In vitro strain measurements of stent-artery interactions using 3D digital image correlation method

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Abstract
In the present work, 3D digital image correlation has been employed *in vitro* to evaluate the strain imposed by a stent on the surface of a porcine artery. The aim of this study was to dynamically evaluate the local strain at the distal end of the stent during the so-called dogboning phase, which may contribute to the degree of in-stent restenosis. A localised region of strain of approximately 30% was observed in this phase, which suggested an asymmetrical balloon unfolding and stent deployment. Future studies will investigate the stent expansion behaviour along the whole stent length and use these experimental findings to validate numerical models of stent-artery interactions.

Introduction

Balloon angioplasty with stenting is an effective procedure to widen narrowed blood vessels and restore blood flow within them. However, non-uniform transient expansion of the balloon-stent system may induce injury to the vessel wall, leading to in-stent restenosis [1]. Experimental measurements of strain on the vessel surface during stenting can provide valuable insight into stent-artery interaction behaviour and validate numerical models of stent expansion. In our previous study [2], we demonstrated that the errors in reconstructing strain in a porcine artery using 3D digital image correlation (3D-DIC) method were acceptable for the expected magnitude of deformation of the vessel [3]. Therefore, in the current work, we applied the 3D-DIC technique to measure the strain in a porcine artery during *in vitro* deployment of a stent. Specifically, the aim of this study was to report the localised, detailed characterisation of strain on the arterial wall during the dogboning phase, which may be responsible for vessel damage at the ends of the stented region.

Methods and Materials

A porcine carotid artery obtained from a local slaughterhouse was excised (inner diameter of 3.5 mm, wall thickness of 1.5 mm and length of 40 mm) and placed in the experimental setup with both ends clamped to two connectors, as shown in Fig. 1. Afterwards, a speckle pattern for DIC measurements was created to the sample surface, as previously described [4–5]. Firstly, a blue dye (methylene blue, Sigma-Aldrich, UK) was applied on the artery surface and successively white speckles (Com-Art, Iwata, UK) were sprayed with an airbrush (HP-CH, Iwata, UK). A balloon-stent tipped catheter with a stent (4 mm diameter, 25 length, Biotronik, Germany) was inserted through the artery and deployed using an inflation device (Encore™ 26, Boston Scientific, USA). The balloon was inflated for approximately 30 s up to 0.6 MPa (nominal pressure). Two digital CCD cameras (1024 × 768 pixels, 8-bit, Point Grey, Inc., Canada) with 25 mm lenses (Comar Optics, UK) were arranged as a calibrated, synchronised stereo system to capture image pairs during stent deployment. The dimensions of the field of view of the cameras were approximately 40 mm × 30 mm, thus, magnification and image resolution were 0.12 and 39 µm/pixels, respectively. A region of interest (ROI) of roughly 21 × 3 mm on the artery surface was selected for the DIC analysis that was carried out using Ncorr [6]. DIC parameters subset and step size were 33 pixels and 9 pixels, respectively, which guaranteed a good spatial resolution as well as an acceptable strain uncertainty for the type of deformations measured (less than 2% [3]). Green-Lagrange strains were computed between the reconstructed deformed meshes over 672 triangular facets assuming deformation to be homogenous over each element [3] using custom Matlab codes (Mathworks, USA).

Results

Fig. 2 depicts the 3D reconstructed artery surface with a strain colour map at the maximum of the dogboning extent. The dynamic strain behaviour of a reference point P during the dogboning phase is shown in Fig. 3. Strain variation along the transverse direction of the sample at the end of the dogboning phase is illustrated in Fig. 4. Strain components were plotted together with error bars representing the estimated strain uncertainty (~2%). The results show the variation in Ey, which is oriented in the circumferential direction based on the reconstructed coordinate system.

Figure 1. Experimental setup showing porcine carotid artery prior to stent deployment.

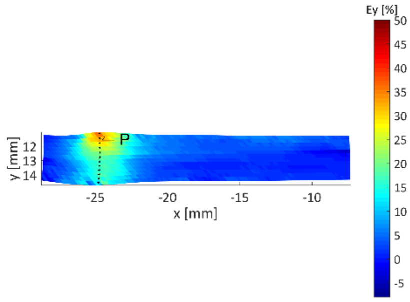

Figure 2. Reconstructed artery surface with the strain (Ey) colour map at the maximum extent of dogboning.

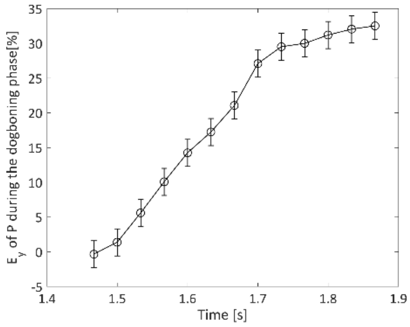

Figure 3. Strain (Ey) behaviour of the reference point P marked in Fig. 2 during the dogboning phase.

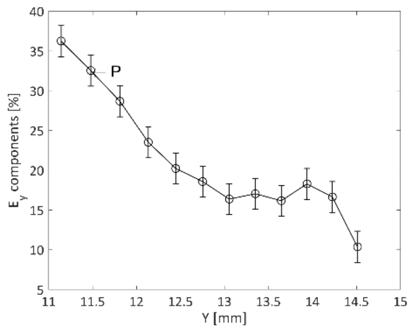

Figure 4. Strain (Ey) variation along the dotted line in Fig. 2

Discussion and conclusion

In this work, the dynamic strains generated on the artery surface following a stent expansion have been quantified during *in vitro* experimental tests. Particular attention has been paid to strain assessment during the dogboning phase. Strain uncertainties evaluated through a zero-strain test were below 2% and acceptable for the magnitude of deformations measured. Results show a highly localised strain of approximately 30% in the distal region of the stent, which may be related to vessel prolapse between the stent struts. This work shows the potential of 3D-DIC in capturing localised strain variations on the vessel surface during stent placement, which can be used to validate computational models of stent-artery interactions for future application to improve stents designs.

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