

REVIEW ARTICLE

Recent advances and applications in biodegradable vascular stents

Kaiyu Gu, Yuxiao Li, Chengli Song, Lin Mao

Shanghai Institute for Minimally Invasive Therapy, School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China.

Corresponding author: Lin Mao.

Address correspondence to: Lin Mao, School of Health Science and Engineering, University of Shanghai for Science and Technology, No. 516 Jungong Road, Yangpu District, Shanghai 200093, China.

Tel: +86-21-55572159.

E-mail: linmao@usst.edu.cn.

Received March 22, 2026; Accepted April 17, 2026; Published September 30, 2026

DOI: 10.61189/289827yamkxh

Abstract

Vascular stent implantation is one of the most important and effective methods for treating vascular stenosis or occlusion. To overcome the long-term side effects associated with permanent traditional bare-metal stents and drug-eluting stents in vivo, biodegradable vascular stents (BVSs) have been developed. BVSs can be classified into biodegradable polymer stents and biodegradable metal stents based on their material properties. In recent years, numerous preclinical studies and clinical trials have verified the feasibility and safety of different BVSs, including polymer-, magnesium-, iron-, and zinc-based stents, demonstrating their unique advantages while also revealing their limitations in clinical translation. This review summarizes the current status, challenges, and optimization strategies of BVSs according to existing research and discusses the translational applications of these stents in different vascular systems. Coronary artery stents are currently the most mature BVSs in clinical application, while cerebrovascular stents, peripheral vascular stents, and extravascular stents still require further research and development as well as clinical validation. As research and technological advancements continue, BVSs are expected to gradually be applied in most treatment scenarios for vascular diseases, ultimately realizing the goal of physiological vascular repair and regeneration. Next-generation BVSs will integrate diverse intelligent functions and precision customization strategies while satisfying fundamental clinical requirements, thereby helping overcome the bottlenecks of current BVSs.

Keywords: Biodegradable vascular stents, Biodegradable materials, Vascular diseases, Vascular stenosis, Translational application

Highlights

- Comparison and assessment of the material properties of biodegradable polymer stents, magnesium-based stents, iron-based stents and zinc-based stents.
- Application of biodegradable vascular stents (BVSs) in coronary arteries, cerebral vessels, peripheral vessels, and grafted veins.
- Strategies for achieving high flexibility and multifunctionality in future BVSs through material innovation, electronic integration, and personalized 3D/4D printing.

1 INTRODUCTION

With global population aging and the continuous increase in life expectancy, the risk of cardiovascular diseases (CVDs) has been growing significantly worldwide. CVDs, which include a

group of disorders of the heart, cerebral vessels, and systemic vasculature, are among the leading causes of death worldwide [1-3]. According to relevant statistics, the number of deaths attributable to CVDs reached 19.2 million in 2023. This number is estimated to rise to more than 23.6 million deaths annu-



ally by 2030 [3, 4]. Among various types of CVDs, structural and functional abnormalities of the vascular lumen constitute a major pathological basis of these diseases, with the most typical manifestations being vascular stenosis and vascular occlusion [5]. Vascular stenosis is primarily caused by atherosclerosis, intimal hyperplasia, chronic inflammation, fibrosis, and other related pathogenic factors. It is marked by progressive luminal narrowing and diminished blood perfusion, which may lead to severe complications that directly threaten organ function and patient survival. In some clinical scenarios in which balloon dilatation or pharmacotherapy alone fails to restore vascular anatomy and patency, the deployment of vascular stents is a critical intervention [6].

Vascular stents are expandable tubular mesh devices implanted into diseased vessels to maintain luminal patency and restore physiological blood flow [7]. They typically comprise a rigid supporting scaffold and, in some cases, an optional covering membrane, with the design tailored to meet specific clinical requirements. The earliest clinical application of vascular stents occurred in 1986 [8]. Bare-metal stents (BMSs) were successfully implanted into a human coronary artery at that time. BMSs provide adequate structural support to keep blood vessels open, but they also induce a series of complications, including an inflammatory response, stent thrombosis, and in-stent restenosis (ISR). BMSs are produced from inert and corrosion-resistant materials. They remain as permanent foreign bodies in the vascular system after implantation. These non-biodegradable implants can trigger inflammatory and immune reactions in the vascular wall. Such reactions stimulate vascular smooth muscle cell (VSMC) proliferation and neointimal hyperplasia, gradually narrowing the vascular lumen [8, 9]. Researchers developed drug-eluting stents (DESs) after recognizing that these adverse events are associated with long-term direct contact between the stent and the vascular wall. DESs are similar to BMSs in structural composition. They use a metallic scaffold, usually made of stainless steel or cobalt-chromium alloys, and their struts are covered with a unique biocompatible polymer coating [5]. This coating is used to load anti-proliferative drugs such as sirolimus, paclitaxel, and everolimus. These drugs can effectively inhibit the excessive proliferation of VSMCs, and they reduce the incidence of ISR more effectively than BMSs. However, the permanent metallic scaffolds of DESs remain in the vascular lumen as long-term foreign bodies. These scaffolds may induce chronic local inflammatory reactions, prevent complete endothelialization, and raise the risk of late stent thrombosis (LST) [10, 11].

Therefore, to overcome some limitations of permanent stents, biodegradable vascular stents (BVSs) have been developed as a promising alternative in the field of vascular interventions. BVSs are designed to provide essential mechanical support during the vascular repair process, degrade safely and gradually after vascular remodeling is completed, and are ultimately absorbed by the body without leaving residual foreign bod-

ies. The transient presence of BVSs not only restores the physiological vasomotor function and structural integrity of native blood vessels but also effectively mitigates the risks of chronic local inflammation, LST, and other long-term adverse complications associated with permanent stents (as shown in **Figure 1**) [11, 12]. In recent years, with the widespread exploration and application of various biodegradable materials in the development of BVSs, the clinical applications of these stents have been steadily expanding. BVSs are progressively being used to treat an extensive variety of vascular pathologies, including coronary artery disease, cerebrovascular stenosis, peripheral vascular disease, and grafted vein stenosis [11, 13-17].

This review focuses on summarizing the recent progress and translational applications of BVSs in the treatment of vascular diseases. This review first systematically summarizes the design criteria, material categories, major challenges, and optimization strategies of BVSs. The practical applications of BVSs in different vascular systems are then described in detail, including coronary arteries, cerebral vessels, peripheral arteries, and veins. Finally, future directions for BVSs are discussed, with emphasis on potential breakthroughs in material innovation, functional integration, and personalized stent customization.

2 PROPERTIES OF BVSS

The design of BVSs must meet strict and comprehensive performance requirements to ensure safety, effectiveness, and clinical applicability. Ideal BVSs should first offer sufficient radial strength, adequate flexibility, and long-term fatigue resistance to maintain luminal patency and adapt to dynamic vascular conditions. Meanwhile, a controllable degradation rate matched to vascular healing, nontoxic degradation products, and gradual loss of mechanical strength without abrupt failure are indispensable characteristics of such scaffolds. Moreover, qualified stents should exhibit superior biocompatibility, promote rapid endothelialization, and effectively mitigate local inflammatory responses [18, 19]. To satisfy these performance demands, the rational selection of suitable biodegradable materials is a core prerequisite for BVS development. At present, diverse biodegradable materials have been used in BVS research and fabrication, including biodegradable polymer vascular stents (BPVSSs) made from polymers such as poly(lactic acid) (PLA) or poly(ϵ -caprolactone) (PCL), as well as biodegradable metal vascular stents (BMVSSs) based on magnesium (Mg), iron (Fe), and zinc (Zn) alloys.

2.1 BPVSSs

Researchers have long considered biodegradable polymers promising raw materials for BVS preparation, thanks to their great processability, favorable biocompatibility and adjustable degradation behavior [20]. Common polymers used in BPVSSs include PLA, poly(L-lactic acid) (PLLA), PCL, poly(L-lactide-co-caprolactone), poly(lactic-co-glycolic acid), and poly

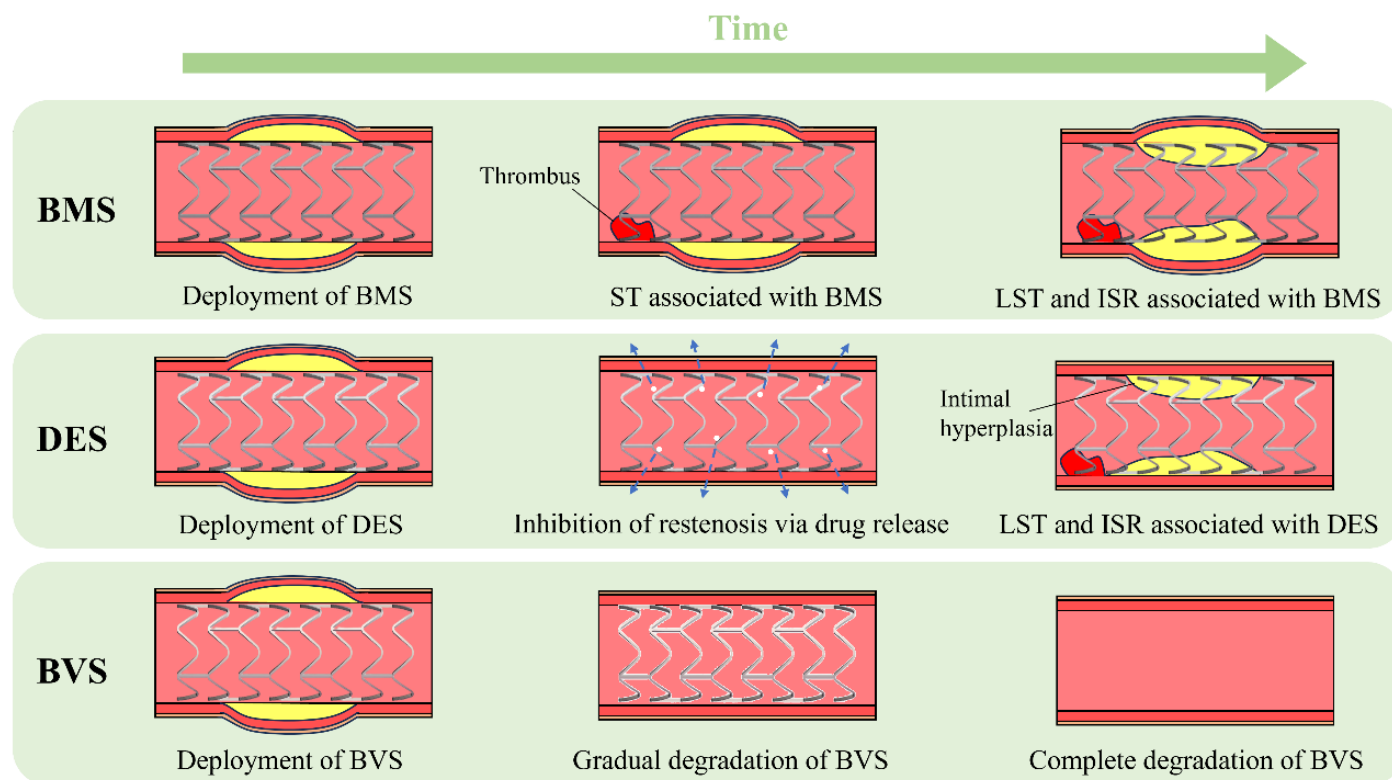


Figure 1. Schematic comparison of vascular responses after implantation of different stents. BMS, bare-metal stent; DES, drug-eluting stent; BVS, biodegradable vascular stent; ST, stent thrombosis; LST, late stent thrombosis; ISR, in-stent restenosis.

(glycolic acid) [21, 22]. Within living organisms, hydrolysis serves as the key degradation pathway for BPVSs. At the initial phase, water molecules diffuse into the inner polymer matrix, which induces water uptake and the swelling of polymer chains. Hydrolytic cleavage then takes place, leading to the gradual splitting of long polymer chains into shorter fragments. As this reaction progresses, these fragments are further decomposed into low-molecular-weight segments that can be phagocytosed by foreign-body giant cells and leukocytes. Carbon dioxide and water are the final metabolic products of these segments, which will be processed and eliminated from the body naturally. The degradation rate of polymer materials shows obvious differences. For pure PLLA, the whole degradation process often lasts 6 to 24 months. It is worth noting that the degradation rate can be tailored by altering key parameters of polymers, including molecular weight, composition, glass transition temperature and material morphology [11, 21].

Despite these advantages, BPVSs normally show lower radial stiffness than metal stents, and this shortcoming has limited their further clinical application to a certain extent. Many targeted optimization methods have proven useful in strengthening BPVSs, among which are structural optimization, material modification and improvements to manufacturing techniques [22]. One of the simplest and most effective ways to raise radial strength is to increase the thickness of stent struts. Yet thicker struts not only reduce stent flexibility but also

increase the risk of thrombosis. Studies have revealed a clear relationship between stent strut thickness and thrombosis. Overly thick struts in the vascular lumen will disrupt hemodynamic stability and induce flow turbulence, which speeds up platelet adhesion and aggregation, causes acute thrombosis and slows down vascular re-endothelialization [21]. Rational design of stent geometry is therefore needed to achieve a desirable balance among radial stiffness, flexibility and vascular adaptability. When it comes to material modification, the addition of biodegradable nanofillers can greatly strengthen the polymer matrix without compromising its biocompatibility or degradability. Improving the crystallinity of semicrystalline polymers used in BPVSs is another effective way to enhance radial rigidity, thermal stability and chemical stability. Besides, precise control over the orientation of polymer chains through molecular structure engineering can also greatly improve the overall mechanical strength of BPVSs. Different manufacturing and processing methods also have an impact on the mechanical performance of BPVSs. For example, precision manufacturing with carbon dioxide laser processing or the use of a new slide-and-lock mechanism has been shown to effectively optimize the mechanical properties of BPVSs.

2.2 BMVSs

Not every biodegradable metallic element can be directly applied as a stent material. Liu et al. adopted comprehensive

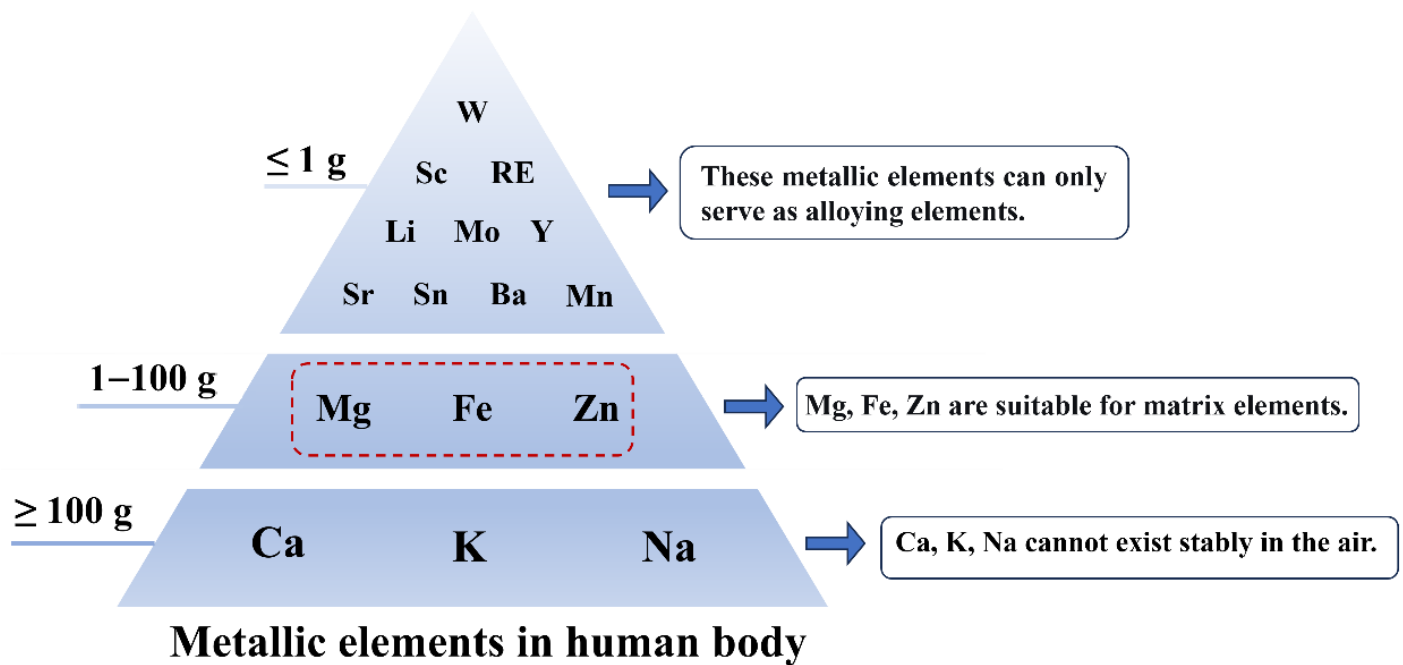


Figure 2. Schematic diagram of selection of biodegradable metallic elements.

evaluation criteria covering biocompatibility, biodegradation performance, and physiological abundance in the human body, and pointed out that Mg, Fe, and Zn are the most suitable matrix metals (as shown in **Figure 2**) [23]. Consequently, Mg-based, Fe-based, and Zn-based materials have become the three primary candidates for BMVSs.

Mg is an essential macroelement in the human body and participates in many key physiological processes. The total content of Mg in an average adult is about 25 g. Mg has relatively low toxicity and can be rapidly excreted. Meanwhile, the recommended daily intake of Mg ranges from 375 to 500 mg [23, 24]. Mg-based stents present distinctive biodegradable properties in the human physiological environment. The degradation process starts with the anodic oxidation of Mg, during which elemental Mg is transformed into Mg^{2+} ions and releases electrons. Mg^{2+} ions produced during corrosion can be gradually absorbed or metabolized by surrounding tissues or excreted from the body. At the same time, water undergoes cathodic reduction to generate hydroxide ions and hydrogen gas. As corrosion progresses, Mg reacts with water to form magnesium hydroxide ($\text{Mg}(\text{OH})_2$) as the main corrosion product, while magnesium oxide and magnesium carbonate act as secondary byproducts [24, 25]. These corrosion products can form a protective layer on the alloy surface, which acts as a barrier to inhibit further penetration of corrosive substances and provide moderate protection [26]. The reaction mechanisms are listed as follows:

Overall reaction: $\text{Mg} + 2\text{H}_2\text{O} = \text{Mg}(\text{OH})_2 + \text{H}_2$

Anodic reaction: $\text{Mg} = \text{Mg}^{2+} + 2\text{e}^-$

Cathodic reaction: $2\text{H}_2\text{O} + 2\text{e}^- = 2\text{OH}^- + \text{H}_2$

Product formation reaction: $\text{Mg}^{2+} + 2\text{OH}^- = \text{Mg}(\text{OH})_2$

A multicenter clinical trial conducted in 2007 further demonstrated the efficacy and safety of Mg-based stents. In this trial, 63 patients who received these stents achieved outcomes similar to those of patients receiving BMSs [27]. In addition, recent studies show that the release of Mg^{2+} and other degradation products has positive effects on the local microenvironment by alkalizing adjacent tissues, which helps reduce inflammation and thrombus formation [28, 29].

However, both preclinical and clinical studies have identified limitations of Mg-based stents in clinical application. First, Mg has a hexagonal close-packed structure, resulting in poor formability and low ductility at room temperature, which may lead to premature fracture of Mg-based stents. Second, Mg shows high reactivity due to its standard reduction potential of -2.372 V in the electromotive force series [25]. The Mg matrix tends to form galvanic cells with alloying or impurity components in corrosive environments, thus causing galvanic corrosion [30, 31]. In addition, chloride ions in body fluids continuously dissolve the hydroxide protective layer on the surface, which significantly accelerates the degradation rate of stents [26]. Meanwhile, Mg^{2+} in $\text{Mg}(\text{OH})_2$ can react with phosphate ions in body fluids to form magnesium phosphate, which will be replaced by calcium ions afterward. This leaves calcium-phosphorus complexes at the degradation site, while their absorption and metabolism in vivo still need to be further studied. Furthermore, the rapid and uneven degradation of Mg-based

stents not only raises the risk of ISR but also causes the burst release of corrosion products and forms gas pockets. These pockets hinder cell adhesion and growth on the stent surface and suppress endothelialization after implantation [32, 33]. In summary, the key challenge in the development of Mg-based stents is to balance mechanical performance, corrosion resistance, and endothelialization rate.

Fe is an essential trace element in the human body. Approximately 4 g of Fe is present in multiple forms in the human body, and the recommended daily intake of this element ranges from 10 to 20 mg [23]. Fe-based stents have a unique advantage over Mg-based stents, as they present much higher material strength and better formability. Fe-based metals show ideal mechanical properties, such as high strength, large elastic modulus, favorable ductility, and a high strain-hardening rate [6]. The corrosion process of Fe-based stents is dominated by redox reactions, and the corresponding reaction mechanisms can be summarized as follows:

Anodic reaction: $\text{Fe} = \text{Fe}^{2+} + 2\text{e}^-$

Cathodic reaction: $2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- = 4\text{OH}^-$

Product formation reaction: $2\text{Fe}^{2+} + 4\text{OH}^- = 2\text{Fe}(\text{OH})_2$ or $2\text{FeO} \cdot 2\text{H}_2\text{O}$

Product formation reaction: $4\text{Fe}(\text{OH})_2 + \text{O}_2 + 2\text{H}_2\text{O} = 4\text{Fe}(\text{OH})_3$ or $2\text{Fe}_2\text{O}_3 \cdot 6\text{H}_2\text{O}$

In contrast to Mg-based stents, Fe-based stents generate hydroxides through oxygen reduction without releasing H_2 . Moreover, research results have confirmed that degradation products from Fe-based stents can restrain the proliferation of VSMCs and reduce neointimal hyperplasia without impairing the biological activity of endothelial cells (ECs) [34, 35]. For this reason, Fe-based stents were the earliest BMVSs used in experimental research. In 2001, Peuster et al. first implanted pure Fe stents into the aortas of New Zealand rabbits and performed evaluations at 6, 12, and 18 months after implantation [36]. No obvious intimal hyperplasia or thromboembolic events were found during the 6- to 18-month follow-up period, and complete endothelialization was achieved.

However, studies have also shown that Fe-based stents largely maintained their integrity for up to 53 months after implantation, indicating their slow degradation rate. In a porcine coronary artery model, a 70- μm Fe-nitride scaffold required 4–5 years to fully corrode and 5–6 years to be completely absorbed [37]. Corrosion products, mainly Fe oxides, accumulate substantially at the implant site and are difficult to remove or metabolize. During hydroxide formation, the deposition of calcium and phosphate further hinders the subsequent degradation process [26]. The ferromagnetic property of Fe may also disturb magnetic resonance imaging results, which limits its clinical application. In preclinical trials, macrophage infiltra-

tion and mild inflammation have been observed, which may result from the poor clearance of degradation products [30]. Even with excellent mechanical performance, Fe-based stents have received much less research attention than Mg-based stents due to slow degradation, difficult-to-clear corrosion products, and ferromagnetic features [6].

Zn has a standard corrosion potential of -0.763 V, lying between Mg (-2.372 V) and Fe (-0.440 V), so it is presumed to have a suitable degradation rate [38]. Zn is the second most abundant transition metal element in the human body, with an average content of about 3 g, and the recommended daily intake of Zn ranges from 2 to 13 mg/day depending on age [38]. Zn degradation primarily releases Zn^{2+} and OH^- , with corrosion products including zinc hydroxide and zinc oxide (ZnO). The reaction mechanisms are given as follows:

Anodic reaction: $\text{Zn} = \text{Zn}^{2+} + 2\text{e}^-$

Cathodic reaction: $2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- = 4\text{OH}^-$

Product formation reaction: $\text{Zn}^{2+} + 2\text{OH}^- = \text{Zn}(\text{OH})_2$

Product formation reaction: $\text{Zn}(\text{OH})_2 = \text{ZnO} + \text{H}_2\text{O}$

Zn has become a promising candidate for BMVSs in the past several years, which has prompted numerous feasibility and safety evaluations. In 2013, Bowen et al. analyzed the corrosion behavior of pure Zn wires used to simulate single stent struts implanted into rat abdominal aortas for 6 months [39]. At the initial stage, Zn showed uniform corrosion within the first 3 months, owing to the oxide layer formed on its surface. After retaining mechanical stability for 4 months, this oxide layer was gradually corroded by in vivo chloride ions, triggering severe localized corrosion between 4.5 and 6 months. Later, in 2015, Bowen et al. further assessed the biocompatibility of pure Zn wires implanted in rat abdominal aortas [40]. No inflammatory response, local necrosis, or progressive intimal hyperplasia was detected at 2.5, 4, and 6.5 months after implantation. In 2017, Yang et al. further investigated the degradation mechanism and biocompatibility of pure Zn stents in rabbit abdominal aortas [41]. They found that the stents underwent uniform degradation first, followed by endothelialization and subsequent localized corrosion. The stents retained mechanical integrity for 6 months within the 12-month observation period, with no severe inflammation, platelet aggregation, thrombus formation, or obvious intimal hyperplasia, demonstrating the favorable biocompatibility of Zn-based stents.

Nevertheless, Zn-based stents still face a number of key unsolved obstacles. The most prominent problem is their insufficient mechanical performance, especially the extremely low tensile strength (as low as 20 MPa) and poor elongation (4%), which cannot provide effective vascular support. Zn-based metals also show obvious strain softening, and tend to undergo creep deformation and self-aging at room temperature, further

weakening their long-term mechanical stability [38-40]. It has been reported that Zn^{2+} has a concentration-dependent biphasic effect on cell viability, proliferation, spreading, and migration, so its long-term biosafety and in vivo metabolism still need systematic verification. Moreover, Zn alloys are limited by poor thermal stability and processability, which restricts the precise fabrication of stent struts. For the future development of Zn-based stents, improving mechanical properties and alleviating strain softening are the most urgent priorities [42].

Optimization strategies for BMVSs can be explored from three core aspects: structural design, material properties, and polymer coatings, which are key factors in BMVS development [43]. Reasonable structural design is an important prerequisite for BMVSs to achieve outstanding overall performance. Without changing the inherent properties of base materials, customized stent structures can be designed to improve radial support, expandability, and compliance. Meanwhile, the stent structure needs to match the inherent features of the selected material. For example, Mg-based stents show weaker compressive resistance than traditional permanent metal stents of the same dimensions. Although increasing strut thickness can strengthen radial strength, it will also simultaneously increase the risk of LST [31, 44]. Li et al. optimized the arc-shaped connectors between rings in a sinusoidal Mg-based stent and refined the strut thickness to 130 μm using finite element analysis [45]. Both simulation and experimental results demonstrated that this stent achieved higher radial strength than a 150 μm -thick counterpart (129 ± 5 vs. 97 ± 2 kPa). To further reduce the thickness to 100 μm , the researchers adopted response surface methodology-based surrogate model optimization to determine optimal geometric parameters [46]. Experimental validation revealed that the radial strength of the optimized 100 μm -thick stent was comparable to that of the commercial 150 μm stent (89 ± 4 vs. 86 ± 6 kPa). Apart from structural design, material optimization is the most common strategy to enhance BMVS performance. In addition, surface modification can also be adopted to tailor the surface properties of biodegradable metals, so as to improve biocompatibility, corrosion resistance, and mechanical stability [47]. To address the rapid degradation and insufficient endothelialization of Mg-based stents, Hou et al. prepared a novel bioactive coating (MgF_2 /polydopamine (PDA)-exosome) on Mg-Zn-Y-Nd alloy [32]. The rare earth element Nd enhanced the mechanical properties (UTS=230 MPa, YS=146 MPa, EL=35%) and corrosion resistance of the Mg alloy [48]. Mg-Zn-Y-Nd tubes were laser-cut for stent fabrication and then immersed in 40% hydrofluoric acid, diluted dopamine solution, and exosome suspension to form the MgF_2 -PDA-exosome coating. The MgF_2 layer reduced the degradation rate of Mg alloy stents and promoted vascular EC growth, while the PDA-exosome component enhanced stent biocompatibility. Animal experiments confirmed that these treatments significantly improved the anti-inflammatory and endothelial regeneration capabilities of Mg alloy stents, as well as their

corrosion resistance (the corrosion current density was 0.688 $\mu A/cm^2$, which is only 42.2% of that of Mg alloy) [32].

3 APPLICATIONS OF BVSS

In general, the clinical indications of BVSs encompass the majority of vascular disorders characterized by luminal stenosis, occlusion, dissection, or abnormal vascular remodeling. The research and translational applications of BVSs have been extensively explored across different anatomical areas in recent years (as shown in **Table 1**), covering coronary arteries, cerebral vessels, peripheral blood vessels and grafted vein (as shown in **Figure 3**) [56]. Different vascular systems have different blood flow, wall stress, and degradation environments. Thus, the performance of a BVS derived from one vascular model cannot be directly generalized to another. Therefore, more research using disease- and vessel-specific models is needed before drawing firm conclusions.

3.1 Biodegradable coronary stents

Coronary artery disease is a severe CVD that endangers human health with high morbidity and mortality, imposing a heavy burden on the global public health system. Currently, the most effective clinical treatment for coronary stenosis is still the implantation of coronary stents, which provide temporary mechanical support for diseased vessels and rapidly restore coronary blood perfusion.

Biodegradable coronary stents have experienced decades of research and clinical exploration. Early relevant studies can be traced back to the late 1980s, and this kind of stent was the first category of BVSs to realize clinical translation. The Igaki-Tamai stent represents the first clinically applicable BVS. The REMEDY stent, subsequently developed based on the Igaki-Tamai stent for peripheral arterial applications, obtained Conformitp Europmitp (CE) marking in 2007 [49, 57]. Unfortunately, the 1-year follow-up outcomes of this stent failed to meet the current clinical standards of nickeltitanium stents, and satisfactory therapeutic effects were not achieved [49]. Abbott Vascular launched the Absorb BVS in 2010. This product obtained CE marking and the U.S. Food and Drug Administration approval in succession, which officially opened the clinical application era of biodegradable coronary stents [21]. Nevertheless, the first-generation Absorb BVS showed a significantly higher LST rate than traditional DESs in subsequent large-scale clinical trials. This defect led to its global withdrawal in 2017, but it did not stop the continuous innovation in this field. Several BVSs, including DeSolve, ART's pure BRS, Fantom, MeRes, NeoVas, XINSORB and Firesorb have been successively launched and all obtained CE marking or China National Medical Products Administration approval [5, 21, 22, 52].

Table 1. Common commercially available BVSS that have obtained CE marking, FDA approval, or NMPA approval

Stent name	Manufacturer	Materials	Drug	Application site	Degradation time	Status
REMEDY BRS [49]	Kyoto Medical Planning Co.	Strut: PLLA	None	Peripheral arteries	24 months	CE marking (2007)
Absorb BVS [21]	Abbott Vascular	Strut: PLLA Coating: PDLLA	Everolimus	Coronary artery	24-36 months	CE marking (2011), FDA approval (2016), discontinued (2017)
DeSolve [21]	Elixir Medical Co.	Strut: PLLA Coating: PLLA	Novolimus	Coronary artery	12-24 months	CE marking (2013 for DeSolve 150; 2014 for DeSolve 100)
Pure BRS [21]	Arterial Remodelling Technologies Inc.	Strut: PLA	None	Coronary artery	24 months	CE marking (2015)
Magmaris [50]	Biotronik	Strut: Mg alloy Coating: PLLA	Sirolimus	Coronary artery	12-24 months	CE marking (2016)
Fantom [5]	REVA Medical Inc.	Strut: PTD-PC	Sirolimus	Coronary artery	48 months	CE marking (2017)
MOTIV [51]	REVA Medical Inc.	Strut: PTD-PC	Sirolimus	Peripheral arteries	48 months	CE marking (2018)
MeRes [21]	Meril Life Sciences	Strut: PLLA Coating: PDLLA	Sirolimus	Coronary artery	24 months	CE marking (2019)
NeoVas [52]	Lepu Medical Technology (Beijing) Co.	Strut: PLLA Coating: PDLLA	Sirolimus	Coronary artery	24-36 months	NMPA approval (2019)
XINSORB [52]	Shandong Huaan Biotechnology Co.	Strut: PLLA Coating: PDLLA	Sirolimus	Coronary artery	24-36 months	NMPA approval (2020)
IBS Angel [53]	Lifetech Scientific Co.	Strut: Fe alloy Coating: PDLLA	Sirolimus	Pediatric pulmonary artery	24 months	CE marking (2023)
Esprit BTK [54]	Abbott Vascular	Strut: PLLA Coating: PDLLA	Everolimus	Peripheral artery	36 months	FDA approval (2024)
Freesolve RMS [55]	Biotronik	Strut: Mg alloy Coating: PLLA	Sirolimus	Coronary artery	12 months	CE marking (2024)
Firesorb [22]	Shanghai MicroPort Medical (Group) Co.	Strut: PLLA Coating: PGLA	Sirolimus	Coronary artery	24-36 months	NMPA approval (2024)

Note: BVS, biodegradable vascular stent; CE, Conformité Européenne; FDA, Food and Drug Administration; NMPA, National Medical Products Administration; PLLA, poly(L-lactic acid); PDLLA, poly(D,L-lactic acid); PGLA, poly(glycolide-co-lactide); PTD-PC, poly(tyrosine-derived polycarbonate); BRS, bioresorbable scaffold; RMS, resorbable magnesium scaffold; PLA, poly(lactic acid).

It has been reported that early BPVSs adopt an excessively thick strut design to ensure adequate radial strength [58]. This design results in poor deliverability, prolonged degradation and delayed endothelialization, which are the main causes of LST. Restricted by the inherent technical limitations of BPVSs, the research focus has gradually shifted to biodegradable metallic materials with better mechanical properties in recent years. Biotronik developed the Mg alloy biodegradable stent DREAMS-2 with the trade name Magmaris [50]. This stent obtained CE marking in 2016 and became the world's first commercially available biodegradable metallic coronary stent. The 5-year clinical follow-up data of DREAMS-2 show that its target lesion failure rate is only 8.0%, and the risk of LST is extremely low. The safety and efficacy of this stent are significantly improved compared with other BVSS. The third-generation Mg-based stent DREAMS 3G with the brand name Freesolve RMS was CE-certified again and launched in Hong Kong in 2024 [55]. This stent adopts an integrated design composed of Mg alloy substrate, PLLA carrier and sirolimus elution. It combines high radial strength and excellent biocom-

patibility, and the stent matrix can achieve nearly complete degradation about 12 months after implantation.

3.2 Biodegradable cerebrovascular stents

Cerebrovascular disease is a major disease that seriously threatens human life and has become the second leading cause of death worldwide. Its main pathological types include cerebrovascular occlusion (ischemic stroke) and vascular rupture (hemorrhagic stroke). In addition to pharmacological therapy, neurointerventional therapy has become an important clinical strategy for cerebrovascular disease due to its advantages of minimal invasiveness, high efficacy and favorable outcomes. In recent years, the development of biodegradable cerebrovascular stents has attracted extensive attention. These stents can gradually degrade and be absorbed after completing vascular support and luminal remodeling, which can theoretically effectively avoid the complications caused by permanent metallic stents. Therefore, they are considered as an ideal strategy to

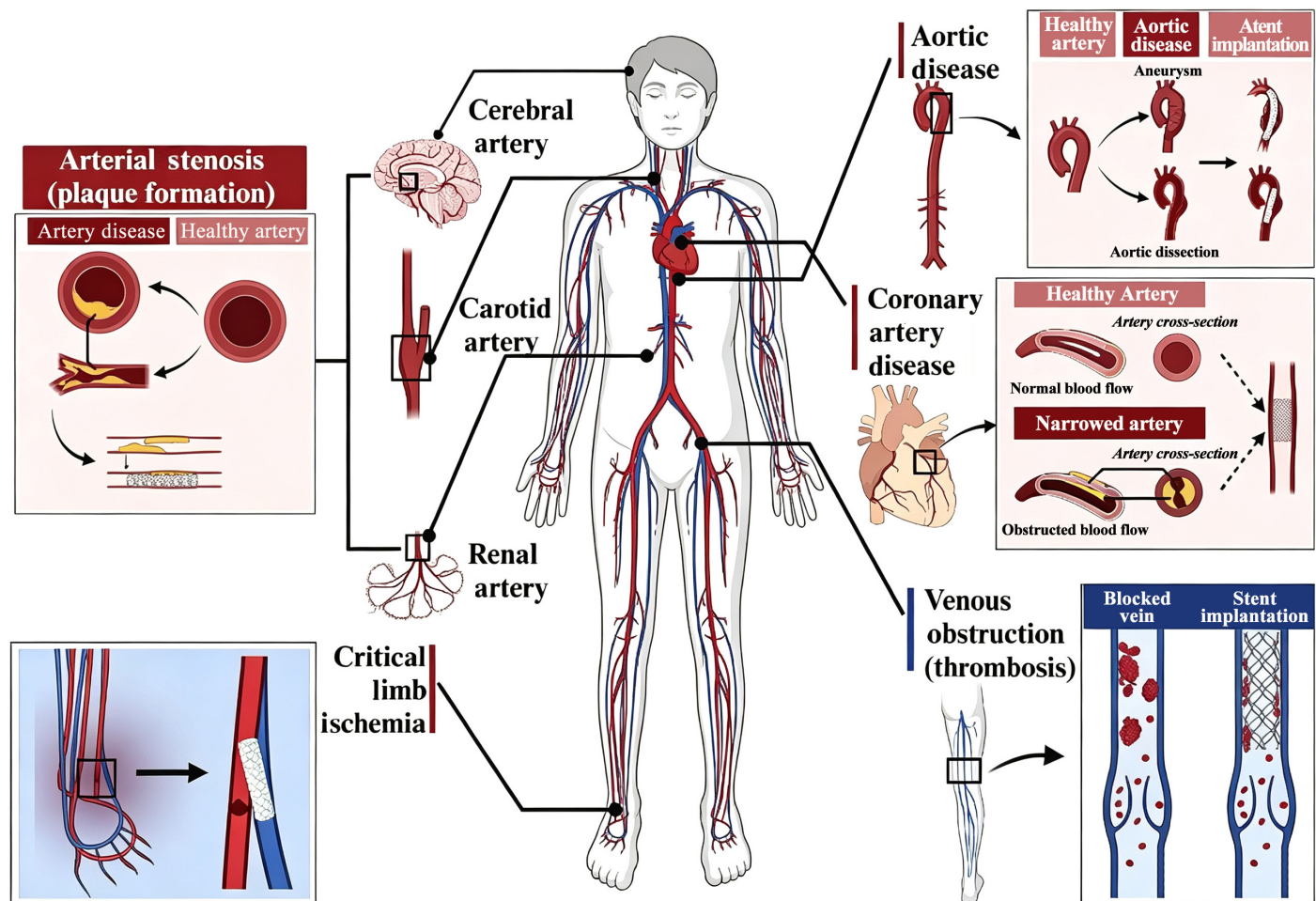


Figure 3. Application of vascular stents in different vascular systems. Reproduced from [56].

reduce the risks of long-term thrombosis, inflammation and restenosis.

At present, most biodegradable cerebrovascular stents are still in the preclinical research stage. Yu et al. fabricated biodegradable stents based on WE43 Mg alloy using laser cutting technology to compare the corrosion and degradation behaviors in cerebral circulation and coronary circulation environments [59]. In vitro results showed that, compared with the coronary environment, WE43 Mg alloy stents exhibited a significantly accelerated corrosion rate and enhanced pitting sensitivity in the cerebral blood flow environment. The researchers speculated that this phenomenon was mainly attributed to the higher blood flow velocity and stronger shear stress in cerebral circulation, which could continuously destroy the integrity of the corrosion product layer on the stent surface, thereby accelerating the corrosion process of the matrix material.

3.3 Biodegradable peripheral vascular stents

Peripheral vascular disease refers to stenosis, occlusion, or dilation of the aorta, venae cavae, and their branch arteries and

veins, excluding the coronary and cerebrovascular circulations. Mild cases present with ischemic limb pain and intermittent claudication, while severe cases can lead to limb gangrene and distal organ failure, seriously threatening patients' lives and quality of life and even their survival. Biodegradable peripheral vascular stents can effectively maintain vascular patency during the treatment period and achieve sustained local delivery of anti-proliferative drugs, and finally degrade and be completely absorbed without residual foreign bodies.

At present, significant progress has been made in the research and clinical translation of biodegradable peripheral vascular stents. The first BVS approved for the treatment of below-the-knee (BTK) arterial lesions is MOTIV. It was made of a new polymer with inherent fluoroscopic visibility and was granted CE marking in 2018. A clinical trial showed a technical success rate of 99% and a primary patency rate of 88.3%, 81.7%, and 80% at 12, 24 and 36 months [51, 53]. Besides, the IBS Angel Fe-based stent for treating pediatric pulmonary artery stenosis obtained CE Medical Device Regulation certification in 2023 [60]. Additionally, Esprit BTK developed by Abbott Vascular is a BPVS with everolimus loading and bioabsorbable polymer

coating, and gained approval from the Food and Drug Administration in 2024. The LIFE-BTK randomized controlled trial carried out systematic evaluation on the safety and efficacy of this stent. The trial defined freedom from major adverse limb events and perioperative death at 6 months as the primary safety endpoint. Results proved that the efficacy of the Esprit BTK stent group was significantly better than that of the percutaneous transluminal angioplasty group, and there was no significant difference in safety between the two groups. This stent provides a new interventional option for the treatment of infrapopliteal arterial stenosis lesions [54, 61].

3.4 Biodegradable extravascular stents

Vein grafts are widely applied in coronary artery bypass grafting and the establishment of hemodialysis vascular access. The high incidence of postoperative graft stenosis and poor long-term patency remain key challenges. Hemodynamic disorders are the main factors leading to venous graft stenosis. After direct arteriovenous anastomosis, the venous system is suddenly exposed to high blood flow and pressure that are similar to those in the arterial circulation. Excessive blood flow and pressure cause severe dilatation and irregular deformation of the venous wall, resulting in turbulent blood flow in the lumen. Turbulent flow and abnormal wall shear stress further trigger local inflammatory responses and continuous injury of ECs. These changes promote abnormal proliferation and intraluminal migration of VSMCs, and are associated with excessive secretion of extracellular matrix. This process eventually aggravates neointimal hyperplasia and causes graft stenosis or even occlusion.

Biodegradable extravascular stents are tubular or mesh-like support structures wrapped on the outer surface of blood vessels. These stents do not invade the lumen, and optimize the hemodynamic state of vein grafts through external mechanical support and geometric remodeling. They can inhibit vascular overexpansion and excessive intimal hyperplasia at the source. The application of such stents can effectively extend the patency time of vein grafts and reduce the risk of postoperative reinterventions, which is an effective method to solve vein graft stenosis. Chu et al. prepared a biodegradable extravascular stent based on nanocellulose-gelatin hydrogel loaded with astragaloside IV [17]. This composite stent has good mechanical properties and biocompatibility. It can activate autophagy to inhibit endothelial-to-mesenchymal transition, and effectively suppress neointimal hyperplasia and restenosis of vein grafts. Rong et al. developed a biodegradable R-NFM to prevent neointimal hyperplasia and stenosis of AVF for hemodialysis [62]. **Figure 4** illustrates the experimental procedure of implanting this R-NFM as a biodegradable extravascular stent into rat models. Experimental results confirmed its good biodegradability, biocompatibility and controlled drug release performance. The R-NFM can significantly reduce neointimal hyper-

plasia in rat models with chronic kidney disease, and effectively improve the long-term patency of hemodialysis vascular access.

4 FUTURE PERSPECTIVES OF BVSS

After resolving the limitations of current BVSSs, ongoing progress in biomaterial research, intelligent device development and personalized manufacturing technology will promote the further upgrading and multifunctional innovation of BVSSs.

4.1 Material innovation

Generally, BVSSs rely on balloon expansion for implantation, which often causes vascular endothelial injury, non-uniform expansion, and poor mechanical matching with the dynamic vascular environment. In contrast, shape memory materials (SMMs) enable stent self-expansion driven by physiological stimuli without balloon dilation, effectively overcoming the above drawbacks. SMMs are intelligent materials that can complete reversible shape transformation under external stimuli such as heat, light and magnetic fields. They provide unique advantages for the structural design and implantation of vascular stents. BVSSs made of SMMs can maintain excellent flexibility and low profile during low-temperature endovascular delivery owing to the shape memory effect. They will automatically revert to the preset tubular structure with sufficient radial strength when activated by body temperature or specific physiological stimuli after reaching the target lesion. This feature strikes an ideal balance between deliverability and mechanical support. It also enables uniform expansion and optimal vessel wall apposition, and reduces endothelial injury caused by balloon dilation. Shape memory polymers (SMPs) and shape memory alloys (SMAs) are the two main types of SMMs [63].

SMPs feature low manufacturing cost, easy preprocessing, high recoverable deformation and low recovery temperature. Their biodegradability and biocompatibility can be adjusted by varying the material composition. This enables biodegradable SMP stents to degrade completely in vivo within a specified time. Biodegradable SMP stents still suffer from insufficient mechanical properties, a limitation shared with most BPVSSs. This limitation may lead to stent migration and restrict their translational application. The research focus of biodegradable SMP stents is to strike a balance among mechanical properties, shape memory effect and biocompatibility [64, 65]. Joo et al. prepared biodegradable and biocompatible thermally responsive SMPs by blending polyurethane and PCL with different weight ratios [64]. Experimental data show that the 30% polyurethane/PCL blend has favorable shape memory performance and adjustable mechanical properties. These biodegradable SMPs have broad application prospects in medical devices including surgical sutures and vascular stents.

SMAs offer greater advantages over SMPs, including high mechanical strength, long cycle life, pseudoelasticity and

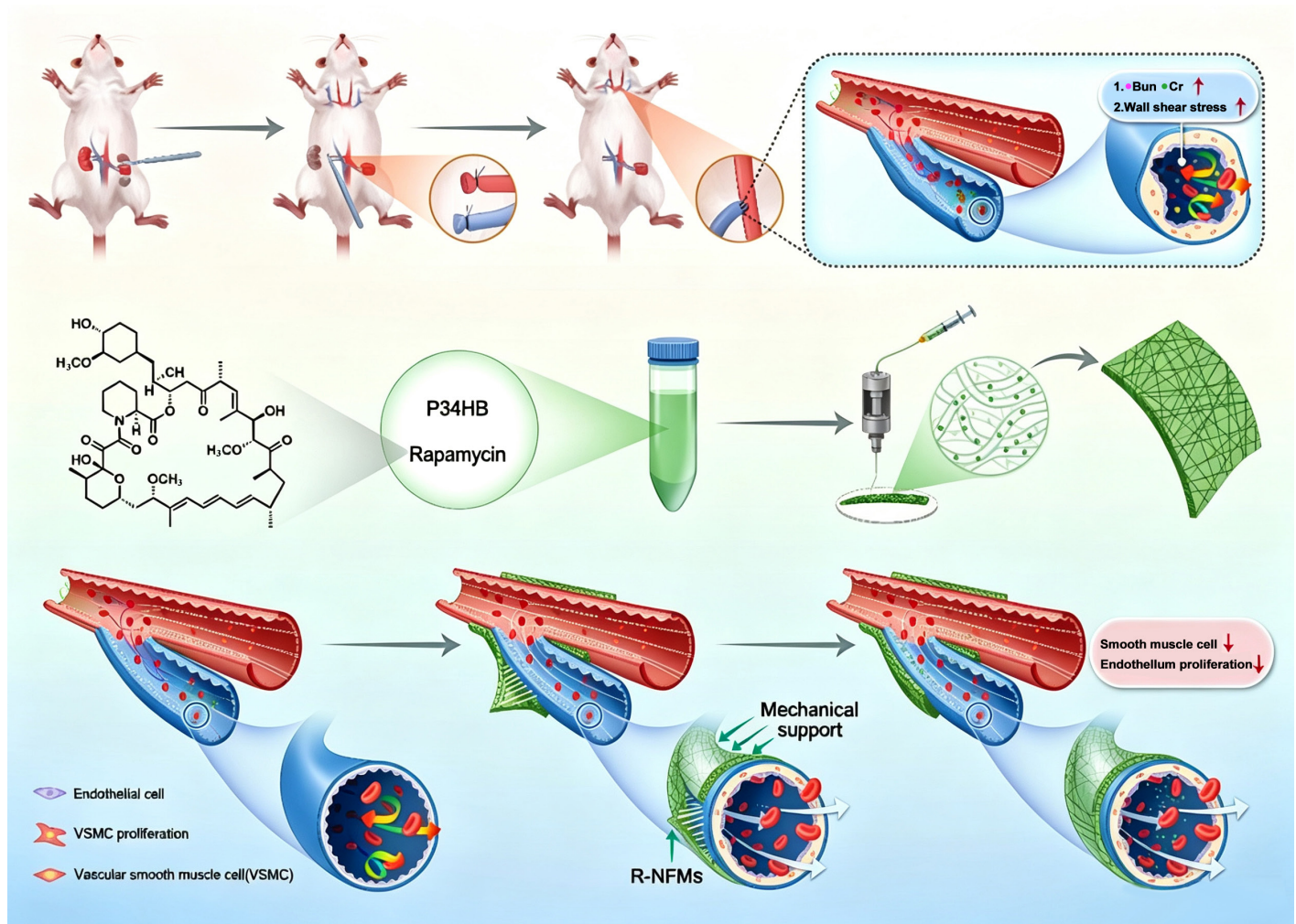


Figure 4. Schematic diagram of the application of biodegradable extravascular stents in rat AVF stenosis model. Reproduced from [62]. R-NFM, rapamycin-loaded P34HB nanofibrous membrane; P34HB, poly(3-hydroxybutyrate-co-4-hydroxybutyrate); VSMC, vascular smooth muscle cell; AVF, arteriovenous fistula.

superelasticity. At present, SMAs are mainly divided into nickel titanium-based, copper-based, Mg-based and Fe-based systems. Mg-based and Fe-based SMAs such as Mg-Sc, Fe-Mn-Si, Fe-Pd and Fe-Pt have been reported to have biodegradability and biocompatibility [66]. Their unique properties show great potential for promoting the future development of vascular stents. Further research on the microstructure of these materials is needed to clarify the mechanism of their unique properties for the translational application of SMA stents. Preclinical studies are also required to verify the safety, efficacy and long-term performance of these smart stents.

4.2 Intelligent integration

At present, most BVSs only offer mechanical support to diseased vessels and keep luminal patency after implantation, but they cannot perform in vivo evaluation of the perivascular microenvironment and vascular health. Clinical methods for monitoring and diagnosing post-implantation complications,

such as angiography, intravascular ultrasound and optical coherence tomography, are unable to achieve real-time, continuous, and efficient monitoring [67]. Researchers have developed a new generation of biodegradable electronic stents (BESSs) to enable early identification of complications. These stents integrate degradable biosensors, which can capture key physiological signals in blood vessels in real time and wirelessly transmit data to external monitoring equipment.

Appropriate antenna design plays a key role in enabling electronic stents to provide mechanical support and wireless signal transmission at the same time. Chow et al. first put forward a feasible concept that a self-expandable medical stent integrated with a miniaturized pressure sensor could serve as both a structural support and a signal transmission antenna [68]. This novel structural design not only endows the stent with real-time in vivo monitoring capacity, but also builds a dual-function platform that combines diagnostic monitoring and therapeutic intervention.

Son et al. subsequently proposed advanced nanomaterial design and integration schemes for BESs [69]. The BES they developed takes an Mg alloy scaffold as the core, and integrates anti-inflammatory nanoparticles, drug-loaded core-shell nanospheres, flexible nanomembrane flow and temperature sensors, and memory storage devices. The stent itself acts as a wireless telemetry antenna by virtue of the excellent electrical conductivity and biodegradability of the Mg alloy. The memory storage device on the stent is coated with a PLA solution loaded with therapeutic nanoparticles, and the sensor membrane is transfer-printed onto the surface of an adhesive polymer. This integrated design can simultaneously enable physiological signal collection, data storage, anti-inflammatory effects, local drug delivery and photothermal therapy. Mg alloy stents have inherent corrosion susceptibility. The research team extended the degradation period through multi-layer encapsulation, but the *in vivo* experimental results still failed to meet expectations.

The electronic system design of biodegradable polymer electronic stents needs to comprehensively consider multiple key indicators, including electrical conductivity, mechanical properties, biocompatibility, processability and synthesis feasibility. Park et al. developed a poly(D-lactic acid)-based wireless pressure sensor and integrated it into a 3D-printed PCL polymer stent [70]. This stent shows ideal performance in *in vitro* simulation tests, and its feasibility and transformation potential still need to be verified by further *in vivo* research.

BVSs with sensing function represent a disruptive innovation in the field of vascular stents, as they break through the limitation that traditional BVSs can only be used as passive mechanical supports. BESs still face many technical challenges at present, but their unique advantages in real-time *in vivo* monitoring and even active therapeutic intervention have attracted widespread research attention [71]. This innovation will fundamentally change the treatment and long-term management model of vascular diseases, and point to new directions for the next-generation development of BVSs.

4.3 Personalized customization

Traditional standardized BVSs are poorly adapted to complex vascular anatomy and lesion morphology, and personalized customization can effectively solve this clinical challenge. Based on the patient's preoperative imaging data, stent geometry, strut structure, diameter and length can be personally designed through 3D vascular reconstruction to perfectly match the patient's vascular anatomical characteristics and lesion morphology. With the rapid iteration of 3D and 4D printing additive manufacturing technology, the efficient and precise preparation of customized BVSs has gained reliable technical support [5, 72].

3D-printed BPVSs have drawn broad research attention in the field of vascular stents. Lee et al. prepared 3D-printed PLA stents, and modified stent surfaces with PDA, polyethyleneimine and heparin to prevent restenosis and thrombosis [73]. A 12-week *in vivo* test in rat models demonstrated the stents' favorable antithrombotic activity and hemocompatibility. Shen et al. developed 3D-printed PCL stents based on animal vascular magnetic resonance imaging data, and performed covalent grafting of heparin to improve anticoagulant performance [74]. These stents were implanted into rabbit abdominal aortas to assess post-implantation efficacy. Results showed the stents maintained excellent biocompatibility and mechanical stability over 12 weeks, and preserved vascular patency without triggering acute thrombosis. These studies confirm the significant application potential of customized stents in vascular repair.

Although personalized BVSs have significant clinical advantages, this cutting-edge technology still faces many bottlenecks that hinder clinical translation. On the one hand, the whole process from personalized design and imaging modeling to 3D printing relies heavily on high-precision medical equipment and professional technical teams, and the high cost restricts large-scale promotion of the technology. On the other hand, there are currently no unified quality control standards and standardized evaluation protocols for 3D-printed personalized BVSs, so the mechanical properties, degradation kinetics and surface modification efficacy of different stents cannot be kept consistent. In addition, the long-term biosafety of customized stents, the consistency between *in vivo* degradation and vascular healing, and hemodynamic compatibility still need to be verified through large-scale animal experiments and multicenter clinical trials [75].

5 CONCLUSION

BVSs are highly attractive because they may overcome the inherent limitations and complications associated with permanent stents, bringing new opportunities and challenges to the treatment of vascular diseases. BVSs provide temporary support to the narrowed blood vessel wall and completely degrade after fulfilling their function, thus avoiding adverse events caused by the long-term presence of permanent stents.

Depending on the manufacturing material, BVSs can be divided into BPVSs and BMVSs. Although BPVSs exhibit outstanding biocompatibility, they generally face challenges of insufficient mechanical strength, particularly poor radial strength. BMVSs, represented by Mg-, Fe-, and Zn-based metals, generally possess superior comprehensive mechanical properties over polymers, but each type has its own drawbacks. Mg-based stents exhibit favorable mechanical performance and biocompatibility, but their major drawback is rapid degradation. In contrast, better mechanical strength is a unique advantage of Fe-based stents, but their degradation is excessively slow, limit-

ing their further clinical applications. Pure Zn has the lowest mechanical strength among biodegradable metal materials and faces challenges such as room temperature aging and strain softening. To overcome the aforementioned challenges, numerous experimental studies have demonstrated that specific properties can be achieved by altering the shape and structure of stents, modifying the material properties at the microscale, and improving manufacturing technologies.

To date, the applications of BVSS have expanded from coronary artery stenosis to complex cerebrovascular lesions, peripheral arterial diseases and venous graft stenosis, filling the gaps where permanent stents are difficult to apply. Although challenges still exist in the precise regulation of degradation kinetics, systematic verification of long-term biosafety, and large-scale clinical translation, the continuous integration of materials science, precision manufacturing and biomedical engineering will steadily promote the iterative optimization of BVSS.

In addition, material innovation will enable stents to achieve higher mechanical strength and greater flexibility, effectively reducing strut thickness and reducing complications. Personalized customization enables BVSS to precisely match individual vascular anatomical structures and complex lesion characteristics, thereby significantly improving vascular adaptability and long-term patency rates. Intelligent BVSS integrating biosensing, responsive drug release and complete biodegradability can enable real-time in vivo monitoring of stent degradation, vascular repair and hemodynamic changes, as well as on-demand drug delivery to prevent restenosis and thrombosis. Ultimately, BVSS will revolutionize the treatment paradigm of vascular diseases and bring substantial benefits to patients worldwide.

DECLARATIONS

Author contributions

Kaiyu Gu and Yuxiao Li contributed to the writing of the original draft and the investigation. Lin Mao and Chengli Song contributed to the writing, review, and editing of the manuscript, as well as supervision.

Funding

This research received no external funding.

Data availability

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

Not applicable.

REFERENCES

- [1] Tian F, Chen L, Qian ZM, Xia H, Zhang Z, Zhang J, et al. Ranking age-specific modifiable risk factors for cardiovascular disease and mortality: Evidence from a population-based longitudinal study. *EClinicalMedicine*. 2023 Oct 1;64:102230. <https://doi.org/10.1016/j.eclinm.2023.102230>
- [2] Zhang Y, Deng Q, Hu P, Zeng Q, Li B, Liu J. Burden and risk factors of cardiovascular diseases in Asia, 1990–2021: An analysis for GBD 2021. *JACC Asia*. 2026 Aug 1;6(8):1750-1761. <https://doi.org/10.1016/j.jacasi.2025.08.024>
- [3] Stark BA, DeCleene NK, Desai EC, Hsu JM, Johnson CO, Lara-Castor L, et al. Global, regional, and national burden of cardiovascular diseases and risk factors in 204 countries and territories, 1990-2023. *JACC*. 2025 Dec 2;86(22):2167-2243. <https://doi.org/10.1016/j.jacc.2025.08.015>
- [4] Di Mauro V, Lauta FC, Modica J, Appleton SL, De Francis V, Catalucci D. Diagnostic and therapeutic aptamers: A promising pathway to improved cardiovascular disease management. *JACC Basic Transl Sci*. 2024 Feb 1;9(2):260-277. <https://doi.org/10.1016/j.jacbts.2023.06.013>
- [5] Huang Y, Xu Y, Chen X, Armstrong JPK, Caputo M, Qi Q, et al. 3D printing of biodegradable polymer vascular stents to treat cardiovascular diseases: A review. *Addit Manuf*. 2025 Aug 5;111:104984. <https://doi.org/10.1016/j.addma.2025.104984>
- [6] Zhang Y, Roux C, Rouchaud A, Meddahi-Pellé A, Gueguen V, Mangeney C, et al. Recent advances in Fe-based bioresorbable stents: Materials design and biosafety. *Bioact Mater*. 2024 Jan 1;31:333-354. <https://doi.org/10.1016/j.bioactmat.2023.07.024>
- [7] Sadegh Ebrahimi M, Noruzi M, Hamzehei R, Etemadi E, Hashemi R. Revolutionary auxetic intravascular medical stents for angioplasty applications. *Mater Des*. 2023 Nov 1;235:112393. <https://doi.org/10.1016/j.matdes.2023.112393>
- [8] Im SH, Im DH, Park SJ, Jung Y, Kim DH, Kim SH. Current status and future direction of metallic and polymeric materials for advanced vascular stents. *Prog Mater Sci*. 2022 May 1;126:100922. <https://doi.org/10.1016/j.pmatsci.2022.100922>
- [9] Oliver AA, Sikora-Jasinska M, Demir AG, Guillory RJ. Recent advances and directions in the development of bioresorbable metallic cardiovascular stents: Insights from recent human and in vivo studies. *Acta Biomater*. 2021 Jun 1;127:1-23. <https://doi.org/10.1016/j.actbio.2021.03.058>
- [10] El Khoury R, Tzvetanov I, Estrada EA, McCarroll E, Goor JB, Guy LG, et al. Drug-eluting, balloon-expandable, bioresorbable vascular scaffolds reduce neointimal thickness and stenosis in an animal model of percutaneous peripheral intervention. *JVS Vasc Sci*. 2023 Jan 1;4:100114. <https://doi.org/10.1016/j.jvssc.2023.100114>

- [11] Zong J, He Q, Liu Y, Qiu M, Wu J, Hu B. Advances in the development of biodegradable coronary stents: A translational perspective. *Mater Today Bio*. 2022 Dec 1;16:100368. <https://doi.org/10.1016/j.mtbio.2022.100368>
- [12] Iglesias JF, Roffi M, Losdat S, Muller O, Degrauwe S, Kurz DJ, et al. Long-term outcomes with biodegradable polymer sirolimus-eluting stents versus durable polymer everolimus-eluting stents in ST-segment elevation myocardial infarction: 5-year follow-up of the BIOSTEMI randomised superiority trial. *Lancet*. 2023 Nov 25;402(10416):1979-1990. [https://doi.org/10.1016/S0140-6736\(23\)02197-9](https://doi.org/10.1016/S0140-6736(23)02197-9)
- [13] Li M, Jiang M, Gao Y, Zheng Y, Liu Z, Zhou C, et al. Current status and outlook of biodegradable metals in neuroscience and their potential applications as cerebral vascular stent materials. *Bioact Mater*. 2022 May 1;11:140-153. <https://doi.org/10.1016/j.bioactmat.2021.09.025>
- [14] Shi W, Li H, Zhu T, Jin Y, Wang H, Yang J, et al. Study on the bending behavior of biodegradable metal cerebral vascular stents using finite element analysis. *J Biomech*. 2020 Jul 17;108:109856. <https://doi.org/10.1016/j.jbiomech.2020.109856>
- [15] Büniger CM, Grabow N, Sternberg K, Kröger C, Ketner L, Schmitz KP, et al. Sirolimus-eluting biodegradable poly-L-lactide stent for peripheral vascular application: A preliminary study in porcine carotid arteries. *J Surg Res*. 2007 May 1;139(1):77-82. <https://doi.org/10.1016/j.jss.2006.07.035>
- [16] Cui H, Li M, Wu Y. Efficacy of bioresorbable vascular scaffolds in below-the-knee arterial disease: A single-arm systematic review and meta-analysis. *Ann Vasc Surg*. 2026 Apr 1;125:206-217. <https://doi.org/10.1016/j.avsg.2025.12.027>
- [17] Chu T, Li Q, Dai C, Li X, Kong X, Fan Y, et al. A novel Nanocellulose-Gelatin-AS-IV external stent resists EndMT by activating autophagy to prevent restenosis of grafts. *Bioact Mater*. 2023 Apr 1;22:466-481. <https://doi.org/10.1016/j.bioactmat.2022.10.013>
- [18] Wang Z, Song J, Peng Y. New insights and perspectives into biodegradable metals in cardiovascular stents: A mini review. *J Alloys Compd*. 2024 Oct 15;1002:175313. <https://doi.org/10.1016/j.jallcom.2024.175313>
- [19] Chen S, Du T, Zhang H, Qi J, Zhang Y, Mu Y, et al. Methods for improving the properties of zinc for the application of biodegradable vascular stents. *Biomater Adv*. 2024 Jan 1;156:213693. <https://doi.org/10.1016/j.bioadv.2023.213693>
- [20] Xie A, Hao J, Duan F, Mitchell K, Jin Y, Zhao D. Mechanical analysis of radial performance in biodegradable polymeric vascular stents manufactured using micro-injection molding. *J Mech Behav Biomed Mater*. 2024 Feb 1;150:106362. <https://doi.org/10.1016/j.jmbbm.2023.106362>
- [21] McMahon S, Bertollo N, Cearbhaill EDO, Salber J, Pierucci L, Duffy P, et al. Bio-resorbable polymer stents: A review of material progress and prospects. *Prog Polym Sci*. 2018 Aug 1;83:79-96. <https://doi.org/10.1016/j.progpolymsci.2018.05.002>
- [22] Arokiyasamy DA, Tamilperuvalathan S. A comprehensive evaluation of material properties, degradation kinetics and clinical performance of biodegradable polymer cardiovascular stents: A review. *Int J Biol Macromol*. 2026 Feb 1;343:150358. <https://doi.org/10.1016/j.ijbiomac.2026.150358>
- [23] Liu Y, Zheng Y, Chen X, Yang J, Pan H, Chen D, et al. Fundamental theory of biodegradable metals—definition, criteria, and design. *Adv Funct Mater*. 2019 Feb 25;29(18):1805402. <https://doi.org/10.1002/adfm.201805402>
- [24] Seitz JM, Eifler R, Bach FW, Maier HJ. Magnesium degradation products: Effects on tissue and human metabolism. *J Biomed Mater Res A*. 2014 Oct 1;102(10):3744-3753. <https://doi.org/10.1002/jbm.a.35023>
- [25] Jana A, Das M, Balla VK. In vitro and in vivo degradation assessment and preventive measures of biodegradable Mg alloys for biomedical applications. *J Biomed Mater Res A*. 2022 Feb 1;110(2):462-487. <https://doi.org/10.1002/jbm.a.37297>
- [26] Li C, Guo C, Fitzpatrick V, Ibrahim A, Zwierstra MJ, Hanna P, et al. Design of biodegradable, implantable devices towards clinical translation. *Nat Rev Mater*. 2020 Jan 1;5(1):61-81. <https://doi.org/10.1038/s41578-019-0150-z>
- [27] Erbel R, Di Mario C, Bartunek J, Bonnier J, de Bruyne B, Eberli FR, et al. Temporary scaffolding of coronary arteries with bioabsorbable magnesium stents: A prospective, non-randomised multicentre trial. *Lancet*. 2007 Jun 2;369(9576):1869-1875. [https://doi.org/10.1016/S0140-6736\(07\)60853-8](https://doi.org/10.1016/S0140-6736(07)60853-8)
- [28] Sreenivasamurthy SA, Akhter FF, Akhter A, Su Y, Zhu D. Cellular mechanisms of biodegradable zinc and magnesium materials on promoting angiogenesis. *Biomater Adv*. 2022 Aug 1;139:213023. <https://doi.org/10.1016/j.bioadv.2022.213023>
- [29] Xu B, Song Y, Yang K, Li Y, Chen B, Liao X, et al. Magnesium metal and its corrosion products: Promising materials for tumor interventional therapy. *J Magnes Alloy*. 2023 Mar 1;11(3):763-775. <https://doi.org/10.1016/j.jma.2023.02.007>
- [30] Drelich JW, Goldman J. Bioresorbable vascular metallic scaffolds: Current status and research trends. *Curr Opin Biomed Eng*. 2022 Dec 1;24:100411. <https://doi.org/10.1016/j.cobme.2022.100411>
- [31] Wang S, Du C, Shen X, Wu X, Ouyang S, Tan J, et al. Rational design, synthesis and prospect of biodegradable magnesium alloy vascular stents. *J Magnes Alloy*. 2023 Sep 1;11(9):3012-3037. <https://doi.org/10.1016/j.jma.2023.07.020>
- [32] Hou Y, Li J, Cao C, Su C, Qin Z, Zhang G, et al. Biodegradable Mg alloy modified with bioactive exosomes for cardiovascular stent application. *J Magnes Alloy*. 2024 Dec 1;12(12):4988-5004. <https://doi.org/10.1016/j.jma.2023.05.007>
- [33] Pan C, Liu X, Hong Q, Chen J, Cheng Y, Zhang Q, et al. Recent advances in surface endothelialization of the magnesium alloy stent materials. *J Magnes Alloy*. 2023 Jan 1;11(1):48-77. <https://doi.org/10.1016/j.jma.2022.12.017>
- [34] Qiu D, Yin J, Wen Y, Huang J, Lei T, Chen C, et al. Diabetes-induced iron stent degradation but preventing re-endothelialization after implantation. *Mater Des*. 2023 May 1;229:111930. <https://doi.org/10.1016/j.matdes.2023.111930>
- [35] Qiu D, Deng Y, Wen Y, Yin J, Feng J, Huang J, et al. Iron corroded granules inhibiting vascular smooth muscle cell proliferation. *Mater Today Bio*. 2022 Dec 1;16:100420. <https://doi.org/10.1016/j.mtbio.2022.100420>
- [36] Peuster M, Wohlsein P, Brüggmann M, Ehlerding M, Seidler K, Fink C, et al. A novel approach to temporary stenting: Degrade-

- dable cardiovascular stents produced from corrodible metal—results 6–18 months after implantation into New Zealand white rabbits. *Heart*. 2001 Nov 1;86(5):563-569. <https://doi.org/10.1136/heart.86.5.563>
- [37] Lin W, Qin L, Qi H, Zhang D, Zhang G, Gao R, et al. Long-term in vivo corrosion behavior, biocompatibility and bioresorption mechanism of a bioresorbable nitrided iron scaffold. *Acta Biomater*. 2017 May 1;54:454-468. <https://doi.org/10.1016/j.actbio.2017.03.020>
- [38] Mostaed E, Sikora-Jasinska M, Drelich JW, Vedani M. Zinc-based alloys for degradable vascular stent applications. *Acta Biomater*. 2018 Apr 15;71:1-23. <https://doi.org/10.1016/j.actbio.2018.03.005>
- [39] Bowen PK, Drelich J, Goldman J. Zinc exhibits ideal physiological corrosion behavior for bioabsorbable stents. *Adv Mater*. 2013 May 14;25(18):2577-2582. <https://doi.org/10.1002/adma.201300226>
- [40] Bowen PK, Guillory RJ, Shearier ER, Seitz JM, Drelich J, Bocks M, et al. Metallic zinc exhibits optimal biocompatibility for bioabsorbable endovascular stents. *Mater Sci Eng C*. 2015 Nov 1;56:467-472. <https://doi.org/10.1016/j.msec.2015.07.022>
- [41] Yang H, Wang C, Liu C, Chen H, Wu Y, Han J, et al. Evolution of the degradation mechanism of pure zinc stent in the one-year study of rabbit abdominal aorta model. *Biomaterials*. 2017 Nov 1;145:92-105. <https://doi.org/10.1016/j.biomaterials.2017.08.022>
- [42] Chen X, Chang R, Liu H, Zhang L, Zheng Y. Moving research direction in the field of metallic bioresorbable stents-A mini-review. *Bioact Mater*. 2023 Jun 1;24:20-25. <https://doi.org/10.1016/j.bioactmat.2022.12.004>
- [43] Chen C, Chen J, Wu W, Shi Y, Jin L, Petrini L, et al. In vivo and in vitro evaluation of a biodegradable magnesium vascular stent designed by shape optimization strategy. *Biomaterials*. 2019 Nov 1;221:119414. <https://doi.org/10.1016/j.biomaterials.2019.119414>
- [44] Kapoor A, Jepson N, Bressloff NW, Loh PH, Ray T, Beier S. The road to the ideal stent: A review of stent design optimisation methods, findings, and opportunities. *Mater Des*. 2024 Jan 1;237:112556. <https://doi.org/10.1016/j.matdes.2023.112556>
- [45] Li Y, Wang Y, Shen Z, Miao F, Wang J, Sun Y, et al. A biodegradable magnesium alloy vascular stent structure: Design, optimisation and evaluation. *Acta Biomater*. 2022 Apr 1;142:402-412. <https://doi.org/10.1016/j.actbio.2022.01.045>
- [46] Li Y, Wang J, Sheng K, Miao F, Wang Y, Zhang Y, et al. Optimizing structural design on biodegradable magnesium alloy vascular stent for reducing strut thickness and raising radial strength. *Mater Des*. 2022 Aug 1;220:110843. <https://doi.org/10.1016/j.matdes.2022.110843>
- [47] Shi Y, Xue Z, Li P, Yang S, Zhang D, Zhou S, et al. Surface modification on biodegradable zinc alloys. *J Mater Res Technol*. 2023 Jul 1;25:3670-3687. <https://doi.org/10.1016/j.jmrt.2023.06.149>
- [48] Mei D, Zhang Q, Li Y, Liu M, Li W, Jiang P, et al. The misalignment between degradation rate and mechanical integrity of Mg-Zn-Y-Nd alloy during the degradation evaluation in modified Hanks' solutions. *J Magnes Alloy*. 2024 Sep 1;12(9):3661-3674. <https://doi.org/10.1016/j.jma.2023.04.006>
- [49] Bontinck J, Goverde P, Schroë H, Hendriks J, Maene L, Vermassen F. Treatment of the femoropopliteal artery with the bioresorbable remedy stent. *J Vasc Surg*. 2016 Nov 1;64(5):1311-1319. <https://doi.org/10.1016/j.jvs.2016.05.066>
- [50] Bennett J, Ielasi A, Torzewski J, de Hemptinne Q, Cerrato E, Lanocha M, et al. The resorbable magnesium scaffold Magmaris in acute coronary syndrome: An appraisal of evidence and user group guidance. *Cardiovasc Revasc Med*. 2022 Jun 1;39:106-113. <https://doi.org/10.1016/j.carrev.2021.09.012>
- [51] Bosiers MJ, Rand T, Uberoi R, Schroeder H, Malyar N, Scheinert D, et al. MOTIV bioresorbable scaffold in below-the-knee artery disease: European post-market pilot BTK trial: 36-month results. *Cardiovasc Intervent Radiol*. 2025 Nov 1;48(11):1576-1586. <https://doi.org/10.1007/s00270-025-04202-8>
- [52] Lin W, Zhang H, Zhang W, Qi H, Zhang G, Qian J, et al. In vivo degradation and endothelialization of an iron bioresorbable scaffold. *Bioact Mater*. 2021 Apr 1;6(4):1028-1039. <https://doi.org/10.1016/j.bioactmat.2020.09.020>
- [53] El Khoury R, Schneider PA. Nonsystematic review of drug-eluting resorbable scaffolds in infrapopliteal intervention: Unmet need and rationale for use. *JVS Vasc Insights*. 2023 Jan 1;1:100017. <https://doi.org/10.1016/j.jvsvi.2023.100017>
- [54] Varcoe RL, Parikh SA, DeRubertis BG, Jones-McMeans JM, Teraphongphom NT, Wang J, et al. Evaluation of an infrapopliteal drug-eluting resorbable scaffold: Design methodology for the LIFE-BTK randomized controlled trial. *J Soc Cardiovasc Angiogr Interv*. 2023 Jul 1;2(4):100964. <https://doi.org/10.1016/j.jscvi.2023.100964>
- [55] Brandt-Wunderlich C, Fubel A, Stiehm M, Schmidt W, Grossmann S, Bonin F, et al. Recovery of coronary artery distensibility after two and four years in vivo degradation of a resorbable magnesium-based scaffold. *Acta Biomater*. 2026 Jan 1;210:617-628. <https://doi.org/10.1016/j.actbio.2025.12.005>
- [56] Li J, Hu X, Chen Y, Fan D, Tan C, Yang S, et al. Review of recent progress in vascular stents: From conventional to functional vascular stents. *Chin Chem Lett*. 2025 Jul 1;36(7):110492. <https://doi.org/10.1016/j.cclet.2024.110492>
- [57] Feng H, Wang X, Liu M, Liu B, Chen Z, Chen X. First-in-human implantation of a 3D-printing fully bioresorbable drug eluting stent for treatment of superficial femoral artery disease. *Ann Vasc Surg Brief Rep Innov*. 2024 Sep 1;4(3):100299. <https://doi.org/10.1016/j.avsur.2024.100299>
- [58] Foin N, Lee RD, Torii R, Guitierrez-Chico JL, Mattesini A, Nijjer S, et al. Impact of stent strut design in metallic stents and biodegradable scaffolds. *Int J Cardiol*. 2014 Dec 20;177(3):800-808. <https://doi.org/10.1016/j.ijcard.2014.09.143>
- [59] Yu C, Zhang H, Shen Y, Huang Y, Yan X, Li M, et al. Contrastive analysis of degradation behavior for WE43 magnesium alloy stents in cerebrovascular versus coronary hemodynamic environments. *J Magnes Alloy*. 2026 Jun;19:101974. <https://doi.org/10.1016/j.jma.2025.101974>
- [60] Tong Z, Gong G, Huang H, Cai G, Fang L, Yu H, et al. In vitro corrosion and biocompatibility of additively manufactured

- biodegradable molybdenum. *Acta Biomater.* 2025 Jan 1;191:66-79. <https://doi.org/10.1016/j.actbio.2024.11.019>
- [61] Zilinyi RS, Alsalam M, Snyder DJ, Raja A, Mintz AJ, Sethi SS, et al. Surgical and endovascular therapies for below-the-knee peripheral arterial disease: A contemporary review. *J Soc Cardiovasc Angiogr Interv.* 2024 Mar 1;3(3, Part A):101268. <https://doi.org/10.1016/j.jscv.2023.101268>
- [62] Rong D, Wang T, Liu X, Pan X, Wang L, Zhang J, et al. The study of rapamycin nanofibrous membrane for preventing arteriovenous fistula stenosis. *Mater Des.* 2024 Sep 1;245:113297. <https://doi.org/10.1016/j.matdes.2024.113297>
- [63] Peterson GI, Dobrynin AV, Becker ML. Biodegradable shape memory polymers in medicine. *Adv Healthc Mater.* 2017 Nov 1;6(21):1700694. <https://doi.org/10.1002/adhm.201700694>
- [64] Joo YS, Cha JR, Gong MS. Biodegradable shape-memory polymers using polycaprolactone and isosorbide based polyurethane blends. *Mater Sci Eng C Mater Biol Appl.* 2018 Oct 1;91:426-435. <https://doi.org/10.1016/j.msec.2018.05.063>
- [65] Zhang Q, Zhao Z, Wu D, Chen K, Weng S. Mechanics-guided design of inflatable heterogeneous shape memory polymer vascular stents. *Int J Mech Sci.* 2023 Sep 15;254:108405. <https://doi.org/10.1016/j.ijmecsci.2023.108405>
- [66] Wang Y, Venezuela J, Dargusch M. Biodegradable shape memory alloys: Progress and prospects. *Biomaterials.* 2021 Dec 1; 279:121215. <https://doi.org/10.1016/j.biomaterials.2021.121215>
- [67] Garcia-Garcia HM, Serruys PW, Campos CM, Muramatsu T, Nakatani S, Zhang Y, et al. Assessing bioresorbable coronary devices: Methods and parameters. *JACC Cardiovasc Imaging.* 2014 Nov 1;7(11):1130-1148. <https://doi.org/10.1016/j.jcmg.2014.06.018>
- [68] Chow EY, Chlebowski AL, Chakraborty S, Chappell WJ, Irazoqui PP. Fully wireless implantable cardiovascular pressure monitor integrated with a medical stent. *IEEE Trans Biomed Eng.* 2010 Feb 17;57(6):1487-1496. <https://doi.org/10.1109/TBME.2010.2041058>
- [69] Son D, Lee J, Lee DJ, Ghaffari R, Yun S, Kim SJ, et al. Bioresorbable electronic stent integrated with therapeutic nanoparticles for endovascular diseases. *ACS Nano.* 2015 Jun 23;9(6):5937-5946. <https://doi.org/10.1021/acs.nano.5b00651>
- [70] Park J, Kim JK, Park SA, Lee DW. Biodegradable polymer material based smart stent: Wireless pressure sensor and 3D printed stent. *Microelectron Eng.* 2019 Feb 1;206:1-5. <https://doi.org/10.1016/j.mee.2018.12.007>
- [71] Vishnu J, Manivasagam G. Perspectives on smart stents with sensors: From conventional permanent to novel bioabsorbable smart stent technologies. *Med Devices Sens.* 2020 Dec 1; 3(6):e10116. <https://doi.org/10.1002/mds3.10116>
- [72] Hatami H, Almahmeed W, Kesharwani P, Sahebkar A. Exploring the potential of 3D and 4D printing in advancing stent manufacturing for cardiovascular diseases. *Eur Polym J.* 2024 May 27; 212:113035. <https://doi.org/10.1016/j.eurpolymj.2024.113035>
- [73] Lee SJ, Jo HH, Lim KS, Lim D, Lee S, Lee JH, et al. Heparin coating on 3D printed poly (l-lactic acid) biodegradable cardiovascular stent via mild surface modification approach for coronary artery implantation. *Chem Eng J.* 2019 Dec 15;378:122116. <https://doi.org/10.1016/j.cej.2019.122116>
- [74] Shen Y, Tang C, Sun B, Zhang Y, Sun X, El-Newehy M, et al. 3D printed personalized, heparinized and biodegradable coronary artery stents for rabbit abdominal aorta implantation. *Chem Eng J.* 2022 Dec 15;450:138202. <https://doi.org/10.1016/j.cej.2022.138202>
- [75] Abdullah MR, Peng Z, Rajendren VB, Ahmad F, Shah SSA, Zia AW, et al. Comprehensive review of 3D/4D printing of soft materials, methods and applications. *Appl Mater Today.* 2025 Apr 1;43:102667. <https://doi.org/10.1016/j.apmt.2025.102667>