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# Polyurethane/polycaprolactane blend with shape memory effect as a proposed material for cardiovascular implants

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**Abstract**

Shape memory materials have been proposed for cardiovascular stents due to their self-expansion ability. The most ideal way to anchor a stent is using self-expansion in the range of body temperature. This work, for the first time, reports the use of polyurethane/polycaprolactone (PU/PCL) blend as a proposed material for shape memory stents. Polyurethane copolymer based on poly(ε-caprolactone) diol was melt blended with PCL in four different ratios of 20, 30, 40 and 50 wt.% and their shape memory behaviors were examined. All blends except for PU/PCL(80/20) showed shape memory effects with recovery temperatures of around the melting temperature of PCL in the blends. The melting behavior of the PCL in the blends is strongly influenced by composition. Changing the composition of the blend system and crystallization conditions adjusted shape recovery to the range of body temperature for PU/PCL(70/30) blend. The in vitro biocompatibility of PU/PCL(70/30) blend was evaluated in this study using human bone marrow mesenchymal stem cells (hBMSCs). The adhesion, morphology and mitochondrial function were analyzed in order to investigate the cell viability during cell culture on PU/PCL(70/30) blend surface. The results showed that the blend supported cell adhesion and proliferation, which indicated good biocompatibility. Our results suggested that this blend might be a potential material as a stent implant.


*Keywords:* Shape memory; Stent; Polyurethane; Polycaprolactone; Cell culture

## 1. Introduction

Shape memory alloys (SMAs) have found wide technical applications such as sensors, transducers, actuators, and cardiovascular implants for placing small devices via minimally invasive surgeries [1–7]. During the last 20 years, with the growth of minimally invasive techniques, there has been a general trend towards stenting using self-expandable systems, where a thin stent is placed in a narrowed artery to expand and dilate it [8]. Stents have been clearly shown to be beneficial in preventing restenosis after angioplasty [3]. Nitinol and other alloys which are used as stents exhibit outstanding features, such as small size and high strength, but at the same time they have obvious disadvantages like high manufacturing cost, limited recoverable deformation and complicated surgery process [6,9]. Furthermore, metal stents are more rigid compared to the surrounding vessel, and thus an abrupt change of compliance in the junction of the host artery and the stent will lead to an abnormal stress concentration which will initiate an adaptive response in the vascular tissue [10]. Therefore, shape memory polymers (SMPs) have come to the focal point over the last decade as proposed materials for stents [11–19]. Most of SMPs are thermo-responsive materials; i.e. their temporary deformation can be eliminated or their permanent shape can be recovered at a critical temperature [6]. Based on this ability, large bulky devices could thus potentially be introduced into the body in a compressed temporary shape by means of minimally invasive surgery and then expand to their permanent shape to fit as required

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[11]. The advantages of polymer stents are the dramatic increase of drug loading and biodegradation capabilities. The improvement of compliance matching, ease of fabrication, lower production cost and the use of shape memory effect for stenting are the other advantages of polymers as stents [19]. The Igaki–Tamai stent was the first to be implanted in humans and has been shown to be safe [15]. This stent, made from poly(L-lactide) or PLLA, is self-expanding; however, the self-expansion which is a transition from the temporary to the permanent shape can be achieved only by heating the stent above the switching temperature ($T_{switch} = 70$ °C). This may cause some trauma to cells during deployment. Incorporating elastic memory in polymeric stents to recover the original shape has been investigated by some researchers. The Igaki–Tamai stent was used with hot liquid in the balloon to heat up the stent above the $T_{switch}$ of the polymer [15]. Peng et al. [14] tried a similar method to expand a polycaprolactone stent, and also suggested microwave heating and electrical heating in the balloon. The mandatory heating process is a drawback of the system as it is time-consuming and will cause tissue damage. The most ideal way to apply a stent would be using self-expansion in the range of body temperature [18]. This is in principle feasible with a two-phase polymer system with elastic property: one phase for recovering the permanent shape and another one for fixing the temporary shape. In this paper, we proposed the blend of segmented PU based on polycaprolactone diol and PCL, the biocompatibilities of which have been demonstrated in biomedical applications [20,21], as novel shape memory material. The blends' compositions, PU and PCL, are segmented copolymer and homopolymer of polycaprolactone, respectively, which is well known for its low degradability [22]. We have used this biodegradable blend system to create a polymeric stent that uses the concept of elastic memory to achieve self-expansion in the range of body temperature. It is believed that shape recovery of PU/PCL blends can take place at melting temperature ($T_m$) of PCL crystals which are formed during the deformation and fixation. The driving force for this shape recovery is related to elastic strain generated during deformation due to the elasticity of PU as a matrix phase in these blends. PU and PCL are partially miscible and the melting temperature of PCL crystals in their blends, which is 60 °C in pure PCL, will decrease with an increase in PU content [23–24]. In this study, we tried to adjust the shape recovery temperature of this blend system, by changing the composition and crystallization conditions in the range of body temperature. As an initial step for developing stent, the in vitro biocompatibility of the selected blend was evaluated using NIH-3T3 fibroblasts [25]. The growth or proliferation of fibroblasts was assessed using a colorimetric MTT assay during 7 days of culture. The results demonstrated a continuous increase in cell density on PU/PCL(70/30) blend surfaces during the culture time. Because the optic density (OD) value in the growth curve of seeded cells increased in a time-dependent manner (OD value at 570 nm reached a value of 1.5 at day 7 from 0.3 at day 1, $p < 0.05$). Morphological studies using scanning electron microscopy showed the cells with a closely adhering and well-spread morphology (Fig. 1). The cell morphology, coupled with in vitro cell culture data, indicated the ability of the blend to support the attachment and proliferation of fibroblasts [25]. However, the development of stent required the culture of specific cell type on the material in order to produce the characteristics of the vascular tissue and improve biocompatibility [12]. MSCs can be ideal candidates as a natural coating on the stent material. They were shown to have immunoregulatory properties and they are able to differentiate into all cell types [26]. It is expected that MSCs have the ability to differentiate into endothelial cells after being located near the blood vessel endothelium microenvironment. Coating of MSCs on the stent can therefore be a new method for limiting the inflammatory reaction and possibly the formation of neointima in the vessels. Thus, as an initial step for developing this approach, in vitro cell culture of hBMSc was cultivated on the proposed blend in order to study the cell behavior in contact with the blend surface.

## 2. Experimental

### 2.1. Materials

Polyesterurethane (LPR2102-85 AE) was delivered from Coim Co. (Italy) with a density of 1.16 g cm$^{-3}$. This polyurethane consists of hard segments based on 4,4'-methylenediphenyl diisocyanate (MDI) and 1,4-butanediol (BDO) and soft segments of polycaprolactone with a $M_n$ of 2000 g mol$^{-1}$. Polycaprolactone (PCL) was obtained from Sigma–Aldrich Co. (Germany) with a $M_n$ of 42,500 g mol$^{-1}$, a density of 1.145 g cm$^{-3}$ and a melting point of 60 °C. PU was dried at 100 °C for 24 h and PCL at 40 °C for 5 h, in a vacuum oven. The dried materials were blended by melt mixing in a Brabender internal mixer at 200 °C and a rotor speed of 50 rpm for approximately 10 min (time to reach to a constant torque). The procedure is as follows: first PU was fed

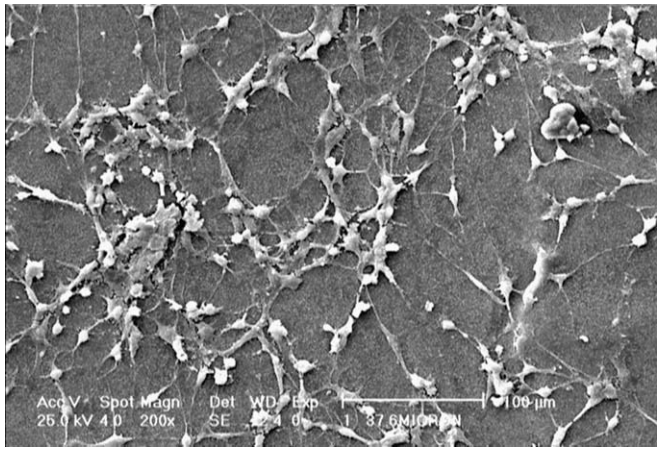


Fig. 1. SEM image of NIH-3T3 cells proliferated on PU/PCL(70/30) blend sheet after 7 days [25].

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