Mechanical Properties of Collagen-Polylactide/Caprolactone Composite for Pulmonary Artery Banding

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Abstract: Pulmonary artery banding is a surgical procedure used in neonates to induce a mechanobiological response, leading to natural repair of certain congenital heart defects. Current banding methods involve a two-step procedure that requires the use of a non-absorbable material, necessitating surgical removal after a specific period of time. The objective of our project is to develop a banding material for pulmonary artery banding that eliminates the need for surgical removal in the second step by enabling resorption. In this study, we compare the mechanical properties of a composite banding material consisting of a copolymer of caprolactone (PCL) and lactide acid (PLA) used as reinforcement in a collagen matrix (COLL) with a commercially available banding material from W. L. GORE. Through uniaxial tensile testing, we demonstrate that our COLL-PLCL banding material exhibits greater compliance compared to GORE materials while maintaining sufficient strain at failure.

Keywords: Collagenous nanofiber matrix; Polycaprolactone; Polylactide; Uniaxial tensile test; Young modulus of elasticity

1 Introduction

Cardiovascular diseases (CVD) remain a leading cause of death worldwide, contributing to significant morbidity and prompting the ongoing development of both non-invasive and invasive treatment approaches [1-3]. Our research group focuses on the development of new materials for cardiovascular surgery, with the ultimate aim of creating a resorbable fabric composed of a composite material comprising a polylactide and polycaprolactone (PLA/PCL) copolymer nanofibrous reinforcement combined with a collagen matrix. One potential application for this material, among others, is in pulmonary artery banding (PAB) procedures [4,5]. PAB is a palliative surgical technique employed to reduce pulmonary overcirculation in neonates with various types of congenital heart disease [6-8]. It is primarily performed in cases where a left-to-right shunt is present. According to various databases, the total number of PAB procedures accounts for approximately 2% of all surgeries for congenital heart disease [9]. The key advantage of utilizing our COLL-PLCL material for PAB is its resorbability, eliminating the need for debanding surgery and minimizing the burden on patients due to repeated surgical interventions.

2 Methods

Composite COLL-PLCL (Fig. 1A) bandings were fabricated using nanofibrous layers based on a L-lactide/caprolactone copolymer (PLCL; 70/30 mol/mol; Purasorb PLC 7015, Corbion, The Netherlands). The nanofibrous layers were prepared using a needleless electrospinning technique (Production line NS 1S500U with precisely controlled air conditioning unit NSAC150, Elmarco, Czech Republic) with a direct current applied to a 10 wt% (PLCL) solution of chloroform and ethanol (Penta, Czech Republic) in an 8:2 weight ratio. The surface density of the layers was 30 g/m^2, and the fiber diameter ranged from 50 to 1000 nm. The matrix of the composite was composed of collagen type I (calf skin, VUP Medical, Czech Republic). Five separate layers of nanofibrous reinforcement were impregnated with a 5 wt% aqueous dispersion, placed in a mold, and left at room temperature for 36 hours. The volume fraction of all fibrous reinforcement in the composite was 70 ± 10 vol%. The stability of the collagen matrix was further enhanced by cross-linking using a 95 wt% ethanol solution containing EDC (N-(3-dimethylaminopropyl)-N-ethylcarbodiimide hydrochloride) and NHS (N-hydroxysuccinimide) at a 4:1 w/w ratio (Sigma Aldrich, USA).

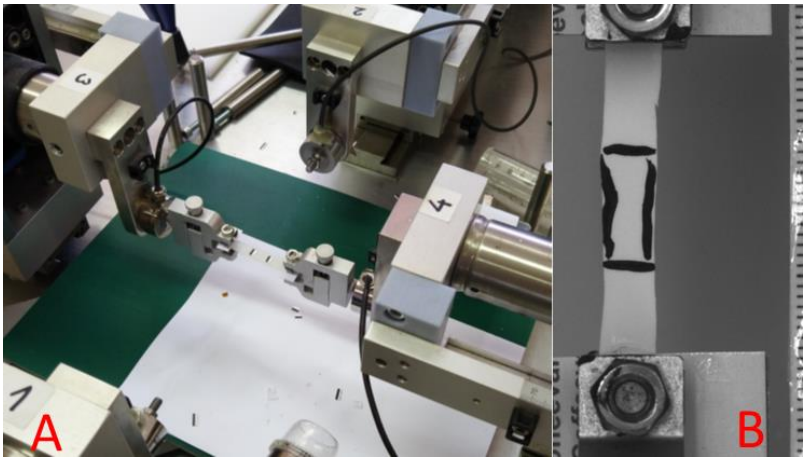

Fig. 1 Experimental setup with mounted COLL-PLCL specimen (panel A), GORE Cardiovascular patch strip (panel B).

For comparison with our artery banding material, we acquired commercially available materials from GORE (W. L. Gore & Associates, Inc., USA) that are currently used for banding purposes. These were strips prepared from GORE Preclude Pericardial Membrane (3 pieces) and GORE Cardiovascular Patch (3 pieces, Fig. 1B). Further details can be found at https://www.goremedical.com/products.

The mechanical behavior of all materials was assessed through uniaxial tensile testing using a Zwick/Roell universal testing machine (Zwick/Roell, Germany, Fig. 1A) specifically designed for testing soft tissues (blood vessels) and polymeric materials. The testing machine was equipped with electromechanical actuators with a working load range of -200 N to 200 N in compression-tension mode. In our experiments, HBM U9C +/- 25N load cells were utilized. The displacement range of the machine is from 0 mm to 140 mm, with a position resolution of 1 µm. The deformations of the specimens were measured using a built-in video extensometer consisting of a 5 Mpx uEye 3.0 CMOS camera. The applied loading rate was set to 0.5 mm/s. All data were recorded and stored on a control PC at a sampling rate of 20 Hz for subsequent post-processing.

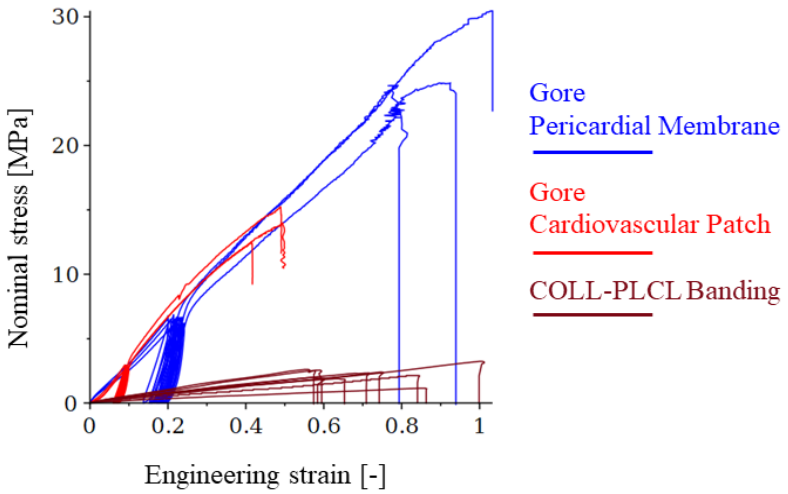

Fig. 2 Stress-strain relationships determined in uniaxial tensile tests within the primary loading (pristine material).

The mechanical response of the measured specimens was described by the nominal stress $\sigma = F/S_0$, where F is the recorded loading force and S_0 is the reference cross-sectional area of the specimens. Deformation was expressed as the engineering strain $\varepsilon = l/L - 1$. Here, L is the distance between the marks made on the surface of a specimen prior to the test, and l is this distance in the deformed state.

The mechanical properties of the COLL-PLCL material were determined in its hydrated state, with the experiment conducted in air immediately after exposing the material to a phosphate buffer solution at 37°C for 2 hours. As it was already obvious during manual (sensory) testing that the elongation at intermediate strength for the GORE material was far beyond what was expected under physiological loading (several hundred percent of the original length), and on the other hand we knew nothing about COLL-PLCL at the beginning, it was decided to use a slightly different loading scheme for each type of material. The COLL-PLCL material was tested monotonically, while the GORE materials underwent 5 loading-unloading cycles, followed by a 6th loading branch that continued until failure (refer to Fig. 2).

3 Results and discussion

Fig. 2 presents the results obtained from our experiments, which involved a total of 15 uniaxial tests (9 using COLL-PLCL strips and 6 using GORE materials). All three materials displayed an approximately linear mechanical response under primary loading. For the GORE materials, Fig. 2 illustrates the complete cyclic loading pattern. In contrast, Fig. 3 provides a detailed view of only the 1st and 5th segments of the loading branch. The cyclic loading induced a preconditioned state in the GORE materials, resulting in a slightly non-linear response that can still be effectively modeled using a linear model. Furthermore, the preconditioned GORE-Tex materials were considerably stiffer compared to their pristine state (Fig. 3).

The GORE materials exhibited higher stress at failure than the COLL-PLCL material, while the strain at failure was approximately the same (Fig. 2). Notably, the COLL-PLCL material demonstrated significantly greater compliance than the GORE materials (Figs. 2 and 4). Based on our findings, we hypothesize that the COLL-PLCL material will induce a reduced mechanobiological response to compliance-mismatch during banding procedures.

If a linear constitutive model is used to describe the material behavior, the mechanical properties can be expressed in terms of the Young's modulus of elasticity (E). Our experiments revealed that the Gore Pericardial Membrane and Gore Cardiovascular Patch exhibited a Young's modulus of E = 35.7 MPa ± 2.12 MPa and E = 33.7 MPa ± 1.76 MPa, respectively, under primary loading. After preconditioning, their response stiffened, resulting in a Young's modulus of E = 167.4 MPa ± 6.88 MPa (Pericardial membrane) and E = 119.9 MPa ± 10.9 MPa (Cardiovascular patch). On the other hand, the COLL-PLCL material demonstrated a Young's modulus of E = 3.78 MPa ± 1.02 MPa, indicating significantly greater compliance. While some may express concerns regarding this result, it is important to note that the COLL-PLCL material falls within the range of physiological properties observed in arteries, thereby facilitating the avoidance of the compliance mismatch effect [10].

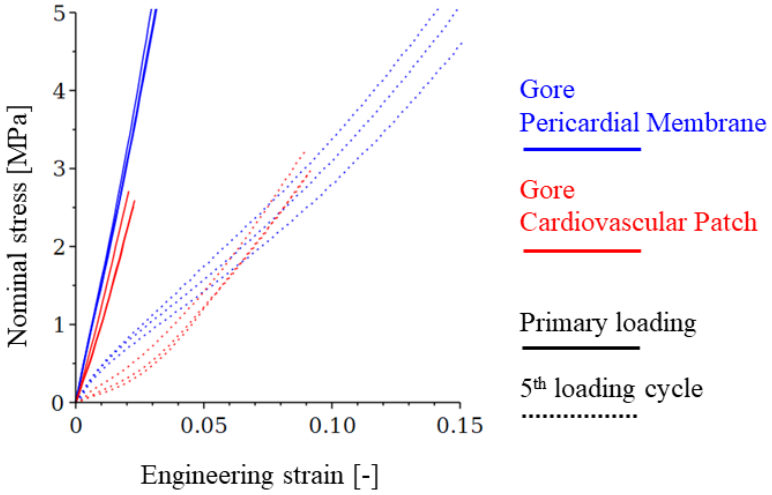

Fig. 3 Comparison of the primary loading response and 5th cycle (preconditioned).

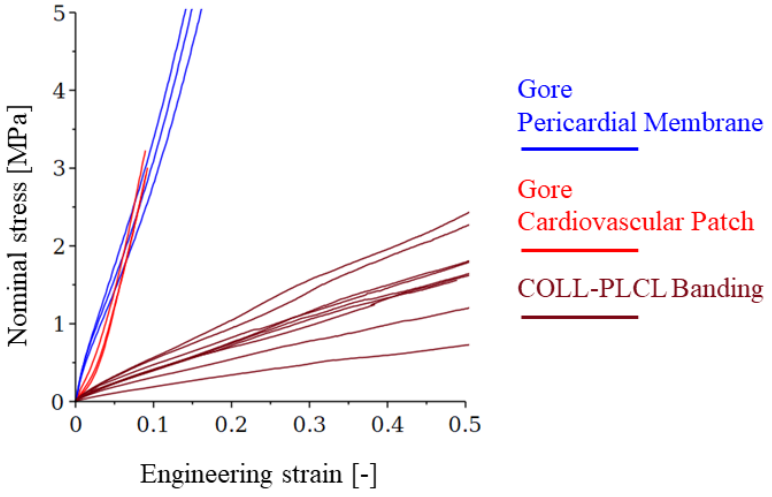

Fig. 4 Stress-strain relationships determined in uniaxial tensile tests within the primary loading of commercially available banding materials (GORE) and our COLL-PLCL composite.

Conclusions

In this study, we presented the results of our comparison of the mechanical properties between our COLL-PLCL material and two commercially available Gore materials suitable for pulmonary artery banding: Gore Pericardial Membrane and Gore Cardiovascular Patch. Uniaxial tensile tests were conducted on strips made of all three materials. The COLL-PLCL material underwent monotonic tensile testing, while the Gore materials were subjected to cyclic loading. The COLL-PLCL material was tested in its hydrated state. The results of the uniaxial tensile tests demonstrated that our COLL-PLCL banding material exhibited greater compliance compared to the GORE materials while still exhibiting sufficient strain at failure.

Acknowledgements

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