carcinogenesis. These fibers may be designed to effectively block or attenuate harmful UV radiation, a primary etiological factor in the development of skin cancer. Integration of such fibers into wearable protective garments – e.g., shirts, hats, or scarves – provides continuous, passive photoprotection, particularly beneficial for high-risk individuals or patients with a history of skin malignancies.

9. Customizable Treatments for Individual Patients: Personalized Therapeutic Delivery via Hollow Fiber Systems, Hollow fiber-based delivery platforms can be customized to accommodate patient-specific therapeutic requirements in the treatment of skin cancer. These fibers may be selectively loaded with pharmacological agents tailored to the histopathological subtype and molecular profile of the tumor. By targeting specific biomarkers or genetic mutations present within the cancerous tissue, hollow fiber systems enable precision medicine approaches, enhancing therapeutic efficacy while minimizing off-target effects and systemic toxicity.

10. Personalized Treatment Approaches: Tailored Hollow Fiber Fabrics for Patient-Specific Therapies Hollow fiber-based textile systems can be customized to accommodate interpatient variability in skin cancer type, location, and molecular characteristics. These fabrics may be engineered to target tumor-specific biomarkers, enabling site-specific delivery of personalized therapeutics. By aligning drug release profiles and fiber properties with the unique biological profile of the tumor, such systems offer a precision medicine approach that optimizes treatment efficacy while minimizing adverse effects [19].

Conclusion:

Prospective Applications of High-Performance Hollow Fiber Systems in Skin Cancer Therapy, High-performance hollow fiber (HF) injection systems present a novel and promising modality for the localized treatment of skin malignancies. The biocompatibility of these systems – achieved through strategic material selection, surface functionalization, and control over degradation kinetics – ensures minimal immunogenicity and cytotoxicity, rendering them suitable for clinical deployment in immunocompromised patients [45]. Their design facilitates precise, sustained, and site-specific delivery of chemotherapeutics, immunomodulators, and regenerative agents, thereby enhancing therapeutic efficacy while minimizing systemic toxicity.

Integration of HF systems into textile-based platforms extends their applicability to multifunctional therapeutic fabrics capable of addressing diverse clinical needs such as wound healing post-excision, photodynamic therapy, thermal ablation, and gene therapy. These smart textiles may significantly enhance patient compliance by providing non-invasive, wearable, and comfortable solutions for long-term treatment.

Future development must address the following critical parameters to ensure clinical viability:

Biocompatibility: HF systems must exhibit non-immunogenic behavior and maintain structural and chemical stability upon prolonged dermal contact, especially in oncology patients.

Controlled Drug Release: Engineering release kinetics through morphological or chemical modulation of HF walls is vital for achieving therapeutic concentrations while preventing dose spikes.

User Comfort: The textile matrix must exhibit mechanical flexibility, breathability, and skin-friendliness to mitigate treatment-related discomfort and encourage prolonged use.

Continued translational research and clinical validation will be essential to optimize these systems for large-scale adoption, focusing on long-term biosafety, drug loading versatility, and efficacy across various skin cancer subtypes.

Recommendations: Mitigation of Systemic Pesticide Exposure via Cotton-Based Medical and Personal Textiles To enhance public health safety and minimize potential dermal and systemic exposure to hazardous agrochemicals, the following recommendations are proposed:

1. Agricultural Practices: It is recommended that cotton cultivators discontinue the application of systemic pesticides during cotton production. This measure is critical to reducing the residual pesticide content in raw cotton fibers intended for biomedical and personal use.

2. Textile Manufacturing Standards: Manufacturers of cotton-based medical textiles – including gauze, bandages, and personal garments such as underwear – should implement rigorous sourcing and testing protocols to ensure the exclusion of cotton treated with systemic pesticides from their production lines.

3. Global Health Policy Update: It is recommended that the World Health Organization (WHO) revise and enhance its health and safety specifications concerning medical-grade cotton textiles. New guidelines should mandate the use of organically cultivated cotton, verified to be free of systemic pesticide contamination, in products intended for direct skin contact to ensure optimal patient and consumer safety.

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ВЫСОКОЭФФЕКТИВНЫЕ БИОСОВМЕСТИМЫЕ ПОЛЫЕ ВОЛОКНА ДЛЯ ЛЕЧЕНИЯ ЛОКАЛИЗОВАННОГО РАКА КОЖИ: ПОДХОД НА ОСНОВЕ ТЕКСТИЛЯ

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Рак кожи стал серьезной проблемой общественного здравоохранения во всём мире, причём показатели заболеваемости неуклонно растут из-за таких факторов, как длительное воздействие ультрафиолетового

излучения, старение населения и загрязнение окружающей среды. По данным Всемирной Организации Здравоохранения, рак кожи занимает 17-е место по распространённости в мире и особенно распространён в странах с высоким уровнем воздействия ультрафиолета, таких как Австралия, Соединенные Штаты и некоторые регионы Европы. Только в 2022 году во всём мире было диагностировано более 330000 новых случаев заболевания. Наиболее распространённые формы – базалиома, плоскоклеточный рак и меланома – не только представляют серьёзную угрозу здоровью, но и влияют на качество жизни из-за обезображивания и агрессивных протоколов лечения. Хотя современные методы лечения, такие как хирургическое удаление, лучевая терапия и системная химиотерапия, могут быть эффективными, они часто имеют существенные недостатки. Хирургические вмешательства могут привести к появлению видимых рубцов и длительному восстановлению; химиотерапия воздействует как на здоровые, так и на раковые ткани, что приводит к системной токсичности; а лучевая терапия может повредить окружающую здоровую кожу. Более того, такие подходы часто причиняют дискомфорт пациенту и повышают риск рецидива. Чтобы устранить эти ограничения, в данном исследовании рассматривается использование высокоэффективных полых текстильных волокон в качестве системы локальной доставки лекарств для лечения рака кожи. Эти волокна, созданные с использованием передовых технологий, таких как электроспиннинг и микрофлюидное прядение, обеспечивают целенаправленное и длительное высвобождение терапевтических агентов, включая химиотерапевтические препараты, иммуномодуляторы или молекулы для редактирования генов, непосредственно в очаге опухоли.

Ключевые слова: рак кожи, полые волокна, инъекции, биосовместимость, иммунотерапия, химиотерапия

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