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Research on Natural Polymer-Based Double-Network Hydrogel Coatings for Intestinal Obstruction Catheters: Acid Resistance, Low Swelling, and Enhanced Lubricity

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Abstract
Intestinal obstruction is a common clinical emergency, where the application of catheters plays a critical role in treatment. However, traditional catheter materials face limitations such as high friction and poor biocompatibility. In recent years, natural polymer-based double-network hydrogel coatings have attracted widespread attention due to their superior acid resistance, low swelling, and enhanced lubricity. This review summarizes recent advances in the application of natural polymer-based double-network hydrogel coatings for intestinal obstruction catheters, focusing on their acid resistance, low swelling, and lubricity, and discusses their clinical potential and challenges.

Keywords: *Intestinal obstruction; Double-network hydrogels; Acid resistance; Low swelling*

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I. Introduction

The mortality of intestinal obstruction is closely associated with complications, particularly in acute cases. For instance, patients with complicated colonic diverticular disease (CCDD) exhibit significantly increased 1-year mortality rates[1]. Acute intestinal obstruction accounts for a high proportion of all cases, especially in malignant colonic obstruction, which often requires emergency surgery or stent placement[2]. Additionally, acute intestinal diseases (rotavirus infection) are highly prevalent worldwide, further highlighting the importance of addressing acute intestinal obstruction and related conditions[3]. The treatment of intestinal obstruction includes a variety of strategies such as pharmacologic therapy, minimally invasive surgery, and biomodulation[4][5], all of which have shown favorable clinical outcomes. For example, lanreotide microspheres[6] and 5-HT4 receptor agonists[7] have demonstrated significant efficacy in relieving inoperable and postoperative intestinal obstruction, while colonic stenting[2] is superior to emergency surgery in acute malignant colonic obstruction. Minimally invasive techniques have demonstrated significant benefits in the treatment of intestinal obstruction, reducing the risk of postoperative complications and improving long-term prognosis. Studies have shown that minimally invasive surgery can reduce the incidence of intestinal obstruction in duodenal obstruction, small bowel obstruction associated with colon cancer, and diaphragmatic hernia repair [8]~[10]. In addition, minimally invasive techniques have been used in the treatment of acute superior mesenteric artery obstruction[11]and malignant colonic obstruction[12], further confirming their safety and efficacy in complex cases. Catheters for intestinal obstruction are effective in relieving intestinal pressure through mechanical evacuation or drainage, buying time for subsequent treatment[13]. There are still many challenges in the performance of catheter materials, and the traditional catheter materials for the gastrointestinal tract are polyvinyl chloride (PVC) and polyurethane (PUA)[14]. There are many limitations including high friction[15], the risk of retention for long periods of time in complex environments such as plastid migration of PVC catheters that may trigger inflammatory reactions[16], and problems with biocompatibility[17], which may cause patient discomfort and complications. These issues limit the the effectiveness of catheter technology. The key to clinical care is early diagnosis and timely intervention[18].

To overcome the limitations of traditional catheter materials, coating technology is widely used to modify the catheter surface. Hydrogel coatings have become an important direction for catheter modification due to their excellent hydrophilicity and low friction, antimicrobial properties, biocompatibility and modifiability, self-healing, and temperature-sensitivity[19]~[24]. Natural polymers (chitosan[25], dopamine[26][27] and sodium alginate[28]~[30]), are widely used for the preparation of hydrogel coatings due to their good biocompatibility, degradability and sustainability. Compared with conventional synthetic materials, natural polymer-based hydrogels can significantly reduce friction during catheter insertion while improving the lubricity and acid resistance of the material [31][32].

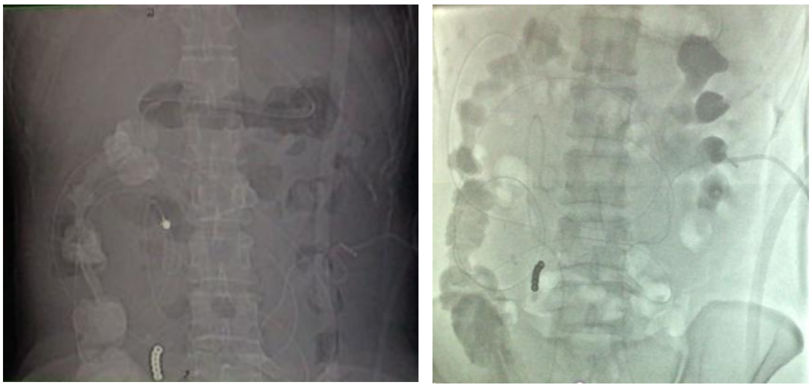

Figure 1. Schematic of an intestinal obstruction catheter entering the gastrointestinal tract

II. Double Network Hydrogels

Double Network Hydrogels (DNHs)[33] are composites consisting of two interconnected networks, whose unique structure confers excellent mechanical properties (e.g., high strength and toughness)[35]~[37]. Compared to conventional single network hydrogels, DNHs show significant advantages in acid resistance[38], low swelling properties[39] and lubricity, which show significant advantages. These properties make it an ideal candidate for catheter coatings for intestinal obstruction.

2.1. Classification of natural hydrogels

Chitosan has good bioactivity and utilizes charged antimicrobial properties[40]. It is commonly used to promote tissue healing and anti-infective therapy[41][42]. Gelatin is derived from the degradation of collagen[43], which has excellent biocompatibility and promotes cell growth[44][45]. Sodium alginate, an anionic polysaccharide, is easily formed into gels, is non-toxic to cells, and is suitable for use in drug delivery systems and trauma dressings[46][47]. Cellulose, one of the most abundant renewable resources on earth, provides good mechanical support and can be modified to suit different application scenarios[48][49]. Hyaluronic acid, which possesses excellent moisturizing ability and improves lubrication[50], is widely used in medical applications such as ophthalmic surgery and joint injections[51].

Table 1. Applications of natural polymers.

Polymer	Applications	Key Data
Chitosan	Tissue repair, anti-infection[52]	Accelerates healing by 74.46%[53]
Gelatin	Drug carriers[54]	Drug release efficiency: 84.4%[55]
Sodium alginate	Drug carriers, wound dressings	Solubilisation of insoluble drugs, anticancer drug delivery, gene and immunotherapy[56]~[58]
Cellulose	Scaffolds, structural reinforcement	Porous aerogels 96% porosity[59][60]
Hyaluronic acid	Lubricants, fillers	Cof ≈ 0.001[61]

2.2. Synthesis strategies for dual network hydrogels

In order to prepare high-performance dual network hydrogels, several cross-linking techniques are commonly employed to achieve desired mechanical properties and functionality. These methods include, but are not limited to: physico-chemical hybrid cross-linking[62][63], one-pot methods[64], and reciprocal network cross-linking[65]. The primary network polymers provide the backbone[66] through covalent or physical cross-linking[67] , and the secondary networks such as polymer networks of polyacrylamides[68], polypyrroles[69] dissipate the energy. The design of composite bi-network hydrogels achieves significant optimization of properties through the synergistic interaction of different biomolecules (polysaccharides, proteins). For example, the synergistic combination of collagen and chitosan improves antimicrobial properties and cytocompatibility[70] , whereas hybridized networks of gelatin with other natural materials enhance mechanical strength and tunability through dynamic cross-linking strategies[71]. These designs typically employ a multilayered network construction strategy of physical entanglement, chemical cross-linking (covalent bonding, hydrogen bonding), and dynamic interactions (metal coordination, π-π stacking)[72]~[74]. For example, the interpenetrating network (IPN) structure forms dual cross-links via enzymatic or chemical triggering, allowing the material to obtain mechanical properties close to those of a natural tendon (rupture stress up to 23.5 MPa, fracture energy 210 MJ/m^3) while maintaining a highwater content[75]. In addition, the introduction of biomimetic hierarchical structures (e.g., nanofibers-micropore composites) has allowed hydrogels to mimic the extracellular matrix. gels to mimic the mechanical properties of the extracellular matrix while realizing multifunctional integration such as controlled drug release and antimicrobial properties[76][77].

III. Preparation, Design, and Evaluation System of Double Network Hydrogel Coatings

To prepare double network hydrogel coatings with excellent performance, several techniques can be employed. According to Li and colleagues' research, immersion-crosslinking involves alternating soaking in $CaCl_2$ solution and sodium alginate/chitosan solutions to achieve stable double network structures[78]. Another approach by Li et al. utilizes photopolymerization, combining methacrylated hyaluronic acid (GelMA) with sodium alginate, which forms double networks through UV-initiated polymerization[79]. Surface grafting methods, as described by Zhang and coworkers, involve grafting hyaluronic acid onto substrates to enhance anti-fouling properties[80].

The mechanical performance of these coatings can be assessed through various metrics. Wang and associates investigated adhesion strength, abrasion resistance, and flexibility using standard testing methods[81]~[83]. Functionality evaluations include assessing lubricity, acid resistance, and swelling ratio. For instance, friction coefficients are measured according to ASTM D1894 standards using in vitro intestinal friction tests to evaluate coating lubricity [83]. Acid resistance is tested by exposing the coatings to simulated gastric fluids (pH = 1.2-3.5) and intestinal fluids (pH = 6.8), observing changes in mass and morphology[84]. The swelling ratio is determined under physiological conditions over 24 hours, with the target being less than 5%[85].

Biological evaluations are crucial for ensuring the safety and efficacy of these coatings. Yang and colleagues conducted cytotoxicity tests using intestinal epithelial cells such as Caco-2 to assess biocompatibility[86]. Immunomodulatory effects are also evaluated, with studies by Hasani-Sadrabadi and co-workers providing insights into immune responses[87]. In vivo degradation behavior and inflammatory reactions have been further examined in animal models, confirming the safety and effectiveness of the coatings[88][89].

3.1. Functionalized design for acid resistance

When designing the dual network hydrogel coating for intestinal obstruction catheters the challenge of acidic conditions (pH=1.5-3.5) in the intestinal environment was taken into account for the stability of the material, in order to improve the adaptability of the material in acidic environments the following strategy can be adopted Chitosan undergoes protonation under acidic conditions thus forming a more stable network structure this property makes chitosan becomes an ideal acid-resistant material according to Nie et al[90]. By introducing pH-sensitive groups hydrogels can be made to exhibit different swelling behaviors in different pH environments thus enhancing their stability in acidic environments as noted by Protsak and Morozov[91]. Restriction of chain segment movement adjustment of crosslinker density as well as hydrophobic modification to regulate the crosslink density reduces the swelling of the material under acidic conditions maintaining its mechanical properties and stability[92]~[94].

3.2. Low Swellability

Swellability has a significant impact on the mechanical strength and lubricity of the catheter increasing the risk of clinical complications such as infection[95] or thrombosis[96] and therefore needs to be optimized to ensure efficient catheter function. By increasing the number of cross-linking points effectively reduces the swelling of the hydrogel improves its mechanical strength as demonstrated by Nakano et al[97] High-density covalent cross-linking or dynamic physical cross-linking like hydrophobic interactions ligand bonding restricts the penetration of water molecules. Polyacrylamide/poly(vinyl alcohol) (PVA/PAAc-N^+) porous hydrogels achieve ultra-low swelling (0.29) by forming a stabilizing network by phase separation-solvent exchange method[98]. Enhancement of hydrogel network density by adjusting cross-linking agents such as HMBA content limits water absorption and swelling PVA-PAH bi-network hydrogels achieved low swelling rate volume change of less than 5% by optimizing the ratio of cross-linking agents[99]. Addition of delignin can significantly reduce the swelling rate of polyacrylamide hydrogels while enhancing the overall mechanical properties of the material[100]. Addition of hydrophobic polymers such as polyvinyl alcohol can reduce the swelling of hydrogels without affecting the biocompatibility Varadarajan et al. discussed[101]. Nanofillers such as cellulose nanocrystals (CNCs) can significantly reduce the swelling rate of hydrogels according to the literature[102] Dynamic crosslinked networks can automatically adjust the network structure to achieve adaptive shrinkage to further reduce swelling when external conditions change[103][104].

3.3. Enhanced lubrication

Lubricity is critical for catheter insertion and patient comfort and a variety of strategies can be used to enhance lubricity Many polymeric materials have good hydrophilic properties and can be used to coat catheters to improve lubricity PAM[105], PEG, the natural polymer HA[106], and hydrophobic polymer coatings can provide additional lubrication[107]. Reversible lubrication layers formed by cross-linking sodium alginate with Ca^{2+} have strong adhesion and can dynamically adjust lubrication properties according to changes in ionic concentration suitable for complex physiological environments in the intestinal tract[108][109]. As shown in Fig. 3, the gradient network design simulates the lubrication characteristics of biological soft tissues to obtain a lubrication effect closer to the natural state[110]. By modulating the coating porosity and surface morphology e.g. 3D porous structure hydrogel can form fluid lubrication layer-like self-assembly technology prepared hydrogel film under acidic conditions due to pore shrinkage to enhance the surface smoothness and reduce the friction resistance[111].

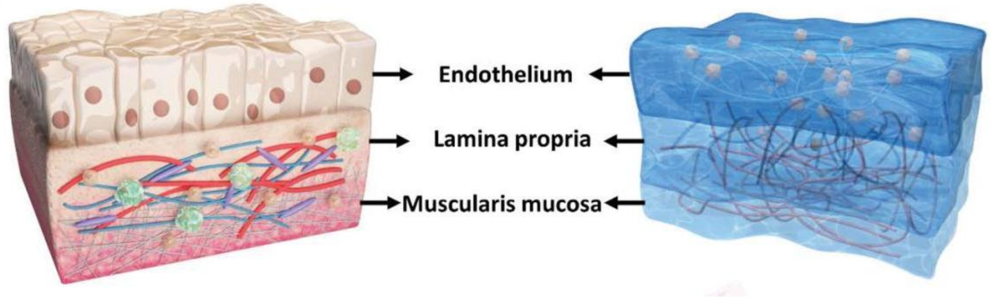

Fig.3. Schematic illustration for the resemblance of our conformal hydrogel coating with the mucosa[109].

IV. Clinical Applications and Case Studies

In recent years, multifunctional integrated coatings have shown significant potential for clinical applications in the development of catheters for intestinal obstruction. It was found that chitosan and polyacrylamide are often combined through a dual network (DN) structure, in which polyacrylamide provides a high-strength backbone (e.g., shear modulus of about 10 Pa and tensile strength of about 100 kPa), while chitosan enhances the toughness through physical cross-linking (hydrogen bonding, ionic bonding) or chemical cross-linking (Schiff base bonding) to enable the hydrogel to reach a fracture elongation of more than 1,000%[112][113]. The study The effectiveness of the coating in preventing microbial adhesion and reducing friction during surgical manipulation was verified in an animal model. This coating provides additional safety and ease of handling for medical devices and lays the foundation for clinical applications[114].

Acid-resistant hydrogel coatings for artificial joints or catheters can reduce corrosion by acidic body fluids and decrease friction-induced inflammatory reactions[115][116]; hydrogels containing dynamic bonds (e.g., hydrogen bonding, coordination bonding) can self-repair after damage and maintain lubricating properties. For example, hydrogels based on tannic acid-modified cellulose (TA@CNC) can still rapidly self-heal in acidic environments, ensuring long-term lubrication[117][118].

As shown in Fig. 4 polydimethylsiloxane (PDMS) modified by hydrogel coating significantly reduces the contact angle and enhances the hydrophilicity, which inhibits bacterial (e.g., Escherichia coli and Staphylococcus aureus) adherence[119]. In addition a drug-loaded chitosan-polylactone (PLC) bi-networked hydrogel coating, which achieves targeted drug release of 5-fluorouracil by pH modulation. The results of the study showed that the coating had significant advantages in pH modulation of drug release and provided new ideas for the treatment of intestinal neoplastic obstruction[120][121].

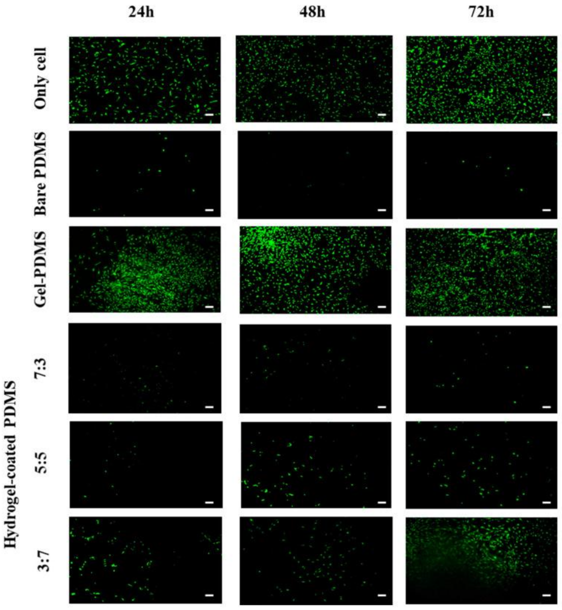

Fig.4. Cell viability on the surfaces of bare poly(dimethylsiloxane) PDMS and PDMS modified with gelatin and hydrogel composed of CHO–HA/Gel–NH2. (The scale bar represents 100 µm.)[118].

V. Conclusion and Perspectives

Natural polymer-based double network (DN) hydrogel coatings demonstrate significant potential for improving intestinal obstruction catheters by providing acid resistance, low swelling, and enhanced lubricity. Innovations such as temperature-responsive hydrogels, enabled by hydrogen-bonded networks incorporating glycerol, exhibit enhanced mechanical stability over 14 days and enable thermally triggered antimicrobial release[122]. Light-responsive systems, such as PAM/agarose/TA-B hydrogels, combine antibacterial activity with optical and conductive properties, offering potential for real-time monitoring via wearable sensors[123]. However, challenges persist, including degradation in complex gastrointestinal environments due to enzymatic corrosion, mechanical erosion, and microbial colonization[124] as well as the need for disease-specific adaptations to balance properties like hardness and lubricity across diverse etiologies[125]. Scalability and standardization for clinical translation remain critical barriers[126]. Future work should focus on optimizing crosslinking strategies (e.g., light-initiated polymerization), integrating smart materials with technologies like magnetic robotics or optogenetics, and fostering interdisciplinary collaboration to address complex gastrointestinal pathologies[127][128]. These advancements could revolutionize catheter design, enhancing patient safety and treatment outcomes while paving the way for broader applications in gastrointestinal medicine.

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