Numerical Analysis of Knitted Nitinol Meshes as External Saphenous Vein Support

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PURPOSE

Investigation of the mechanical behaviour of knitted Nitinol meshes as potential external vein graft reinforcement to address the mechanical mismatch between graft and host vessel - one of the main factors for graft failure.

METHODS

FE Models: Tubular meshes (ID: 3.34 mm) of two knit designs (even vs. uneven loop pairs, see Fig. 1) and three Nitinol wire thicknesses (t_w: 0.05, 0.064 and 0.075 mm) were represented in Abaqus CAE 6.4-5 (Abaqus Inc., Providence, RI, USA) as partial models utilizing geometrical repeatability of single-loop unit cells (Fig. 2). The element number of the tri-linear brick FE meshes varied between 25,000 and 64,000 depending on loop geometry, wire thickness, and partitioning. The FE mesh density was 4 and 6-8 elements through the wire thickness in loop regions with low and high curvature, respectively. Boundary conditions, element type and mesh density were verified through comparative analyses with parameter variations. An axis-symmetric radial displacement was applied to the mesh using a user-defined cylindrical expander surface (Compaq Visual Fortran 6.6A, Compaq Computer Corporation, Houston, TX, USA). Softened contact was defined between expander surface and wires, and between wires at cross-overs. The superelastic Nitinol was modelled as Abaqus shape memory alloy user material. The analysis was executed in two steps: 1) Establishment of contact between expander and loop assembly, 2) Prescription of radial displacement (dilation) of expander and loop assembly.

Nitinol Material Characterisation: The mechanical properties of Nitinol wires were obtained from uni-axial tensile tests of samples with l = 100 mm at 37ºC (H_2O dist). The test protocol comprised: a) pre-conditioning cycling within the recoverable strain region (n_c: 99, ε_{min}: 1.0%, ε_{max}: 4.5%), b) two loading cycles ε_{min}: 1.0% - ε_{max}: 8.0%, c) final loading ε_{min}: 1.0% - ε_{max}: 20.0% (cross-head speed: 38 mm/min).

Data Analysis: Maximum principal stress and strain at integration points and the reaction force of the mesh onto the expander surface were captured at each time increment during the analyses. The diametric vascular compliance, C_D, was calculated from two pairs of luminal pressure, P_i, and prescribed internal mesh radius, R_i, for the diastolic-systolic pressure range of 80-120 mmHg. The luminal pressure could not be accessed directly (not used as loading parameter and not available as result). The pressure was derived from the reaction force, $F_{eff,i}$, of the mesh onto the expander and the expander surface area at each time increment, i, assuming an even pressure distribution over the non-deformable expander surface:

$$P_i = \frac{F_{eff,i}}{LR_i\sqrt{2-2\cos\theta}}$$

with L: length of expander in longitudinal mesh direction, and θ: angle subtending the expander surface.

RESULTS

Radial compliance of the Nitinol meshes at 80-120mmHg was predicted to be 2.5, 0.9 and 0.6%/100mmHg (even loop design; t_w: 0.05, 0.064, 0.075mm) and 1.2, 0.5 and 0.5%/100mmHg (uneven loop design; t_w: 0.05, 0.064, 0.075mm). Maximum stresses at 120mmHg of 268, 132, and 91MPa were observed in the even loop knit of 0.05, 0.064 and 0.075mm wire thickness. The uneven loop knits exhibited lower stress levels with maxima reaching 65.3, 63.6 and 87.9% of stresses in the even loop design (t_w: 0.05, 0.0635, 0.075mm). The maximum strain of 0.7% was predicted at 120mmHg. The distribution of principal stresses and strains is shown in Fig. 3.

Figure 4 illustrates the change in the equivalent luminal pressure with versus inner mesh diameter. For both loop design, the pressure increased more rapidly with mesh dilation as the wire thickness increased. For the even loop mesh with 0.05 mm wire thickness, the pressure increased steadily with mesh diameter from 0 mmHg, whereas all other models displayed a slightly different behavior; a similar initial pressure change irrespective wire thickness up to ca. 10 mmHg, above which the difference in wire thickness came into effect. The diameter increase at the transition at ca. 10 mmHg varied between 0.2 and 1.6% for the different meshes.

CONCLUSION

The maximum stress level remained 45% below the stress initiating the Austenite-Martensite phase transformation during loading (σ_L = 483 MPa). The maximum strain remained un-critical considering a typical high-cycle recoverable strain of Nitinol of 2%. These margins may allow for further design optimisation which, however, needs to consider that peak blood pressure exceeds 120mmHg.

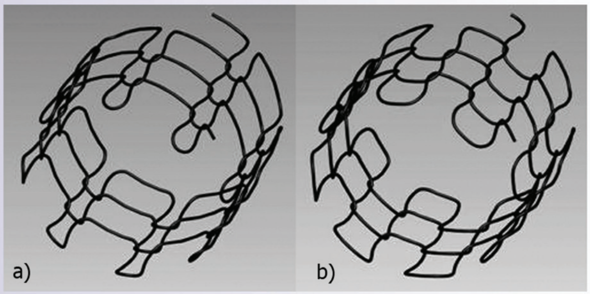

Fig 1. Schematics of tubular knitted meshes with uneven (a) and even (b) loop design.

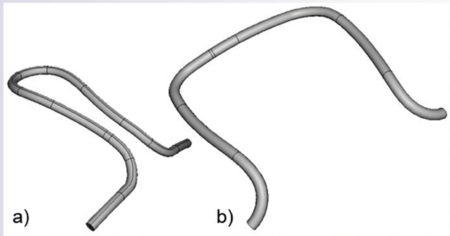

Fig 2. Geometry of a single loop representing a 45 deg section of the mesh. a) Narrow loop, uneven loop geometry. b) Wide loop, uneven loop geometry.

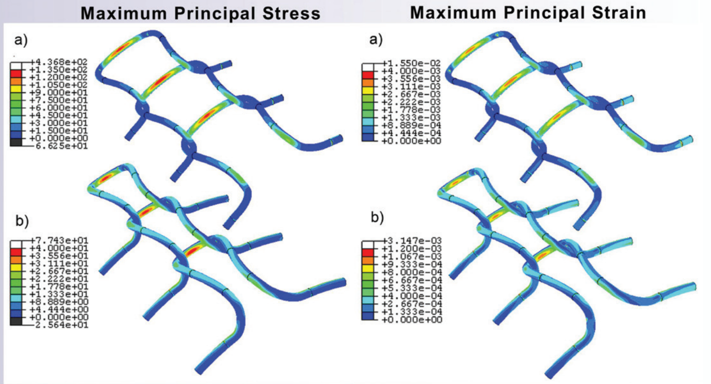

Fig 3. Contour plots maximum principal stress and strain in models with 0.0635 mm wire thickness: a) even loops, b) uneven loops.

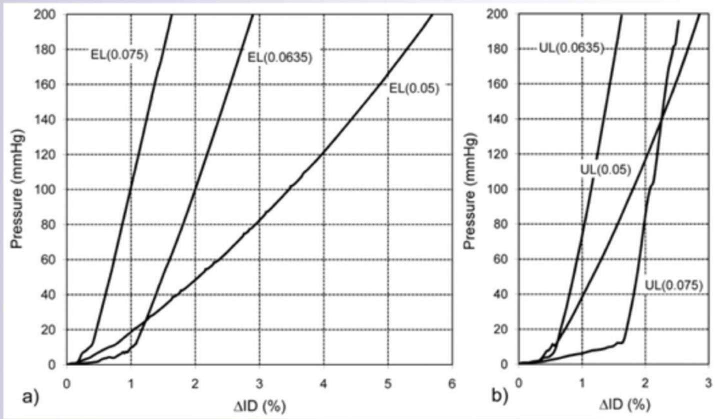

Fig 4. Luminal pressure vs. change in internal diameter of Nitinol mesh internal diameter for Nitinol wire thickness of 0.05, 0.0635, and 0.075 mm: a) Even loop geometry, b) Uneven loop geometry.