Implantation Depth and Rotational Orientation Effect on Valve-in-Valve Hemodynamics and Sinus Flow

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Background. **This study evaluated the effect of transcatheter aortic valve implantation depth and rotation on pressure gradient (PG), leakage fractions (LF), leaflet shear stress, and sinus washout in an effort to understand factors that may dictate optimal positioning for valve-in-valve (ViV) procedures. Sinus flow stasis is often associated with prosthetic leaflet thrombosis. Although recent ViV in vitro studies highlighted potential benefits of transcatheter aortic valve supraannular implantation to minimize PGs, the relationship between transcatheter aortic valve depth and other determinates of valve function remains unknown. Among these, LFs, shear stress, and poor sinus washout have been associated with poorer valve outcomes.**

Methods. **ViV hemodynamic performance was evaluated in vitro vs axial positions –9.8, –6.2, 0, and +6 mm and angular orientations 0, 30, 60, and 90 degrees in a degenerated surgical aortic valve. PGs, LFs, and sinus shear stress and washout were compared. Leaflet high-speed imaging and particle-image velocimetry were performed to elucidate hemodynamic mechanisms.**

Results. **(1) The PG varies as a function of axial position, with supraannular deployments yielding a maximum benefit of 7.85 mm Hg less than PGs for subannular deployments irrespective of commissural alignment ($p < 0.01$); (2) in contrast, LF decreased in relationship to subannular deployment; and (3) at peak systole, sinus flow shear stress increased with deployment depth as did sinus washout with and without coronary flow.**

Conclusions. **First, supraannular axial deployment is associated with lower PGs irrespective of commissural alignment. Second, subannular deployment is associated with more favorable sinus hemodynamics and less LF. Further in vivo studies are needed to substantiate these observations and facilitate optimal prosthesis positioning during ViV procedures.**

(Ann Thorac Surg 2018;106:70–8)

Transcatheter aortic valve (TAV) implantation inside a failed bioprosthetic surgical aortic valve (SAV)—also known as valve-in-valve (ViV)—offers an alternative to a redo operation for high-risk patients. However, elevated pressure gradients (PGs), paravalvular leakage (PVL), and leaflet thrombosis can persist after ViV implantation and limit clinical effectiveness [1–4]. To help understand and mitigate these events and better inform procedural technique, several studies have evaluated implantation depth and rotational orientation of the TAV with respect to the SAV as it pertains to postimplant PGs. However, it remains to be established how various implant depths and rotational orientation affect other surrogates of valve function: PG, leakage fraction (LF), which is an in vitro correlate of PVL, shear stress, and sinus flow stasis, which are in vitro correlates for leaflet thrombosis.

Several studies have demonstrated that supraannular deployment is associated with lower PGs, yet with higher LF in some cases [5–7]. Commissural alignment (valve "rotation") has been less well characterized but to date has not been implicated in ViV hemodynamics [5–8]. Despite a clinical preference for supraannular deployment, elevated PGs (>20 mm Hg) do occur in approximately 15% of these cases compared with 34% of subannular deployments [7]. These observations suggest that other determinants of PG after ViV exist and open the door to consider other

Dr Crestanello discloses a financial relationship with Medtronic.

The Supplemental Material, Figures, and Videos can be viewed in the online version of this article [https://doi.org/10.1016/j.athoracsur.2018.01.070] on http://www.annalsthoracicsurgery.org.

Accepted for publication Jan 22, 2018.

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Published by Elsevier Inc.

0003-4975/$36.00
https://doi.org/10.1016/j.athoracsur.2018.01.070

surrogates of valve function when determining target implant depth.

Sinus flow dynamics are among additional features that may affect valve function and overall longevity. Decreased leaflet mobility after ViV implantation is likely caused by subclinical leaflet thrombosis [9, 10], a phenomenon that has been linked to flow stasis [11–13]. Although higher implants have been associated with more favorable PGs, conflicting reports about their association with less sinus washout and, potentially, a higher risk of flow stasis and thrombosis have been published [14–17]. Accordingly, a ViV implant that incorporates favorable hemodynamics in tandem with sinus washout may be optimal.

This study evaluated the effect of TAV depth and rotation on PG, LF, regional leaflet shear stress, and sinus washout after ViV.

Material and Methods

High-fidelity in vitro measurements of PG, LF, shear stress, and sinus washout were performed, compared, and analyzed for every valve configuration as described in detail below.

Valve Selection and Deployment

Using an aortic root model (Supplemental Fig 1), we implanted a 23-mm Evolut TAV (Medtronic, Minneapolis, MN) in a degenerated 23-mm Perimount Magna SAV (Carpentier-Edwards, Irvine, CA) extracted from a patient who underwent a redo operation (Fig 1A). The TAV was deployed at 16 different combinations consisting of four axial positions of +6.0, 0, –6.2, and –9.8 and four angular rotations of 0, 30, 60, and 90 degrees. Rotational orientation angle is the relative angular difference between the TAV and SAV commissures, with 0 degrees representing complete commissural alignment (Figs 1B–1F).

Hemodynamic Assessment

PGs and LFs were evaluated under pulsatile flow conditions ensured by a left heart pulse duplicator yielding physiologic flow and pressure curves [12, 18]. Base hemodynamics for all conditions were maintained with a systolic/diastolic pressure of 120/80 mm Hg, a 1 beat/s heart rate, a systolic duration of 33%, and a cardiac output of 5 L/min. The working fluid in this study was a mixture of water and 99% pure glycerine producing a density of 1,080 kg/m^3 and a kinematic viscosity of 3.5 centistokes, similar to blood properties. Data for 60 consecutive cardiac cycles of aortic pressure, ventricular pressure, and aortic flow rate were recorded at a sampling rate of 100 Hz. The mean transvalvular PG was defined as the average of positive pressure difference between the ventricular and aortic pressure curves during forward flow. The average LF represents the ratio of the leakage volume (*LV*), without closing volume, to the total forward flow volume (*FV*) as follows:

$$LF = \frac{LV}{FV} \tag{1}$$

High-Speed Imaging and Particle Image Velocimetry

Videos of ViV en face views were acquired throughout the cardiac cycle at 4,000 frames/s to document the opening and closing dynamics of the leaflets using a Fastcam SA3 high-speed video camera (Photron, San Diego, CA) and a high-speed controller (LaVision, Ypsilanti, MI).

For particle image velocimetry (PIV), the flow was seeded with fluorescent poly(methyl methacrylate)-rhodamine B particles with diameters ranging from 1 to 20 μm. For all ViV cases, the velocity field within the sinus region, including the region adjacent to the TAV leaflets, was measured using high spatial and temporal resolution PIV. Briefly, this involved illuminating the sinus region using a laser sheet created by pulsed neodymium-doped:yttrium lithium fluoride single-cavity diode pumped solid-state laser coupled with external spherical and cylindrical lenses while acquiring high-speed images of the fluorescent particles within the sinus region. Raw PIV images were acquired with and without coronary flow, with resulting spatial and temporal resolutions of 0.159 mm/pixel and 4,000 Hz, respectively. Refraction was corrected using a calibration in DaVis 7.2 particle image velocimetry software (LaVision, Göttingen, Germany). Velocity vectors were calculated using adaptive cross-correlation algorithms. Further details of PIV measurements can be found in Hatoum and colleagues [12].

Sinus Vorticity and Shear Stress Dynamics

Using the velocity measurements from PIV, vorticity dynamics were also evaluated for the sinus region, with and without coronary flow. Vorticity is the curl of the velocity field and therefore captures rotational components of the blood flow shearing [19]. Regions of high vorticity along the axis perpendicular to the plane indicate both shear and rotation of the fluid particles. Out-of-plane vorticity in the *z* direction was computed using the following equation:

$$\omega_z = -\left(\frac{dV_x}{dy} - \frac{dV_y}{dx}\right) \tag{2}$$

Where ω_z is the vorticity component with units of s^{-1}, and V_x and V_y are the x and y components of the velocity vector with units of m/s. The x and y directions are axial and lateral respectively with the z direction being out of measurement plane.

Viscous shear stress field was evaluated consistently with Moore and Dasi [20] and Hatoum and colleagues [12].

$$\tau = \mu\left(\frac{dV_x}{dy} + \frac{dV_y}{dx}\right) \tag{3}$$

Where τ is the shear stress in Pa and μ is the dynamic viscosity in N.s/m^2.

Sinus Washout

Velocity measurements from PIV were also used to evaluate sinus washout. Sinus washout is defined as the characteristic curve representing the percentage of fluid