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Commentary

Individual Patient-specific Planning of Minimally Invasive Transcatheter Intervention for Heart Valve Disease

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One million individuals aged 65 and over are affected by heart valve disease in the UK. Given the rapidly ageing population, the prevalence of clinically significant valve disease is projected to double by 2050 [1]. These forecasts carry serious implications for healthcare providers tasked with addressing the needs of this growing cohort of patients, who are mostly too old and frail for open-heart surgery.

Aortic stenosis and mitral regurgitation are the most frequent valve conditions. Both share an adverse prognosis and a lack of effective medical therapies. In response, there have been groundbreaking developments in minimally-invasive transcatheter technology to implant bioprosthetic devices in the failing native valve. Transcatheter aortic valve implantation (TAVI) is already established as an alternative to conventional surgery for inoperable and high/intermediate-risk patients, and trials in low-risk cohorts are currently being concluded. Within 5 years, TAVI is likely to become the default treatment for the majority of patients with aortic stenosis.

Based upon this paradigm shift, attention is now firmly focused on transcatheter mitral valve replacement (TMVR). Unlike TAVI, TMVR requires sophisticated engineering solutions to address the unique challenges posed by the heterogeneity and complexity of mitral valve anatomy and physiology, and its interaction with the left ventricle. Specific concerns include difficulty in anchoring the device to the deformed mitral annulus (with risk of valve migration or paravalvular leak), and potential for left ventricular outflow tract (LVOT) obstruction by the implanted valve (with risk of refractory heart failure and late mortality) [2,3]. The latter is the most important and independent predictor of 30-day and 1-year mortality in patients with mitral annular calcification undergoing TMVR [4]. Robust and consistent evaluation techniques are therefore required to assess which patients will benefit from TMVR and which type of device is best suited for specific anatomical and functional patterns.

Pre- and peri-procedural imaging are key to the success of both TAVI and TMVR, with contrast-enhanced cardiac computed tomography (CT) and echocardiography playing a crucial role in the evaluation of patient suitability and procedural planning (Fig. 1: Panels A–B) [5]. Early attempts to provide pre-procedural guidance by overlaying device geometries using multi-modal imaging provided a swift initial assessment. However, this approach to TMVR has so far failed to establish formal criteria for patient and device selection, due to oversimplification of the multifactorial relationship that links risks of LVOT obstruction to anatomical parameters (shape and kinematics of mitral annulus, calcium distribution, aorto-mitral angulation, septal geometry) and device characteristics (shape, size and positioning).

Although anatomical measurement may be insufficient for effective risk assessment, it can provide key information for performing more sophisticated analyses [6]. Previous experiences with TAVI and the new challenges of TMVR have generated interest in the use of computer simulation to predict the effects of different devices on patient-specific pathophysiology and the risks of procedural complications. These advanced techniques combine state-of-the-art imaging with computer-aided design to model the mechanical behavior of the device during deployment (Fig. 1: Panels C–F) [7]. Finite-element analysis can then simulate deformation of the device after deployment and other interactions of the device with neighbouring anatomy, significantly improving the predictive power of geometric measurement [8,9].

Such analyses can accurately predict the likelihood of LVOT obstruction and paravalvular leak based on device characteristics, ventricular anatomy and kinematics. However, they cannot model the left ventricular haemodynamic response to variations in preload and afterload following resolution of mitral regurgitation or the final device position and shape. Assessment of these crucial aspects of TMVR success has been recently enabled by cutting-edge biophysical computer models that simulate patient-specific ventricular blood flow and quantify metrics such as transvalvular and LVOT pressure gradients (Fig. 1: Panels G–H). Such models can be used before intervention to provide non-invasive assessment of the physiological consequences of mitral regurgitation and enhance patient selection for TMVR. When used to predict TMVR

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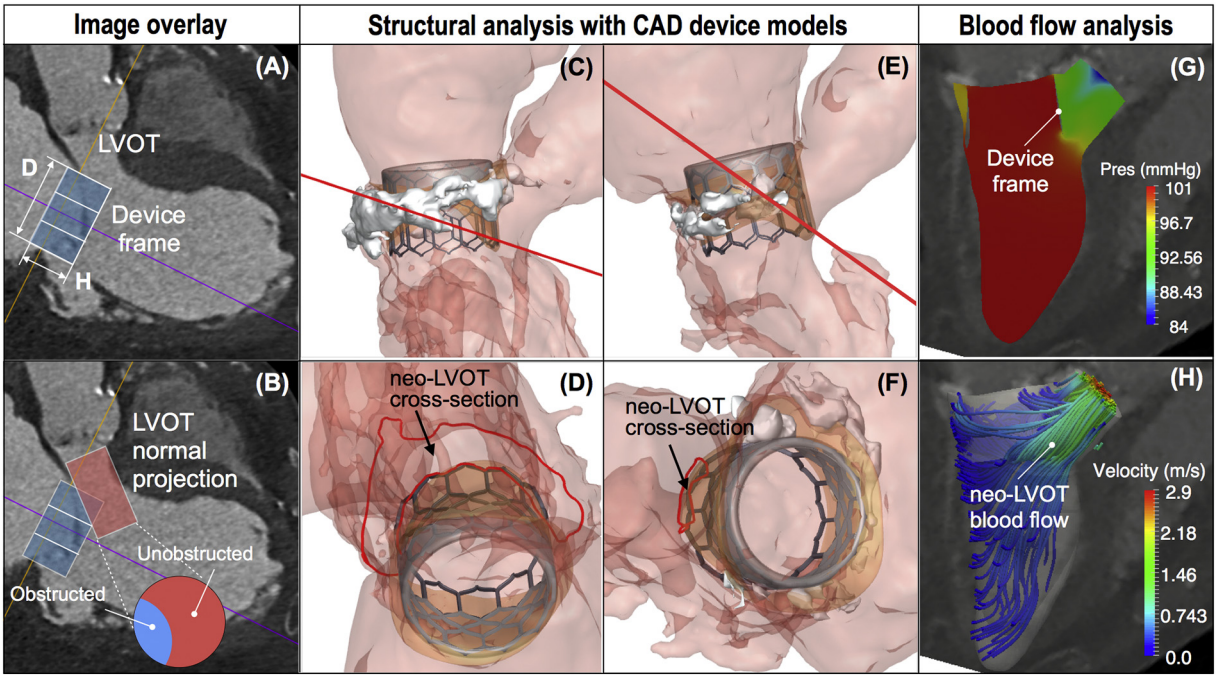

Fig. 1. Patient-specific planning of minimally invasive transcatheter intervention. A: Overlay of simple valve geometry to CT images accounting for different levels of atrial placement. B: Normal projection of the outflow plane into the left ventricle to measure the proportion of outflow area obstructed by the valve frame. C–F: Finite-element simulation of patient-specific device implantation in a calcified mitral annulus (illustrated in white) with low (C–D) and high probability of LVOT obstruction (E–F). G–H: Patient-specific computational fluid-dynamic simulation of intraventricular pressure (G) and blood flow streamlines coloured according to velocity (H) following device implantation.
(Panels A–B and G–H modified from De Vecchi et al. Sci Rep 2018;8:15540)

outcomes, they can also provide a tailored assessment of the ventricular response to device implantation (including detailed quantification of potential paravalvular leaks and the haemodynamic impact of any anticipated LVOT obstruction) in individual patients [10].

Integration of structural mechanics and flow modelling can therefore advance the boundaries of procedural planning to simulate virtual TMVR using different devices in order to select the one that best matches the anatomy and pathophysiology of an individual patient. Over the next decade, these new technologies hold major potential to augment early feasibility trials of new transcatheter valves and improve the quantity and quality of life of a growing cohort of patients.

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