

Design, Biomechanical Performance, and Physiological Considerations of Esophageal Stents in Relation to Esophageal Peristalsis: A Review

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Abstract: Esophageal stents are widely used to restore luminal patency in patients suffering from malignant or benign esophageal strictures. Despite the clinical success of self-expanding metallic and plastic stents, complications such as migration, restenosis, and interference with normal peristalsis remain unsolved challenges. Recent advances in biodegradable materials, 3D printing, and computational biomechanics offer new opportunities for designing patient-specific, physiologically compatible esophageal stents. Moreover, understanding the biomechanics of esophageal peristalsis—particularly the coordination of circular and longitudinal muscle contractions—is crucial for improving stent–tissue interactions. This review provides an overview of recent progress in stent materials, design strategies, and finite element modeling, as well as physiological models of esophageal peristalsis and their implications for future stent development.

Keywords: Esophageal stent; biomechanics; peristalsis; finite element analysis

1. INTRODUCTION

Esophageal strictures caused by malignant tumors or benign diseases such as postoperative scarring and corrosive injury significantly impair swallowing function and quality of life. Self-expanding metallic stents (SEMS) and plastic stents (SEPS) have been extensively used to palliate dysphagia by reopening the narrowed lumen[1–3]. However, conventional stents still face multiple complications, including migration, tissue hyperplasia, and difficult removal[3].

To address these limitations, researchers have turned toward biodegradable and polymeric stents that can gradually degrade within the body, eliminating the need for retrieval[4–5]. Furthermore, 3D printing technology allows for patient-specific stent fabrication with customized dimensions and mechanical properties[6–7]. While materials and structure have received considerable attention, fewer studies have explored how stents interact dynamically with the esophageal wall, which undergoes periodic contraction and relaxation during peristalsis[8]. Since peristaltic motion produces cyclic stress and radial compression on the stent, understanding this physiological mechanism is essential for long-term stent performance.

Therefore, this review aims to (1) summarize recent progress in stent materials and structural design, (2) discuss biomechanical modeling and finite element analysis (FEA) of stent–esophagus interactions, and (3) explore the physiological and computational modeling of esophageal peristalsis relevant to stent behavior.

2. ANATOMY AND BIOMECHANICS OF THE ESOPHAGUS

The esophagus is a muscular conduit composed of circular (CM) and longitudinal (LM) muscle layers, which contract in a coordinated manner to generate peristaltic waves that propel the food bolus toward the stomach. The CM layer shortens radially, while the LM layer shortens axially, reducing wall tension and improving transport efficiency[12–13]. Modeling studies have demonstrated that longitudinal muscle shortening

reduces the energy expenditure of the circular layer and contributes to efficient bolus propulsion[12]. In contrast, discoordination between CM and LM activity is associated with esophageal motility disorders such as diffuse spasm and achalasia[13–14].

From a biomechanical perspective, the esophagus exhibits nonlinear elastic behavior, and its peristaltic contraction creates transient pressure gradients of 30–80 mmHg. When a stent is inserted, it experiences these dynamic loads repeatedly, which may lead to fatigue, plastic deformation, or migration over time[15–16]. Therefore, understanding the mechanical environment of the esophagus is a prerequisite for developing durable, physiologically compatible stents.

3. MATERIALS AND STRUCTURAL DESIGN OF ESOPHAGEAL STENTS

Traditional esophageal stents were made of stainless steel or nitinol, providing strong radial force but limited flexibility. These metallic stents may cause mucosal injury or granulation tissue formation. To overcome such issues, polymer-based biodegradable stents have been proposed[1–2,5]. Poly-L-lactic acid (PLLA), polycaprolactone (PCL), and poly-D,L-lactic acid (PDLLA) are among the most studied materials, providing tunable degradation times and favorable biocompatibility[4,8].

Yang et al.[1] introduced a polymeric biodegradable stent demonstrating complete degradation after several weeks, while maintaining mechanical strength for luminal patency. Yuan et al.[2] further fabricated and evaluated polymer-based stents for benign strictures, confirming consistent radial support and excellent removability. In parallel, Lin et al.[3] utilized 3D printing to develop flexible polymer stents optimized for esophageal malignancies, enabling customized structures and reduced migration risk. Wu et al.[4] combined 3D printing with neural network algorithms to predict biomechanical behavior and optimize design parameters.

Metallic biodegradable alloys such as Fe–Mn–Si have also shown promise due to their high strength and corrosion-controlled degradation[7]. Numerical simulation confirmed that such alloys can maintain adequate radial expansion while minimizing stress concentration on the esophageal wall. To prevent migration, design parameters such as stent flare angle, strut pattern, and surface friction are crucial[11]. Mozafari et al.[11] systematically analyzed how geometric configurations influence migration resistance through finite element simulations.

4. BIODEGRADABLE AND DRUG-ELUTING STENTS

Biodegradable stents represent a promising alternative for benign strictures, as they degrade gradually, reducing the need for removal procedures[6-7]. Liu et al.[6] tested a novel biodegradable stent in animal experiments and found good tissue compatibility and predictable degradation kinetics. However, early migration remains a significant challenge, highlighting the trade-off between flexibility and anchoring stability.

Recent reviews have emphasized combining biodegradable structures with drug-eluting coatings to mitigate inflammation or tumor recurrence[8-9]. Yang et al. [8] provided a comprehensive overview of biodegradable stent materials, emphasizing the integration of drug-delivery functionality. Zheng et al.[9] reported a 3D-printed, drug-controlled release stent capable of localized chemotherapy, offering dual benefits of mechanical support and therapeutic delivery. Such multifunctional stents may become a new direction for esophageal intervention, bridging materials science and targeted therapy.

5. COMPUTATIONAL BIOMECHANICS AND FINITE ELEMENT MODELING

Finite element analysis (FEA) has become a powerful tool for simulating the mechanical interaction between stents and the esophageal wall. Peirlinck et al.[10] conducted an *in silico* biomechanical analysis of the stent–esophagus interaction, considering factors such as stent geometry, wall stiffness, and friction coefficient. Their model revealed that contact pressure distribution depends strongly on both stent structure and esophageal elasticity. Mozafari et al.[11] further investigated migration resistance under various design parameters and confirmed that flared ends substantially enhance anchoring stability.

Recent research has integrated data-driven methods with traditional simulation. Wu et al.[4] employed a back-propagation neural network to predict radial force and wall stress of 3D-printed stents based on finite element data, reducing computational time while maintaining accuracy. Similar hybrid approaches may accelerate personalized stent design using patient-specific anatomical data. Numerical analysis also helps evaluate cyclic stresses caused by peristalsis, which are otherwise difficult to capture experimentally[15].

6. PHYSIOLOGY AND MODELING OF ESOPHAGEAL PERISTALSIS

The biomechanics of esophageal peristalsis have been extensively studied using both experimental and computational models. Brasseur et al.[12] mathematically demonstrated the distinct roles of CM and LM muscles in

generating peristaltic pressure waves. Mittal and Brasseur[13] emphasized how the coordination between these layers regulates normal transport and how dysregulation contributes to motility disorders. Singh et al.[14] confirmed these findings *in vivo* using simultaneous ultrasound and manometry, showing that LM contraction slightly precedes CM activation during normal swallowing.

Advanced numerical models simulate peristaltic motion and bolus transport through fluid–structure interaction (FSI). Kou et al.[16] developed a fully resolved musculo-mechanical model incorporating active muscle contraction and bolus flow, accurately reproducing physiological pressure patterns. Misra and Maiti[17] modeled peristaltic transport of non-Newtonian fluids to analyze the impact of wall stiffness and wave shape on bolus velocity and reflux risk. Emerging methods such as mechanics-informed MRI now enable estimation of esophageal wall stiffness and muscle activity directly from imaging data[15], bridging physiology and computational modeling.

These models collectively form a foundation for analyzing how implanted stents might alter peristaltic pressure propagation, affect bolus flow, or experience fatigue due to cyclic deformation[16-17].

7. COUPLED PERISTALSIS–STENT INTERACTION: CHALLENGES AND INSIGHTS

Despite progress in computational biomechanics, few studies have explicitly coupled realistic peristaltic motion with stent mechanics. Most current analyses assume static or quasi-static esophageal walls, neglecting dynamic cyclic loading[10-11]. In reality, peristaltic contraction can cause periodic compression, inducing mechanical fatigue and potentially altering stent geometry or migration resistance[16].

Integrating peristaltic motion into stent simulations requires solving complex FSI problems involving nonlinear materials and moving boundaries. For example, combining the musculo-mechanical framework by Kou et al.[16] with the stent–esophagus model by Peirlinck et al.[10] could yield realistic predictions of stent performance under physiological motion. Such hybrid models may inform optimal stent stiffness, radial force, and anchoring features for long-term functionality.

Experimental validation remains challenging due to limited *in vivo* measurement methods. Mechanics-informed MRI[18-21] and endoscopic pressure mapping could be used to collect real-time data for model calibration. Future stent designs must therefore balance radial strength, flexibility, and compliance with peristaltic motion, ensuring mechanical stability without impeding natural bolus transport.

8. FUTURE DIRECTIONS

The convergence of materials science, biomechanics, and computational modeling opens several promising directions for esophageal stent innovation:

1. **Patient-specific stent design.** Integration of medical imaging (CT/MRI) with 3D printing enables customized stent geometries tailored to individual anatomy[5,9].
2. **Dynamic biomechanical assessment.** Future studies should incorporate full peristaltic cycles and fatigue analysis using coupled FSI models[16,17].

3. **Smart materials and bioresorbable composites.** Development of shape-adaptive or drug-eluting biodegradable stents may reduce migration and improve tissue healing[8,9].
4. **Mechanics-informed diagnostics.** Quantitative imaging tools like MRI-MECH can evaluate esophageal mechanical function pre- and post-stenting[15].
5. **Long-term clinical evaluation.** Extended in vivo trials are needed to assess degradation, migration, and patient comfort[6,7].

Ultimately, collaboration between engineers, clinicians, and material scientists will be critical to translating these advances into clinical practice.

9. CONCLUSION

Esophageal stent technology has evolved from simple metallic tubes to complex, patient-specific devices that combine mechanical support with physiological compatibility. Advances in biodegradable polymers, 3D printing, and finite element analysis have improved stent performance and customization. However, most current designs still overlook the dynamic influence of esophageal peristalsis, which governs wall motion and stress distribution. Future research integrating physiological modeling, computational biomechanics, and smart materials will be essential for creating next-generation esophageal stents that harmonize with natural peristaltic function.

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