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A biodegradable material for ACL reconstruction

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Abstract

Biodegradable polyurethane urea fibers for ACL reconstruction have been produced by wet spinning. By using a short-chain polyester diol as the soft segment in the polyurethane urea the elongation-to-break of the fibers have been reduced to be below 100% instead of 400-800% for spandex fibers, the modulus is increased from 5 MPa to1 GPa and the tensile strength is increased from 0.1 N/tex to 0.4 N/tex. The composition of the polyester determines at which rate the fiber degrade. Different polyesters have been investigated to find the most suitable degradation rate for ACL application.

Introduction

The anterior cruciate ligament (ACL) is the primary stabilizer of the knee. ACL deficient knees can become unstable leading to joint degeneration and disability. Although primary surgical repair of ACL rupture with existing materials is satisfactory on short terms, there is a need for temporary ACL substitution with biological or synthetic grafts until new natural ACL has formed [1]. We have used polyester based polyurethane urea fibers to make a biodegradable material for ACL reconstruction.

Polyurethanes are block copolymers, which are composed of short alternating soft and hard blocks. They are syntesized from three basic components, a long chain diol, a diisocyanate, and a chain extender, usually a low molecular weight diol or diamine. If the chain extender is a diamine both urethane and urea linkages are present and the polyurethane is termed polyurethane urea (PUUR).

Polyurethane elastomers are an important group of products because of their high hardness for a given modulus, high abrasion and chemical resistance, excellent mechanical properties and tissue compatibility [2, 3, 4]. Another important factor is that polyurethane offers many possibilities to vary the structure and adapt to the requirements for a certain application. The isocyanate can be aromatic, cycloaliphatic or aliphatic. The long chain diol can be varied to a great extent. If polyester diols are used the PUUR becomes biodegradable by hydrolysis. By using diols with functional groups physiologically active substances can be attached to the molecule [5].

One important group of PUUR elastomers is spandex fibers. Due to its chemical structure these fibers have a reversible elongation between 400-800%. By varying the length of the soft segment, which usually are in the molecular weight range from 1000 to 3000 g/mol, the elongation can be varied [6]. The hard segments are responsible for the resetting of the molecular chain and return of fibers to their original form after mechanical deformation. The hard segments consist of short crystalline areas and have strong hydrogen bonding forces between the urethane and urea groups of neighbored molecular chains [7]. The urea groups are of great importance for the recovery of the elastic fiber and formation of strong fibers. By replacing the diamine by a diol, plastic products which cannot be used for production of elastic fibers are obtained. The reason for the difference in behavior between polymers containing urethane bonds and those containing both urethane and urea bonds have been investigated by means of crystallographic analysis.[8]. It was found that in bis-urea each carbonyl oxygen is bonded to both the N-H dipoles of the opposite urea group. The statement was confirmed by shorter heteromolecular distances in bis-urea compared to bis-urethane. This accounts for great heat stability of PUUR. The melting temperature of the hard segment is so high (230-260°C) that they cannot be melted without decomposing. Due to this no melt spinning process can be applied, thus the fiber formation must take place through dry or wet spinning.

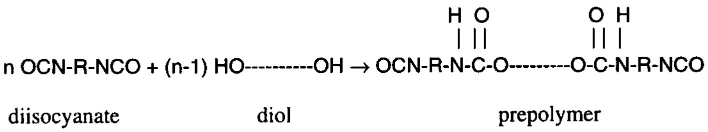
This paper shortly describes wet spinning, mechanical properties, degradation and biocompability of PUUR fibers with low elongation <100%. To obtain the low elongation it is necessary to orient the molecules as much as possible and to shorten the length of the soft segment to about 500 g/mol. However, the length reduction causes solubility problems.

Experimental

Chemistry

The polyurethane ureas were obtained by the prepolymer technique. The prepolymer is formed in the reaction of a long chain polyester in excess of diisocyanate.

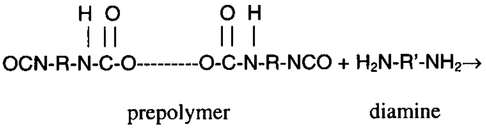
Prepolymer reaction



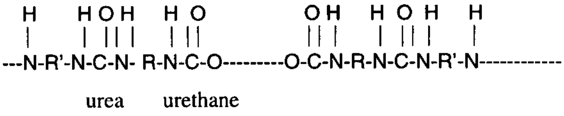
$$n\ OCN\text{-}R\text{-}NCO + (n\text{-}1)\ HO\text{----------}OH \rightarrow OCN\text{-}R\text{-}\overset{\overset{H}{|}}{N}\text{-}\overset{\overset{O}{\|}}{C}\text{-}O\text{---------}O\text{-}\overset{\overset{O}{\|}}{C}\text{-}\overset{\overset{H}{|}}{N}\text{-}R\text{-}NCO$$

The prepolymer was dissolved in DMF and chain-extended with an aliphatic diamine.

Chain extension



$$OCN\text{-}R\text{-}\overset{\overset{H}{|}}{N}\text{-}\overset{\overset{O}{\|}}{C}\text{-}O\text{---------}O\text{-}\overset{\overset{O}{\|}}{C}\text{-}\overset{\overset{H}{|}}{N}\text{-}R\text{-}NCO + H_2N\text{-}R'\text{-}NH_2 \rightarrow$$



$$\text{---}\overset{\overset{H}{|}}{N}\text{-}R'\text{-}\overset{\overset{H}{|}}{N}\text{-}\overset{\overset{O}{\|}}{C}\text{-}\overset{\overset{H}{|}}{N}\text{-}\ R\text{-}\overset{\overset{H}{|}}{N}\text{-}\overset{\overset{O}{\|}}{C}\text{-}O\text{---------}O\text{-}\overset{\overset{O}{\|}}{C}\text{-}\overset{\overset{H}{|}}{N}\text{-}R\text{-}\overset{\overset{H}{|}}{N}\text{-}\overset{\overset{O}{\|}}{C}\text{-}\overset{\overset{H}{|}}{N}\text{-}R'\text{-}\overset{\overset{H}{|}}{N}\text{------------}$$

Wet spinning

The polymer solution (15 weight %) produced in the chain extension reaction was extruded through a spinneret (120 holes, 60 µm in diameter) into a precipitation bath of water in which DMF is soluble but the polymer is not. In a second bath the fibers were drawn 500-1500 % before they were collected on a final take up unit.

Degradation

Samples of band made of PUUR fibers were placed in vials with 0.06 M phosphate buffer solution pH= 7.4 (Na_2HPO_4 and NaH_2PO_4 in 0.9% NaCl). The sealed vials were placed in a 80°C thermostated oven. At intervals the vials were opened and the bands were tensile tested using a electronic tensile tester with constant rate of extension.

Results and Discussion

Wet spinning

The strength of the fiber is dependent on the molecular weight, crystallinity and on the orientation of the molecular chains. The strength of a fiber can be increased 2-3 times by increasing the drawing ratio (Fig 1). The possibility to draw the fiber depends on the viscosity of the solution which in turn depend on the concentration of the solution, molecular weight and degree of physical crosslinking by hydrogen bonding. The degree of hydrogen bonding depends on the temperature, polymer concentration and the fraction of the hard segments [9].

Mechanical properties

To meet the demands of a material suitable for ACL reconstruction both structure and function should duplicate that of mature ACL. The ACL has a tensile strength of about 38 MPa in humans and a viscoelasticy that allows it to elongate to 25 % of its normal length before plastic deformation occurs [10, 11]. In normal use of flexion and extension the ACL

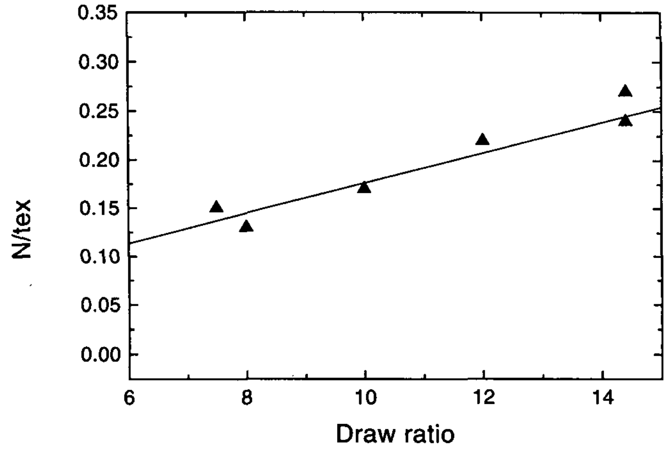


Figure 1 Stress- draw ratio curve of a PCL 530 based PUUR fiber.

goes through 14 % elongation and returns to its resting length without producing any permanent elongation. The fibers formed in the wet spinning process had a strength of up to 0.4 N/tex and elongation to break less than 40%.(Fig 2 a). The fibers were woven into a band consisting of 100 fibers, the band has a tensile strength of 90 MPa and elongation to break of 90% (Fig 2b).

Degradation

Degradation of PUUR takes place by hydrolysis of the polyester. The time for degradation can be altered by changing the composition of the polyester. To get a first indication of degradation rates of different polyesters used in the PUUR fibers, accelerated degradation tests were carried out at 80°C at pH 7.4. (Fig 3). The fastest degradation rate was obtained with polydiethylenadipate diol and the slowest with polycaprolactone diol.

Biocompability

The biocompability has been studied in a rabbit model where the natural ACL has been replaced by a synthetic PUUR ligament. After 6 months the synthetic ligament was well integrated and showed excellent biocompability [12].

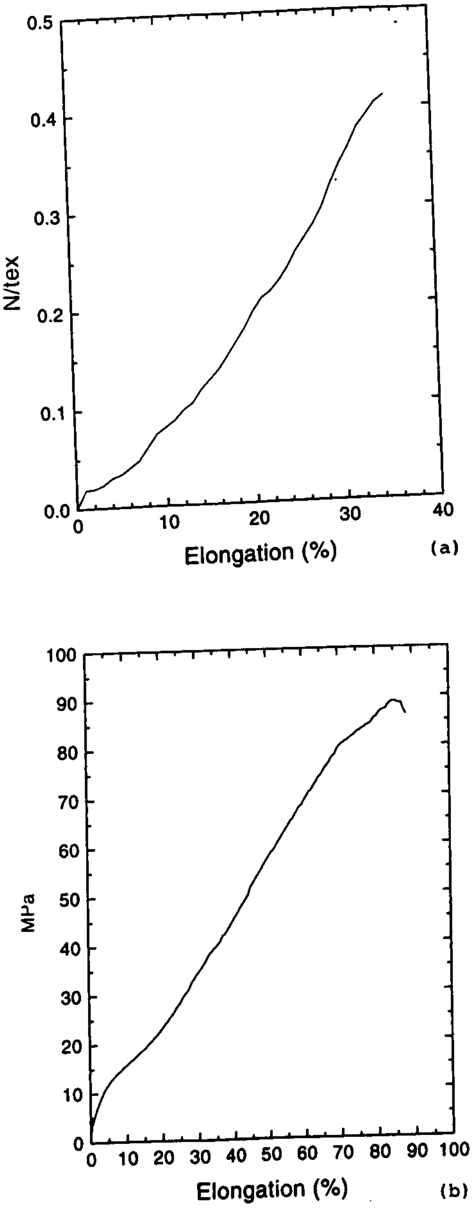


Figure 2 a) Stress- strain curve of a PCL 530 based PUUR fiber

b)Stress- strain curve of a band made of 100 PUUR fibers

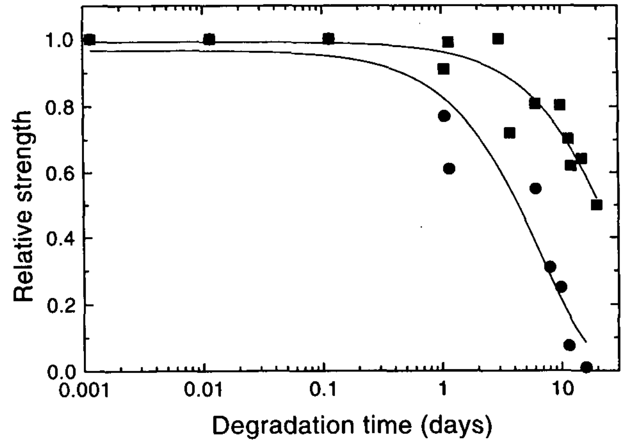


Figure 3 Relative strength of a band made of 100 PUUR fibers as a function of hydrolytic degradation in a buffered solution pH= 7.4 at 80°C. ■ PCL 530 based PUUR ● PDEA 550 based PUUR.

Conclusions

Strong hydrogen bonding between urethane and urea groups of adjacent molecular chains make it possible to form strong fibers, which completely recover after 30% elongation. Combination of short chain polyester diols and strong orientation of the molecules by wet spinning reduces the elongation to break of PUUR fibers to less than 100%. Polyesters degrade by hydrolysis and the time for degradation can easily be altered by changing the composition of the polyester. These properties make the fibers made of PUUR suitable for temporary synthetic ligaments. In a rabbit model it has been shown that PUUR ligaments are well integrated and show excellent biocompability after 6 months.

Acknowledgment

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