# 3D shape and full-field strain measurement in a coronary artery using 3D-DIC

P. Ferraiuoli[1,2,a], J.W. Fenner[1,2], A.J. Narracott[1,2]

[1]Mathematical Modelling in Medicine Group, IICD Department, University of Sheffield, UK

[2]Insigneo Institute for in silico medicine, University of Sheffield, UK

Email: p.ferraiuoli@sheffield.ac.uk

**Abstract**

In the present work, three dimensional digital image correlation (3D-DIC) has been investigated to reconstruct the 3D shape and full-field strain of a porcine coronary artery. Methylene blue has been applied for the first time to a coronary artery surface to enhance the contrast of the speckle pattern and reduce reflection issues common with soft tissue and cylindrical geometries. The mean uncertainty of DIC strain measurements evaluated under rigid body motion (RBM) conditions were less than 0.7%, with a standard deviation ~ 3%. This demonstrates potential of this approach to measure large deformations of arterial tissues at small length scales.

**Introduction**

Percutaneous coronary intervention (PCI) is a medical procedure to treat coronary heart disease, which consists in the expansion of either a balloon (*angioplasty*) or a small mesh tube (*stent*), to widen the narrow lumen of the artery and restore normal blood flow. However, the strain induced may cause injuries to the artery walls resulting in vessel narrowing *(in-stent restenosis).* Therefore, monitoring of shape and strain fields on the coronary artery surface during *ex vivo* stent expansion provides insight into vessel wall injury mechanisms towards improved stent design. Digital image correlation (DIC) can be used to measure shape and deformation of biological tissues [1]. More importantly, the DIC method combined with stereo-imaging can provide full-field surface strain measurements in three dimensions (3D-DIC) at small length scales such as that of the coronary artery [2]. The present work presents the use of a stereo camera system coupled with the DIC method to reconstruct the surface shape of a porcine coronary artery. In addition, rigid body motion (RBM) tests reports the ability of 3D-DIC to reconstruct the translated surface of the artery in the 3D space as well as the baseline strain uncertainty associated with the current system [3].

**Methods and materials**

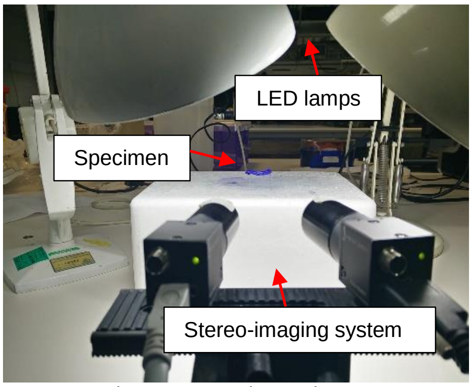



Figure 1. Experimental setup

Fig. 1 describes the experimental setup. The coronary artery was removed from a porcine heart collected from a local slaughterhouse. The speckle pattern on the specimen surface was created in two steps: firstly, the surface of the sample was coated with a 1µL solution of methylene blue (Sigma-Aldrich) [4] providing a dark background to enhance the contrast of the pattern; then a white water-based acrylic paint was sprayed on the sample surface using an airbrush (HP-CH, Iwata). Finally, the specimen was placed over two pins within the field of view (FOV) of the stereo-imaging system. In addition, two LED lamps were used to improve the lighting. Two digital CCD Point Grey cameras with an image resolution of 1028×768 pixels were employed to capture stereo images of the artery. Cameras were set at high magnification (M ≈ 0.4) with C-mount 40 mm focal length lenses. The high magnification of the cameras gave a FOV around 13×10 mm yielding a resolution of roughly 13 µm/pixels.

Intrinsic and extrinsic cameras parameters were computed using the Matlab Stereo Camera Calibrator application and fifteen images of a chequerboard. DIC analysis was performed with Ncorr [5]. The extension to 3D-DIC was achieved using the stereo-calibration data and the triangulation process through the implementation of Matlab routines. The specimen was subject to a rigid translation to two different positions ($P_1$, $P_2$) and DIC was carried out between the stereo images captured in the reference and translated positions of the sample. The region of interest (ROI) selected for the DIC analysis is shown in Fig. 2. Qualitative measurements of the speckle size supported the decision to select subset size greater than 30 pixels. Three different subset size windows (31×31, 51×51, and 71×71 pixels) were used, while the step size was maintained at 5 pixels. Green-Lagrange strain values were computed at $P_1$ and $P_2$ using a Matlab routine.

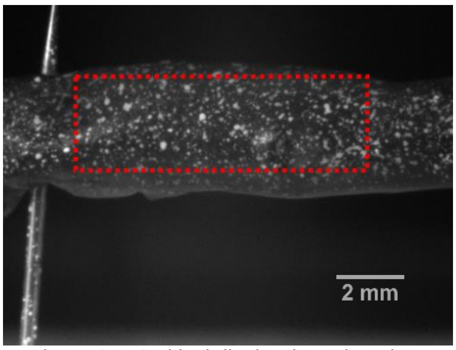
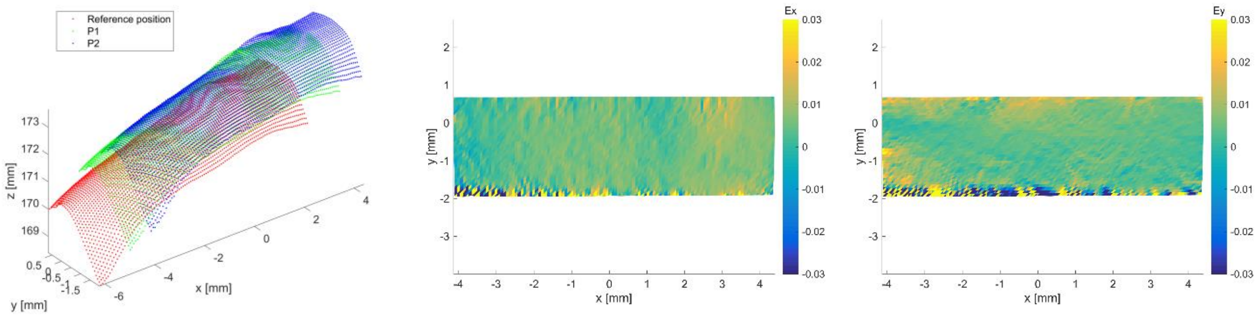



Figure 2. ROI (dash line) selected on the coronary artery for the DIC analysis

## Results




(a) (b) (c)

Figure 3. (a) 3D reconstruction of the the artery surface in the reference position, $P_1$ and $P_2$. Full-field surface strain in the longitudinal (b) and tranverse (c) directions at $P_2$ (projection in the x-y plane). All results obtained with a 51×51 pixel subset.

Table 1. Mean and standard deviation of the strain components along the longitudinal (Ex) and transverse (Ey) directions of the artery at $P_1$ and $P_2$ for the three different DIC subset sizes

| | Ex (%) | | | | Ey (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | $P_1$ | | $P_2$ | | $P_1$ | | $P_2$ | |
| Subset size [pixels] | Mean | Std dev. | Mean | Std dev. | Mean | Std dev. | Mean | Std dev. |
| 31×31 | 0.8 | 4.6 | 0.8 | 5.0 | 1.1 | 6.0 | 0.9 | 4.9 |
| 51×51 | 0.6 | 1.5 | 0.6 | 2.5 | 0.7 | 2.2 | 0.5 | 2.2 |
| 71×71 | 0.6 | 2.1 | 0.6 | 2.3 | 0.7 | 2.8 | 0.6 | 2.9 |

Fig. 3(a) shows the 3D reconstruction of the surface of the artery in the reference position and in the two translated positions after the RBM tests. Mean and standard deviation of the Green-Lagrange strain values on the sample surface at $P_1$ and $P_2$ were computed along the longitudinal (Ex) and transverse (Ey) directions of the artery and reported in Table 1. Full-field surface measurements of the strain components at $P_2$ are shown in Fig. 3(b)-(c).

## Discussions and conclusion

The largest error and standard deviation of the strain values were obtained with the smallest subset size, consistent with the literature [2,3]. When increasing the subset size, noticeable reductions of the standard deviation values were observed. Additionally from Table 1, it is clear that selecting a subset size greater than 51×51 pixels did not introduce any significant change in terms of strain results. Therefore, in the current work the medium subset size represented the more appropriate choice. A smaller subset size is always desirable since it promotes more reliable strain measurements with the DIC method [2]. The mean of strain components after rigid translation of the sample were less than 0.7% although a relatively large standard deviation (< 3%) was observed. Fig. 3(b)-(c) illustrate the source of the large standard deviation of the strain components with higher strain values obtained close to the edge of the ROI where correlation accuracy may become poor due to the curvature of the vessel. In conclusion, the results are encouraging for use of 3D-DIC to reconstruct the surface strain field of coronary arteries with uncertainties acceptable to measure large deformations of the arterial tissues [6]. In addition, the use of methylene blue enhanced the contrast of the speckle pattern and drastically reduced the reflection issues typical of cardiovascular soft tissues and cylindrical shape surface.

## Acknowledgements


This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska Curie grant agreement No 642612.


## References


[1] M. Palanca, G. Tozzi, and L. Cristofolini, “The use of digital image correlation in the biomechanical area: a review,” *Int. Biomech.*, vol. 3, no. 1, pp. 1–21, Jan. 2016.

[2] M. A. Sutton, J.-J. Orteu, and H. Schreier, *Image Correlation for Shape, Motion and Deformation Measurements*. Boston, MA: Springer US, 2009.

[3] H. Haddadi and S. Belhabib, “Use of rigid-body motion for the investigation and estimation of the measurement errors related to digital image correlation technique,” *Opt. Lasers Eng.*, vol. 46, no. 2, pp. 185–196, 2008.

[4] G. Lionello, C. Sirieix, and M. Baleani, “An effective procedure to create a speckle pattern on biological soft tissue for digital image correlation measurements,” *J. Mech. Behav. Biomed. Mater.*, vol. 39, pp. 1–8, Nov. 2014.

[5] J. Blaber, B. Adair, and A. Antoniou, “Ncorr: Open-Source 2D Digital Image Correlation Matlab Software,” *Exp. Mech.*, vol. 55, no. 6, pp. 1105–1122, Jul. 2015.

[6] K. Genovese, Y. U. Lee, and J. D. Humphrey, “Novel optical system for in vitro quantification of full surface strain fields in small arteries: I. Theory and design,” *Comput. Methods Biomech. Biomed. Engin.*, vol. 14, no. 3, pp. 213–225, Mar. 2011.