

# SHAPE-MEMORY POLYMERS FOR BIOMEDICAL APPLICATIONS: MECHANISMS, MATERIALS, AND FUTURE PERSPECTIVES

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## Abstract

Shape-memory polymers (SMPs) represent an emerging class of smart materials capable of undergoing programmed deformations and returning to their original shape upon exposure to external stimuli such as temperature, pH, light, or magnetic and electric fields. Among them, shape-memory polyurethanes (SMPUs) have attracted particular attention due to their segmented structure, tunable thermal and mechanical properties, and, in some cases, biocompatibility. Their versatility enables not only shape recovery but sometimes also biodegradation in physiological environments, which significantly broadens their biomedical applicability. This review provides a comprehensive overview of the fundamental mechanisms behind the shape-memory effect, including the role of hard and soft segments, transition temperatures, and the influence of structural modifications. Special focus is given to the comparison between SMPs and shape-memory alloys (SMAs), highlighting advantages such as lower density, greater deformability, and biodegradability of some of the SMPs. Current biomedical applications of SMPs include vascular stents, drug delivery systems, sutures, scaffolds for tissue engineering, wound dressings, artificial muscles, and orthodontic devices. Additionally, porous polyurethane foams and biodegradable films offer promising solutions in minimally invasive surgery and regenerative medicine. Perspectives for future development emphasize improving long-term stability and degradation control, ensuring non-toxic by-products, and scaling up production for clinical applications. The integration of SMPs with additive manufacturing techniques, nanofillers, and multifunctional stimuli-responsiveness is expected to significantly expand their role in next-generation medical devices. Collectively, SMPs stand out as one of the most promising groups of materials at the interface of polymer science and biomedicine.

**Keywords:** *shape memory polymers, biomedical applications, polyurethanes, smart materials*

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## Introduction

Shape memory polymers constitute an emerging class of smart materials that have attracted increasing scientific and technological interest over recent decades due to their ability to undergo programmed and reversible shape transformations. SMPs belong to the group of so-called smart materials and are characterized by their ability to change their properties in a controlled manner in response to external stimuli such as temperature, light, magnetic field, electric field, changes in pH, humidity, etc. (presented in FIG. 1). Their potential applications, prospects, and ongoing research have been discussed in numerous review papers [1-5].

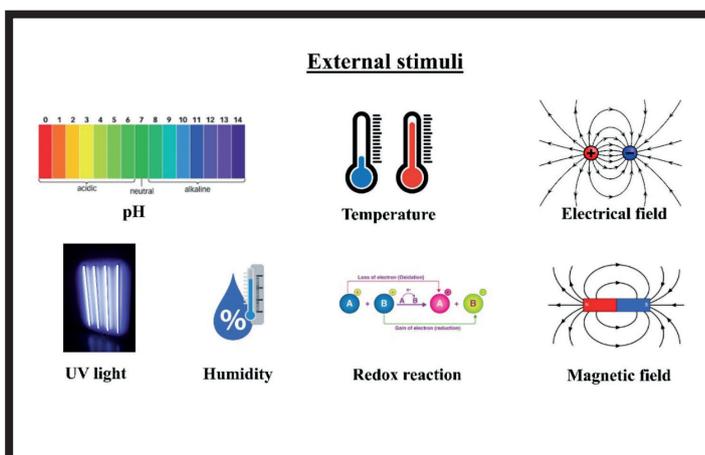


FIG. 1. External stimuli for activation of polymer actuators (adapted from [6], licence CC BY 4.0).

The first observations of the shape memory effect in polymer materials date back to the 1960s, when the ability of some polyurethanes to return to their original shape after heating was noticed. In the 1980s, systematic research into the mechanisms responsible for this effect began, and the development of polymer technologies and analytical tools allowed for a better understanding of the role of the segmental structure of polymers. In the 1990s, the first patents for the use of SMPs in medicine, materials engineering, and electronics began to appear [7-10].

Over the past 25 years, interest in SMPs has grown exponentially, as reflected in the number of scientific publications in databases such as Scopus [11]. Particularly dynamic development has taken place in the last decade, when SMPs began to be combined with nanofillers, 3D printing technology, and biomaterial design. Currently, SMPs are considered one of the most important classes of smart materials with potential for applications in regenerative medicine, implantology, drug delivery systems, and smart textiles.

In the field of shape memory polymers, several key definitions recur consistently across the literature and are essential for a proper understanding of their behavior. Therefore, the most important definitions were collected in TABLES 1 and 2.

Despite their significant potential, shape memory polymers still face several limitations that restrict their widespread use in medical applications. One of the main challenges is the relatively low recovery stress compared to shape memory alloys, which may be insufficient for load-bearing or high-force-demanding implants. In addition, precise control of the transition temperature remains critical, as small deviations may lead to premature activation or incomplete shape recovery under physiological conditions. Long-term mechanical stability, including creep and fatigue

TABLE 1. Fundamental terminology related to shape memory polymers [3-4, 8-9, 17].

Term and abbreviations	Definition
<b>Shape Memory Polymers (SMPs)</b>	Polymers capable of fixing a temporary shape and recovering a permanent shape upon activation by an external stimulus.
<b>Shape Memory Alloys (SMAs)</b>	Metallic alloys capable of recovering a predefined shape upon activation by an external stimulus, typically temperature or stress.
<b>Shape Memory Effect (SME)</b>	The ability of a material to memorize a permanent shape and recover it from a temporary shape upon stimulation.
<b>Permanent Shape</b>	The original shape is defined by the material's network structure, which is recovered after activation.
<b>Temporary Shape</b>	The deformed shape that a polymer maintains until activation by an external stimulus.
<b>Shape Programming</b>	The process of deforming the polymer under specific conditions (e.g., temperature) to fix a temporary shape.
<b>Shape Recovery</b>	The process by which a polymer returns from the temporary shape to its permanent shape upon activation.
<b>Shape Memory Cycle</b>	A complete sequence consisting of programming, fixing, and recovery of shape.
<b>One-way shape memory effect</b>	The ability to recover the permanent shape only once after programming.
<b>Two-way shape memory effect</b>	The ability to reversibly switch between two shapes during heating and cooling without reprogramming.
<b>Multiple shape memory effects</b>	The capability of a material to memorize and recover more than one temporary shape sequentially.

TABLE 2. Thermomechanical and performance-related terminology of shape memory polymers [3-4, 8-9, 17].

Term and abbreviations	Definition
<b>Switching Segments</b>	Polymer segments responsible for fixing the temporary shape; they undergo reversible thermal transitions (e.g., $T_G$ or $T_M$ ).
<b>Hard segments</b>	Rigid polymer domains acting as netpoints, providing mechanical strength and defining the permanent shape.
<b>Soft segments</b>	Flexible polymer chains that function as switching segments and enable deformation and shape fixation.
<b>Transition temperature (<math>T_{Trans}</math>) / Switching temperature (<math>T_{Sw}</math>)</b>	The temperature at which shape recovery occurs; in thermally activated SMPs, it often coincides with $T_G$ or $T_M$ of the switching segments.
<b>Glass transition temperature (<math>T_G</math>)</b>	The temperature at which the amorphous polymer undergoes a phase transition from a glassy to a rubbery state, resulting in increased segmental mobility.
<b>Melting temperature (<math>T_M</math>)</b>	The temperature at which crystalline switching segments melt, allowing molecular mobility and shape recovery.
<b>Strain-induced crystallization</b>	Crystallization triggered by mechanical deformation, contributing to temporary shape fixation.
<b>Shape fixity ratio (<math>R_f</math>)</b>	A measure of how well a material can fix and retain the temporary shape after deformation.
<b>Shape recovery ratio (<math>R_r</math>)</b>	A measure of how completely a material can recover its permanent shape after activation.
<b>Programming strain</b>	The applied deformation (strain) used to program the temporary shape.
<b>Recovery stress</b>	The stress generated when shape recovery is constrained and free deformation is prevented.

under cyclic loading, also poses a concern, particularly for permanent or semi-permanent implants. Furthermore, for biodegradable SMPs, balancing mechanical performance with predictable and biocompatible degradation kinetics remains a major materials design challenge.

This review summarizes the mechanisms governing shape memory behavior in polymers with emphasis on SMPUs. It critically discusses how thermomechanical design parameters ( $T_G/T_M$ , segment architecture, and cyclic durability) constrain clinical translation across minimally invasive devices and regenerative applications. The presented state of knowledge is primarily based on literature from the last decade, complemented by seminal foundational studies.

### Working principles of SMPs

A defining characteristic of shape memory polymers is their segmented molecular architecture, typically consisting of distinct hard and soft segments that govern mechanical integrity and shape memory behavior, respectively. Changing the proportions of both segments in the material affects its properties and transition temperature.

In the literature, SMPs are commonly classified according to their chemical composition and network structure, the type of external stimulus triggering shape recovery, and the number or reversibility of memorized shapes. In terms of composition and structure, the following can be distinguished: block copolymers, supramolecular polymers, polymer composites/blends, and cross-linked polymers. As mentioned above, the most important stimuli include temperature, light, magnetic or electric fields, moisture, pH, and oxidation and reduction reactions [12-15].

In terms of memory/shape change, there are single, double, triple, multiple shape memories, and multifunctional ones [12]. In the case of single shape memory, the material remembers only one temporary shape, from which it returns to its original shape only once. In the case of subsequent deformation, it is necessary to reprogram the material. Bidirectional polymers transition smoothly between two shapes without the need for reprogramming. They respond to changing environmental stimuli, such as

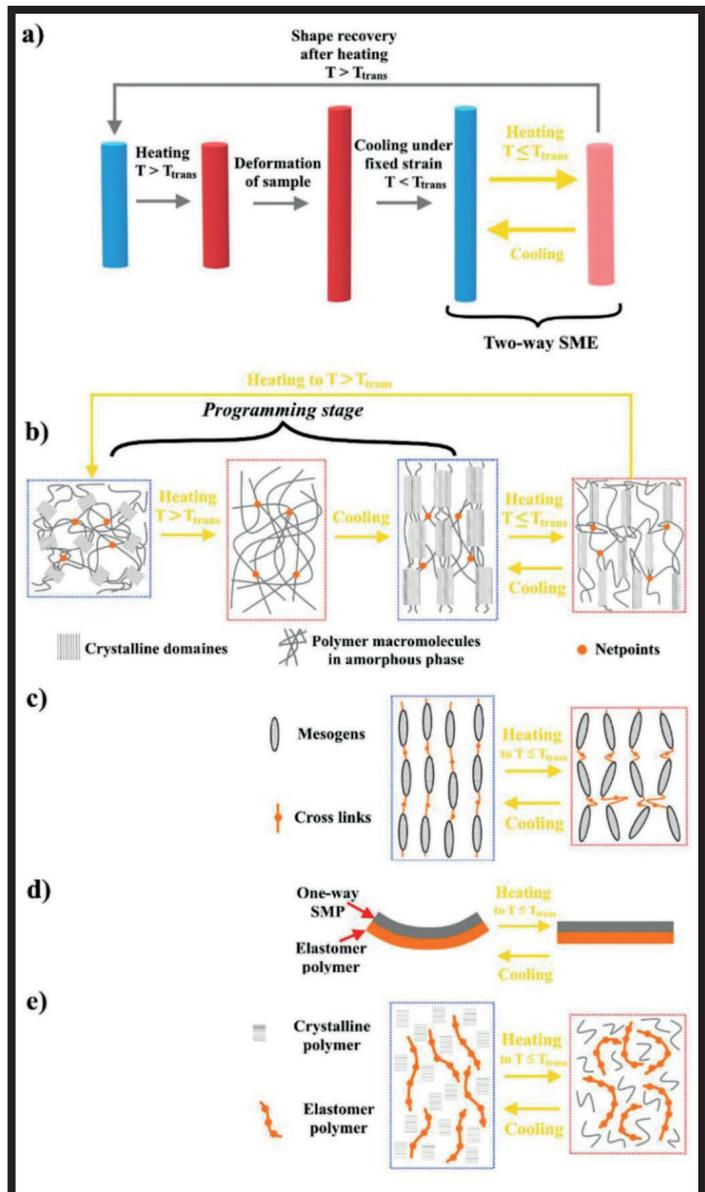


FIG. 3. Two-way shape memory effect in SMPs; a) macroscopic level and structure level of: b) semi-crystalline polymers, c) liquid crystalline elastomers, d) multi-layered polymer composites, e) interpenetrating polymers (adapted from [4], licence CC BY 4.0).

cyclical temperature changes. Polymers with triple shape memory have two temporary shapes and one original shape. They change their form, for example, at two different temperatures. Multiple shape memory polymers, on the other hand, can have multiple temporary shapes and change as a result of multi-stage activation. FIG.2 and FIG.3 schematically show the mechanism of action of SMPs presented by Dayyoub et al. [4].

The most common group of SMPs includes those whose shape change is caused by temperature. It may depend on the melting temperature ( $T_M$ ). In this case, the material recrystallizes to establish a new temporary shape. The shape change may also depend on the glass transition temperature ( $T_G$ ) of the material. In general, the transition temperature (point) is referred to as ( $T_{Trans}$ ) or, in some publications, as switching temperature ( $T_{Sw}$ ). In the case of polymers with a change in shape during glass transition, there is a greater possibility of modifying  $T_{Trans}$ . This is due to the introduction of comonomers, i.e., monomers that form copolymers with a given polymer.

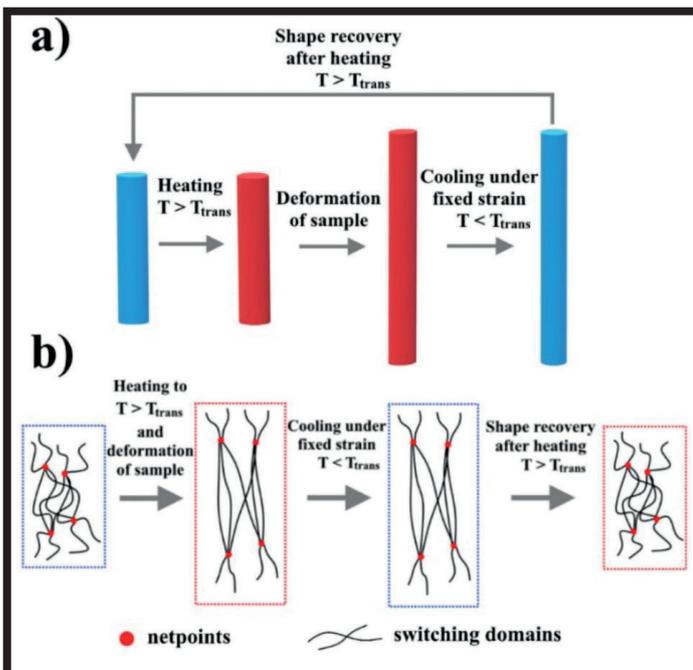
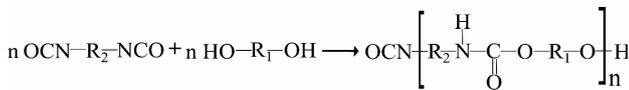


FIG. 2. One-way shape memory effect in SMPs; a) macroscopic level and b) structure level (adapted from [4], licence CC BY 4.0).

## The most popular SMPs – polyurethanes

Shape memory polymers include, among others, polyurethanes (described in more detail in the next paragraph), which are characterized by good elasticity, a high shape recovery ratio, and the ability to tune the transition temperature; epoxy resins, distinguished by high stiffness, dimensional stability, and chemical resistance; polyesters, such as poly( $\epsilon$ -caprolactone), which exhibit low activation temperatures and biocompatibility; polyethers, known for good fatigue resistance and repeatable reversibility of the shape memory effect; and block copolymers and crosslinked polymers, in which a clear separation into hard and soft segments enables precise control of shape memory properties [3, 7, 12].

One of the most popular and frequently described shape memory polymers is polyurethane. This is due to its segmented structure, where diols usually act as the flexible segment, while compounds from the isocyanate group are responsible for the hard segment. FIG. 4 illustrates the synthesis of polyurethane via a polyaddition reaction.



**FIG. 4. Polyaddition reaction leading to the production of polyurethane.**

However, the literature often mentions many modifications of basic shape memory polyurethanes. Castor oil and isosorbide are among the most popular. Isosorbide is a natural diol produced from starch. It improves the stiffness and hardness of the polymer. Castor oil is another natural, environmentally friendly, and non-toxic additive. It

affects the thermal stability of the material and optimizes its chemical and mechanical properties [16].

## Comparison of SMPs and SMAs

In addition to shape memory polymers, there are also shape memory alloys. However, they differ in their properties. Numerous comparative studies have systematically evaluated the fundamental differences between shape memory polymers and shape memory alloys, particularly with respect to density, deformation capability, processing conditions, and biomedical suitability. Polymers have a significantly lower density in the range of 0.9-1.1 g/cm<sup>3</sup> compared to alloys, whose density is 6-8 g/cm<sup>3</sup>. In terms of deformation range, SMPs achieve significantly better results of up to 800%, while SMAs <8%. However, the Young's modulus of SMPs at temperatures below and above the transition temperature is significantly lower than that of SMAs. Another aspect is the deformation time, as SMAs need less than 1 second to return to their original shape, while SMPs need from <1 second to even several minutes. Both types of materials have high corrosion resistance, and some of them are biocompatible. A significant difference, however, is the biodegradability of some SMPs in the human body, while SMAs do not have this feature. Another important difference is the manufacturing conditions, where SMAs usually require higher temperatures above 1000 °C and high pressure, while SMPs usually require lower temperatures below 200 °C and reduced pressure. There are also discrepancies in transition temperature, as SMAs changes its form at temperatures ranging from approx 40-100 °C, while SMPs can have completely different ranges depending on the polymer. For example, the transition temperature of polyurethanes is in the range of approx 20-80 °C [2], [17-19]. The most important information comparing the properties of SMPs and SMAs is summarized in TABLE 3.

**TABLE 3. Comparison of properties of Shape Memory Alloys and Shape Memory Polymers based on [17, 20].**

	Shape Memory Alloys	Shape Memory Polymers
<b>T<sub>sw</sub> [°C]</b>	40-100	It depends on the polymer
<b>Transformation strain [%]</b>	Max. 8	Up to 800
<b>Stress required for deformation [MPa]</b>	50-200	1-3
<b>Stress generated during recovery [MPa]</b>	150-300	1-3
<b>Young's Modulus below Ts [MPa]</b>	83000	10-3000
<b>Young's Modulus above Ts [MPa]</b>	28-41	(0.1-10) x 10 <sup>3</sup>
<b>Poisson's Ratio</b>	0.33	0.30
<b>Density [g/cm<sup>3</sup>]</b>	6-8	0.9-1.1
<b>Recovery speed</b>	<1 s	<1 s to several min.
<b>Processing conditions</b>	Higher temperature (usually >1000 °C) and high pressure	Lower temperature (usually <200 °C, low pressure)
<b>Biocompatibility and biodegradability</b>	Some are biocompatible, i.e., Nitinol, not biodegradable	Can be biocompatible and/or biodegradable
<b>Corrosion resistance in a physiological environment</b>	Excellent	Excellent

## Applications of SMPs in medicine

Shape memory polymers are intensively investigated for medical applications as a response to key challenges in modern medicine, including the need for minimally invasive procedures, the reduction of tissue trauma, and improved implant functionality. Conventional materials used in implantology, particularly metals and rigid polymers, often exhibit a mechanical mismatch with biological tissues, which may lead to inflammation, damage to surrounding structures, or the need for revision surgeries. SMPs offer the ability to temporarily reduce the size and stiffness of medical devices during implantation, followed by controlled deployment and adaptation to the biological environment under physiological conditions. Moreover, the possibility of precisely tailoring the switching temperature, biodegradability, and chemical functionalization makes shape memory polymers an attractive alternative to shape memory alloys, eliminating issues related to high stiffness, the risk of metal ion release, and limited biocompatibility. Consequently, SMPs are regarded as a promising class of materials for the development of next-generation intelligent, adaptive, and safer biomedical solutions, although most current applications remain at the preclinical research stage [21].

The problem of blood vessel obstruction affects not only the elderly, but also young people and newborns [22]. One of the solutions to this problem is the use of small implants

known as stents, which are placed in areas where blood flow is reduced. These devices are typically metallic meshes made of medical-grade stainless steel or shape memory alloys such as nitinol. However, these materials exhibit several disadvantages and limitations, including restenosis, defined as the re-narrowing of the vessel lumen, which often necessitates the use of anticoagulant therapy. An alternative approach involves biodegradable stents, such as the Igaki–Tamai stent, which gradually degrade in vivo into harmless by-products. Another innovative solution is the development of polymer-based shape memory stents, which, in addition to exhibiting shape recovery behavior similar to nitinol-based devices, can also be biodegradable. This feature is particularly advantageous in pediatric applications, where rapid growth renders permanent stents unsuitable. As a result, significant attention has been directed toward shape memory polymers as candidate materials for next-generation vascular implants.

Among the most widely investigated polymers for the fabrication of shape memory stents are polyurethanes, including both commercially available materials [23] and tailor-made systems synthesized for specific biomedical purposes [24], [25]. These implants may take various geometrical forms, including cylindrical tubes [23], planar films that self-roll into tubular structures (presented in FIG. 5) [26], or strip-based constructs that adopt a spring-like configuration upon activation [26, 27].

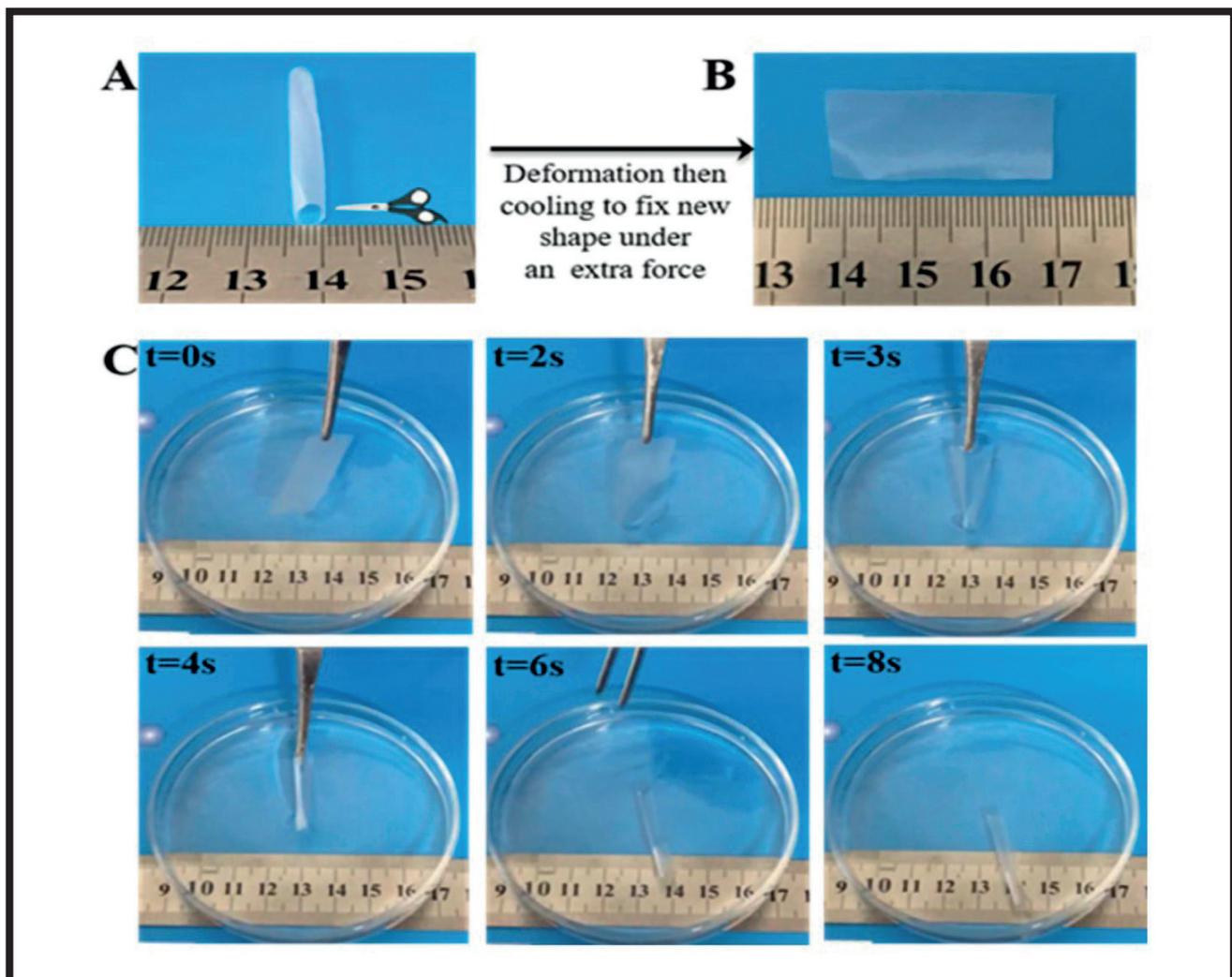


FIG. 5. (a) Original shape of the Polyhydroxyalkanoate-Based Polyurethane (PHP) tube. (b) The tube was cut off and fixed into temporary planar shapes at  $-10^{\circ}\text{C}$ . (c) Time sequence of photographs showing self-folding of PHP films. The film was initially spread without water ( $t = 0$ ), and then immersed in PBS ( $t = 2\text{--}4$  s), causing rapid curling. The permanent shapes (at  $37^{\circ}\text{C}$  in PBS) of the PHP tube in water resulted in instantaneous entangling to its original shape ( $t = 6\text{--}8$  s), (adapted from [28], licence CC BY 4.0).

Among the most mature biomedical applications of SMPs are surgical sutures and fixation systems, which exploit the one-way shape memory effect to achieve controlled tissue approximation under physiological conditions. However, apart from classic products designed for tissue bonding, there are also other lesser-known methods, and new concepts are being developed. In their work, Zhao et al. presented many possibilities for using SMPs as materials for bonding separated tissues [29]. In addition to classic shape memory surgical sutures, which were already being developed 20 years ago [30], the authors also presented the concept of a self-clamping staple that would bring two pieces of tissue together [31-33]. Alternative fixation concepts include PLA-based SMP springs that enable seamless tissue approximation while minimizing mechanical stress concentrations [31]. For surgical sutures and fixation systems, SMPs must exhibit high repeatability of the shape memory effect and mechanical stability in a moist physiological environment. A critical limitation is the risk of excessive local stresses in tissues, which may lead to necrosis or delayed healing if the recovery force of the material is not properly controlled. Moreover, these materials must be fully biocompatible and resistant to sterilization processes that must not degrade the programmed shape memory behavior.

Drug delivery systems based on SMPs represent another important biomedical application. Therefore, considerable effort has been devoted to the most optimal solution in this regard is constantly being sought. In this context, shape memory polymers represent a promising platform due to their stimulus-responsive expansion and retention capabilities. Under the influence of an appropriate stimulus, they release active substances in our body. In their work, Maroni et al. presented the possibilities of using SMPs as a matrix for retention drug delivery systems in the field of urology and gastroenterology [34]. In another paper, Uboldi et al. [35]

described the use of SMPs made of pharmaceutical-grade PVA. They obtained promising results without modifying the existing polymer in the context of a drug delivery system. In this context, the primary requirement is the ability of the material to undergo controlled expansion and long-term retention in hollow organs such as the urinary bladder or gastrointestinal tract (FIG. 6). A critical limitation is the necessity for precise control over the kinetics of drug release to prevent burst release or premature depletion of the active substance. In addition, SMPs must demonstrate chemical stability in biological media and exhibit no adverse interactions that could deactivate the therapeutic agent.

In the context of muscles, particular attention is paid to SMPUs with a bidirectional shape memory effect, capable of repetitive contraction-relaxation cycles under the influence of temperature changes, which functionally imitate the action of muscle tissue. Hybrid solutions, in which SMPUs are combined with pH- or humidity-sensitive hydrogels, additionally allow for smoother and more environmentally adapted movements, as well as multiple programming of the material in different shapes. In the context of artificial muscles and functional implants, SMPs are required to withstand multiple reversible shape change cycles while maintaining stable mechanical properties over time. A major limitation is material fatigue, which may result in a gradual loss of actuation amplitude or uncontrolled deformation. Furthermore, the activation temperature must remain within a safe physiological range to ensure that long-term implant operation does not cause damage to surrounding tissues.

In the case of artificial skin, attention is also paid to shape memory polyurethanes, which are used to design flexible films and coatings that can adapt to wound surfaces and dynamically change their structure during the healing process. Literature examples show that SMPUs modified with natural diols, such as isosorbide or castor oil, provide favorable biocompatibility and adequate mechanical flexibility,

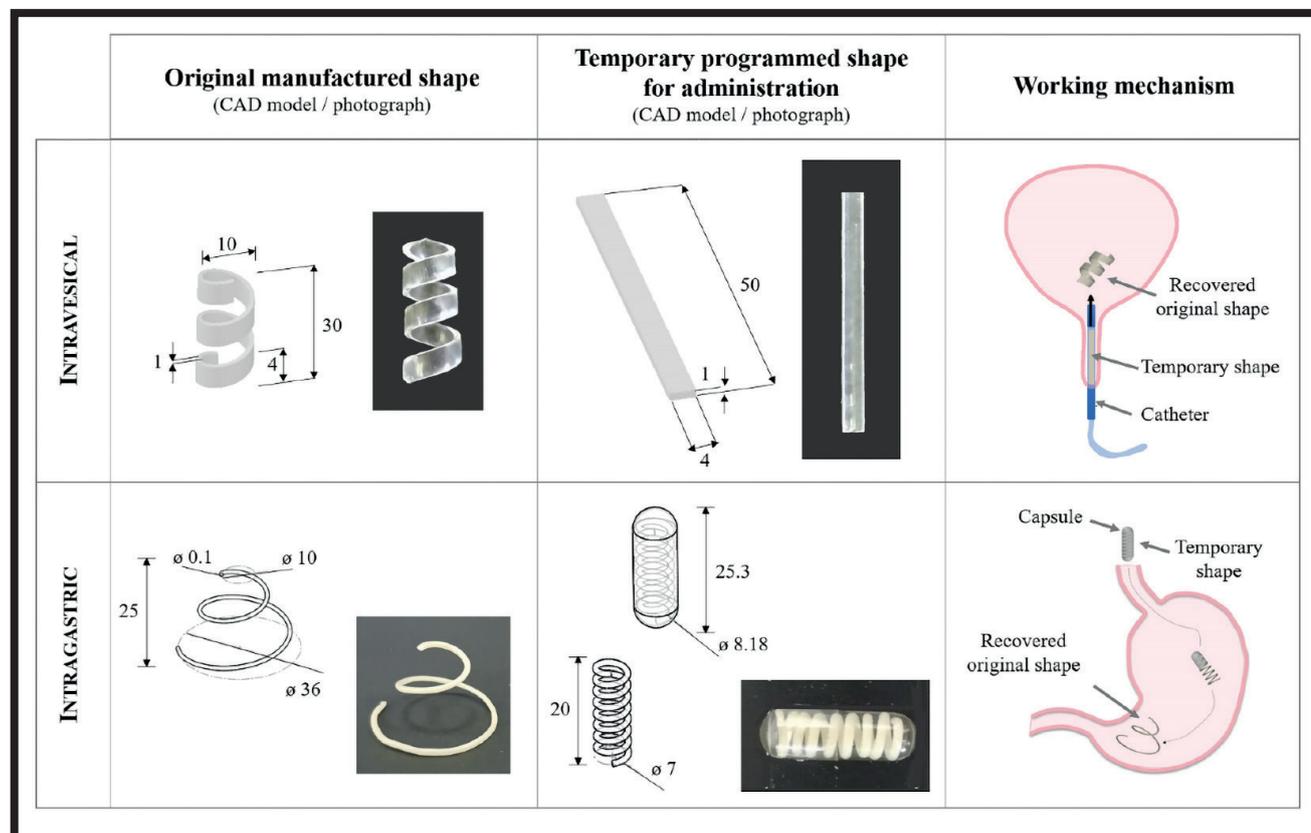


FIG. 6. Design of an expandable drug delivery system based on shape memory polymers for retention in hollow muscular organs (adapted from [35], licence CC BY 4.0).

making them promising candidates for smart dressings or skin regeneration support materials. Thanks to these features, SMPUs combine functionality with biological safety, and their biodegradability further increases their application potential in long-term muscle implants and regenerative medicine solutions [29, 36-38]. For artificial skin and smart wound dressings, a key requirement is high flexibility combined with the ability to conform to the changing geometry of the wound during the healing process. A critical limitation is the need to ensure adequate permeability to water vapor and oxygen while simultaneously maintaining an effective barrier against pathogens. The material must also exhibit full biocompatibility and non-cytotoxic degradation products, which is particularly important during prolonged contact with damaged skin.

The integration of SMPs with textile fibers or coatings allows the creation of smart fabrics that can respond to temperature, humidity, or electric fields. Examples include clothing and technical materials that can regulate water vapor and air permeability thanks to SMP coatings. As a result, sports and protective garments incorporating SMPU-based coatings can dynamically adapt to changing environmental and physiological conditions, e.g., increasing breathability at elevated temperatures and during exertion, and sealing the structure in cool or humid environments [4, 39].

Another area of application for SMPs in combination with textile products is medical textiles. Shape memory films used as thin coatings on fibers allow the creation of smart dressings and compression materials that adapt to the shape of the patient's body and can then change their structure to support the healing process or regulate pressure. The literature also describes prototypes of rehabilitation clothing in which SMPUs fibers act as active elements supporting movement, e.g., by contracting or stretching under the influence of temperature changes [5, 12-13]. In the area of smart and medical textiles, SMPs must demonstrate functional durability under repeated activation cycles and resistance to operational factors such as moisture, sweat, and temperature fluctuations. A critical limitation is the trade-off between material responsiveness and user comfort, as overly stiff or slowly responding coatings may reduce garment ergonomics. In medical applications, an additional requirement is the ability to precisely regulate pressure or mechanical support without causing localized tissue compression.

SMPs can also be used during procedures. Kuram et al. [40] presented numerous concepts for thrombectomy devices, i.e., devices used in procedures involving the mechanical removal of clots from blood vessels. The principle of operation is to insert a thin tube into a vein, then pierce or hook the clot, change its shape, and pull it out, or puncture the clot with the device, then activate it and change its shape into a coil, which is pulled out together with the clot. For thrombectomy devices, SMPs must enable highly precise and rapid transformation from the delivery configuration to the functional shape while maintaining high resistance to mechanical damage. A critical limitation is the safety of interaction with the blood vessel, as the material must not cause perforation or excessive friction during manipulation. In addition, activation of the shape memory effect must be fully controllable by the operator to prevent unintended deployment of the device.

Shape memory polymers in the form of sponges are a particularly interesting category of porous materials that combine the ability to deform and recover their shape with high elasticity and a large specific surface area. Their spongy structure allows them to be used in medicine, where they can serve as smart implants, hemostatic materials, or drug carriers. Thanks to their shape memory effect, SMPs sponges can be compressed to a small size, which facilitates their

minimally invasive implantation, and then, under physiological conditions, they regain their original volume, adapting to the tissue defect. The literature also highlights their potential in wound treatment - SMPs sponges can be impregnated with bioactive substances that are gradually released at the application site, supporting the healing process. In addition, their porous structure promotes cell adhesion and proliferation, making them attractive for tissue engineering. An additional advantage of SMP sponges lies in the possibility of tailoring porosity, elasticity, and recovery behavior through controlled synthesis parameters, which allows their mechanical properties to be tailored to specific clinical needs, e.g., in orthopedics, surgery, or regenerative [5, 29]. With respect to porous SMP foams used as implants, hemostatic materials, or tissue engineering scaffolds, a key requirement is the ability to undergo large, reversible deformations while preserving the integrity of the porous structure. A critical limitation is the need to balance porosity, which promotes cell adhesion and proliferation, with sufficient mechanical strength. Furthermore, the degradation rate must be matched to the tissue regeneration process to prevent premature loss of mechanical support.

Orthodontics is another potential area of application for SMPs [29], specifically orthodontic ligatures. These are small, flexible rings, usually made of rubber or metal. They attach the orthodontic wire to the braces. The main task of this element is to keep the wire in place, allowing the teeth to be moved precisely in the desired direction. Mehrbakhsh et al. describe the use of PCL/PEG-based SMPUs for the above-mentioned elements [21]. They obtained materials that were capable of 100% recovery of their initial shape. In addition, the samples were evaluated in an *in vitro* study simulating the oral environment. Furthermore, the materials had acceptable hydrophobicity for orthodontic applications, as water absorption is a significant disadvantage of orthodontic ligatures. In the case of orthodontic ligatures based on SMPs, the material must maintain stable mechanical properties in the oral environment, which is characterized by variable pH, enzymatic activity, and continuous moisture exposure. A critical limitation is excessive water absorption, which may lead to a reduction in applied force and deterioration of tooth movement control. In addition, the material must retain repeatable shape memory behavior over extended periods of use without degradation of aesthetic or functional performance.

Another interesting application of SMPs is biodegradable films used postoperatively as anti-adhesion barriers [36]. In their work, Wang et al. synthesized shape memory polyurethane with the addition of isosorbide. They used PDLLA and PEG400 for the synthesis of SMPUs. They produced a film that had a beneficial shape memory effect at a temperature close to body temperature. The material produced was non-toxic and was tested *in vivo* on rats. The rate of polymer degradation corresponded to that of wound healing. Regarding biodegradable anti-adhesion barriers, SMPs in the form of thin films must allow easy application and spontaneous adaptation to postoperative organ surfaces. A critical limitation is the need to precisely match the degradation rate to the wound healing process, so that the barrier neither disappears too early nor persists for an excessive period.

## Conclusions and prospects for development

Despite significant progress in the development of shape memory polymers, several critical limitations must be addressed before their widespread clinical and industrial implementation can be achieved. One of the most critical

challenges remains the long-term stability of SMPs and the control of their degradation behavior, particularly in relation to safety and the potential release of toxic by-products during decomposition in biomedical applications. These issues are closely linked to the need for comprehensive preclinical and clinical evaluations under physiological conditions. In parallel, challenges related to scalability and cost-effective mass production must be addressed to enable the successful market introduction of SMP-based devices. Future research should also place greater emphasis on intelligent additive manufacturing approaches, particularly so-called four-dimensional (4D) printing, which integrates shape memory functionality into three-dimensional printed structures and enables the fabrication of complex, stimuli-responsive architectures. Moreover, increasing attention should be directed toward the development of SMPs capable of responding to multiple external stimuli simultaneously, as well as materials exhibiting multiple shape memory effects, which could significantly expand the functional scope of these materials. Finally, systematic investigations into the influence of sterilization processes on thermomechanical performance and shape memory behavior are essential to ensure the reliable and safe application of SMPs, especially in advanced biomedical and industrial systems.

## Summary

This review presents a comprehensive overview of shape memory polymers, with particular emphasis on their structure, operating mechanisms, classification, and performance

parameters governing the shape memory effect. Key terminology related to SMPs was systematically introduced to provide a clear conceptual framework for understanding their behavior and functional characteristics. Special attention has been devoted to shape memory polyurethanes, which represent the most extensively studied and versatile subgroup of SMPs due to their segmented architecture, tunable thermomechanical properties, and potential biocompatibility and biodegradability. Based on recent scientific literature, a broad spectrum of biomedical applications has been discussed, including vascular stents, surgical sutures, drug delivery systems, artificial muscles, smart wound dressings, medical textiles, and tissue engineering scaffolds. The analysis highlights the advantages of SMPs over shape memory alloys, particularly in terms of large deformability, low density, processing flexibility, and the possibility of controlled degradation in physiological environments. At the same time, current limitations related to long-term stability, degradation control, sterilization effects, and clinical translation have been identified. Overall, the dynamic development and expanding range of applications demonstrate that shape memory polymers, especially polyurethanes, constitute a highly promising and rapidly evolving class of smart materials at the intersection of polymer science and biomedical engineering.

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