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Research paper

A biomimetic approach for designing stent-graft structures: Caterpillar cuticle as design model

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ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form
9 October 2013
Accepted 13 October 2013
Available online 25 October 2013

Keywords:
Biomimetics
Stent-graft
Compliance
Hydroskeleton
Caterpillar cuticle
Migration

ABSTRACT

Stent-graft (SG) induced biomechanical mismatch at the aortic repair site forms the major reason behind postoperative hemodynamic complications. These complications arise from mismatched radial compliance and stiffness property of repair device relative to native aortic mechanics. The inability of an exoskeleton SG design (an externally stented rigid polyester graft) to achieve optimum balance between structural robustness and flexibility constrains its biomechanical performance limits. Therefore, a new SG design capable of dynamically controlling its stiffness and flexibility has been proposed in this study. The new design is adopted from the segmented hydroskeleton structure of a caterpillar cuticle and comprises of high performance polymeric filaments constructed in a segmented knit architecture. Initially, conceptual design models of caterpillar and SG were developed and later translated into an experimental SG prototype. The in-vitro biomechanical evaluation (compliance, bending moment, migration intensity, and viscoelasticity) revealed significantly better performance of hydroskeleton structure than a commercial SG device (Zenith™ Flex SG) and woven Dacron® graft-prosthesis. Structural segmentation improved the biomechanical behaviour of new SG by inducing a three dimensional volumetric expansion property when the SG was subjected to hoop stresses. Interestingly, this behaviour matches the orthotropic elastic property of native aorta and hence proposes segmented hydroskeleton structures as promising design approach for future aortic repair devices.

1. Introduction

The worldwide increase in aortic diseases (aneurysm and dissection) has led to several experimental investigations in developing advanced stent-graft (SG) devices (Jackson and Carpenter, 2009). However, apart from improvements in basic components (stent material, graft fabric, fixation technique etc.), the prevalent biomechanical issues have remained

Abbreviations: SG, Stent-graft; Z-SG, Zenith™ Flex stent-graft; CaT-SG, Caterpillar stent-graft; EVAR, Endovascular aneurysm repair; ISM, Intersegmental membrane; HS, Hard segment; SS, Soft segment; PET, Polyethylene-terephthalate; PU, Polyurethane

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http://dx.doi.org/10.1016/j.jmbbm.2013.10.014

largely unaddressed in every new device (Moore, 2009; Raghavan et al., 2005). A generalised scheme of SG design is based on exoskeleton design concept, which involves integration of metallic frame structure (stainless steel or nitinol) with an inelastic tubular fabric graft (polyester Dacron® or polytetrafluoroethylene). However, this integration markedly inhibits circumferential and longitudinal flexibility of the final device structure. Woven Dacron® grafts are thin wall tubular fabric structures used in open surgical repair, which is still a gold standard procedure for treating aortic aneurysms (Piazza and Ricotta Ii, 2012). Despite that, there has been no significant design improvement in woven grafts from the basic crimped configuration introduced decades ago (Hajjaji et al., 2012; Pourdeyhimi, 1986).

An unmatched compliance between stiff SG and elastic aorta can trigger local hemodynamic variations after device implantation (Ioannou et al., 2003; Lantelme et al., 2009). The stented vessel loses its elasticity and thus amplifies systolic blood pressure (Obrien et al., 2008), which is a well-recognized risk factor for pathophysiological events of stroke, coronary artery disease, and myocardial infarction (Safar et al., 2011). Migration is yet another SG related complication and a major reason behind post-EVAR reinterventions. The variation in aneurysm neck diameter (8.4–13.3%) during cardiac cycle can exceed the maximum achievable diameter of a non-compliant SG (van Herwaarden et al., 2006) and thus disengage it from the fixation site (Cao et al., 2002; Volodos et al., 2003). Also, a longitudinally rigid SG is incapable of absorbing pulsatile drag forces within the structure itself (Akin et al., 2009; Hoang et al., 2009). Consequently, the lateral displacement forces in the main-body length are transmitted as migration forces on the terminal fixation sites (Figueroa et al., 2009; Mohan et al., 2002; Rafii et al., 2008; Volodos et al., 2005). Additionally, the stiffness of stent frame prevents the graft to appose adequately with the aneurysm neck wall, specifically in thoracic aorta, which ultimately leads to type-I endoleaks and device migration (Canaud et al., 2010; Nienaber et al., 2007; Ueda et al., 2010). Longitudinal shortening (Harris et al., 1999) and lengthening (Corbett et al., 2008; Vos et al., 2003) of aneurysm post-EVAR has also been reported to cause displacement at fixation sites, as rigid SGs are incapable of responding actively to such dimensional changes. On the other hand, woven surgical grafts do not suffer from migration and flexibility problems, because they are sutured firmly to the aortic vessel. However, their poor circumferential elasticity remains a hemodynamic issue despite decades of clinical use (Kim et al., 1995; Morita et al., 2002, 1991; Tremblay et al., 2009). Principally, the biomechanical criterion for an ideal aortic vessel substitute appears too stringent for conventional device designs to satisfy. Commercial implant devices can only serve the basic function of blood transmission and lack the major ability of aorta to assist heart in its synchronous pumping action. Clearly, successful design of an ideal aortic implant requires innovative design concepts.

According to Krogh's principle, specific animal species can assist in solving multitude of problems in human physiology (Burggren, 1999). Also, the ability of biological structures to exhibit extraordinary mechanical properties using limited structural components has always attracted the attention of material researchers (Meyers et al., 2011; Taylor, 2011). An example of such structural design is observed in invertebrates or arthropods. In the absence of a vertebral column, arthropods can solve the critical problem of body structural support (stiffness and robustness) and locomotion (elasticity and flexibility) in a simple manner (Vincent and Wegst, 2004). The structural geometry of an arthropod skin (or cuticle) is composed of hard (or sclerites) and soft (or intersegmental membrane) segments (Vincent and Wegst, 2004). Hard sclerites provide a protective covering to the internal body organs while being connected to each other via elastic intersegmental membranes (ISM)s. The ISMs allow multiple sclerite segments to bend and slide against each other during bending, abdomen or gut filling, and locomotion (Hepburn and Chandler, 1976; Neville, 1975). Soft-bodied arthropods like caterpillars work on a hydroskeleton principle which utilises cuticle segmentation (sclerites and ISMs) and haemolymph pressures together to control the body stiffness (Hepburn and Chandler, 1976; Lin et al., 2011). Interestingly, this behaviour is analogous to stiffness control principle of aorta which uses combination of elastin and collagen fibres embedded in its extracellular matrix (Wagenseil and Mecham, 2012). A caterpillar cuticle and aorta thus appear to fulfil similar performance requirements (robustness, flexibility, and radial distension) by utilising the combined action of an elastic (caterpillar-ISM and aorta-elastin) and a stiff (caterpillar-sclerites and aorta-collagen) structural component. Therefore, the concept of translating caterpillar's hydroskeleton design to SG devices appears much closer to realistic aortic mechanics.

2. Material and methods

2.1. Conceptual SG model

Monarch caterpillar (*Danaus plexippus*) was selected as the design model due to its distinctive cuticle coloration. Mechanical characterisation of monarch caterpillar reveals structural anisotropy in its cuticle (Fig. 1a). The top (or dorsal) surface of cuticle is less elastic than bottom (or ventral) surface. Similarly, the longitudinal stiffness of thoracic section is higher than the abdominal section. This multi-axial anisotropy can be explained using a spring-mass model (Fig. 1b). The cuticle stiffness can be sequentially ordered as $k_{ad}=k_{td}>k_{tv}>k_{av}$, where k_{ad}, k_{td}, k_{tv}, and k_{av} denote longitudinal stiffness constants of dorsal-abdominal, dorsal-thoracic, ventral-thoracic, and ventral-abdominal spring elements, respectively. The parallel combination of k_{ad} with k_{av} and k_{td} with k_{tv} results in equivalent spring constants of $k_{ad}+k_{av}$ and $k_{td}+k_{tv}$, respectively. Based on this combination, cuticle exhibits viscoelastic behaviour during locomotion when averaged over the complete body circumference. In other words, combinations $k_{ad}+k_{av}$ and $k_{td}+k_{tv}$ represent collagen+elastin fibre network of aortic wall at a macroscopic scale. The series combination of k_{tv} and k_{av} produces an equivalent spring constant of $k_{eq}=(k_{tv}\times k_{av})/(k_{tv}+k_{av})$. The numerical value of k_{eq} is a direct indicator of degree of locomotion wave damping induced by longitudinal anisotropy of the cuticle. These relations explain the sophistication