Role of the sinuses of Valsalva on the opening of the aortic valve

Giuseppe Pisani, MS,[a] Raffaele Scaffa, MD,[b] Ornella Ieropoli, PhD,[c] Edoardo M. Dell'Amico, MS,[c] Daniele Maselli, MD,[b] Umberto Morbiducci, PhD,[a] and Ruggero De Paulis, MD[b]

Objective: The present in vitro study was designed to ascertain whether the presence of sinuses of Valsalva in the aortic root were able to regulate the valve effective orifice area and modulate the gradient across the valve independently from root compliance.

Methods: Four different root configurations were prepared. Of the 4, 2 were silicon configurations with the same compliance, 1 with and 1 without sinuses of Valsalva, in which a 25-mm Solo stentless aortic valve was sutured inside. The other 2 configurations were obtained by substituting the upper part of the root with a straight Dacron graft or with a Valsalva graft in a remodeling fashion to reproduce the surgical situation. All roots were mounted in a pulse duplicator to measure the pressure decrease across the valve and effective orifice area at different cardiac outputs.

Results: With increasing cardiac output up to 7 L/min, an increase in the pressure decrease across the valve was evident in both configurations without sinuses of Valsalva (7.90 ± 1.7 and 11 mm Hg ± 0.1 mm Hg, respectively) but not in those with sinuses (2.87 ± 0.5 and 2.42 mm Hg ± 0.5 mm Hg). Similarly, with increasing cardiac output, the effective orifice area increased significantly only in the roots with sinuses (5.13 ± 0.5 and 5.47 ± 0.5 vs 3.06 ± 0.3 and 2.50 cm^2 ± 0.02 cm^2, respectively).

Conclusions: When the cardiac output is increased to greater than the resting physiologic values, the presence of sinuses of Valsalva, independently of root compliance, prevents an increase in the pressure decrease across the valve by way of an increase of the effective orifice area. (J Thorac Cardiovasc Surg 2013;145:999-1003)

ACD

The role played by the sinuses of Valsalva in regulating smooth and progressive closure of the aortic valve is well known. Vortex structures forming in the sinuses soon after systole has begun are of paramount importance in modulating the leaflet movements, ensuring synchronous, homogeneous, and stress-free leaflet closure. Little is known whether the sinuses might also be important in regulating valve opening and therefore in optimizing ventricular ejection. Our studies,[1] as well as those of other groups,[2] using echocardiography have shown that in the absence of sinuses of Valsalva, the aortic valve opening velocity was altered, implying that the presence of sinuses is also important during systole. Furthermore, the importance of root compliance in ensuring normal leaflet movements is also known. In the presence of a stiff root, the dynamic of the leaflets is altered and somehow mimics that seen in the absence of sinuses.[3] The present study was designed to ascertain the role played by sinuses of Valsalva in regulating aortic valve opening independently from the root compliance.

From the Department of Mechanics,[a] Politecnico di Torino, Turin, Italy; Department of Cardiac Surgery,[b] European Hospital, Rome, Italy; and Sorin Biomedica,[c] Saluggia, Italy.

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Address for reprints: Ruggero De Paulis, MD, Department of Cardiac Surgery, European Hospital, Via Portuense 700, Rome 00149, Italy (E-mail: depauli@tin.it).

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METHODS

Two molds of sintered resin with a diameter of 25 mm, 1 with and 1 without sinuses of Valsalva, were prepared. The maximum diameter at the sinuses was 35 mm. Two silicon roots were then obtained by dipping the 2 molds into a liquid silicon solution. Each immersion left a thin layer of silicon on the mold. Usually, 30 immersions were required to obtain a wall thickness of 1.3 mm ± 0.3 mm with compliance of 3% to 4%. The computation of the compliance of the silicon roots was conducted according to the Food and Drug Administration "Replacement Heart Valve Guidance."[4] A Stentless Solo (Sorin Biomedica, Saluggia, Italy), 25-mm pericardial valve was sutured inside each 1 of the 2 roots with a technique similar to the standard surgical technique using 4-0 polyester sutures and taking care to obtain perfect valve geometry and smooth pericardial tissue apposition with the silicon wall. Thus, 2 silicon configurations were obtained: silicon-straight and silicon-Valsalva. The final configuration showed a perfect fit between the valve and root (Figure 1). Another 2 roots with and without sinuses were then prepared in a similar manner and 2 other Solo valves were sutured inside. Next, the upper part of the silicon root was cut, following the crescent shape of the valve and replaced by suturing in its place a straight or Valsalva (Terumo Vascutek, Renfrewshire, UK) Dacron graft using the classic remodeling technique to reproduce the typical surgical situation. Two hybrid configurations were therefore obtained: hybrid-straight and hybrid-Valsalva (Figure 2). All testing of the 4 roots, 2 silicon and 2 hybrid, both with and without sinuses of Valsalva, was conducted using a Vivitro System pulse duplicator (Vivitro System, Victoria, British Columbia, Canada).[5] The 4 assembled models of aortic root and valve were installed in the aortic position of the pulse duplicator for the hydrodynamic test. A complementary (nontest) valve, the CarboMedics Prosthetic Heart Valve (29 mm; CarboMedics, Austin, Tex), was installed in the mitral position. The simulation conditions included 4 different cardiac output (CO) values (ie, 2, 3.5, 5, and 7 L/min) at a pulse rate of 70 beats/min and a mean aortic pressure of 100 mm Hg. The test fluid used was saline (density, 1000 kg/m^3; dynamic viscosity, 10^{-3} Pa/s). The 4 configurations were tested in different conditions. Hydrodynamic tests on the silicon-Valsalva and silicon-straight configurations were performed by

Abbreviations and Acronyms
CO = cardiac output
EOA = effective orifice area

partially filling the housing aortic chamber with saline solution, mimicking the physiologic-like compliance of the construct. This experimental setting aimed at investigating the behavior of the valve in the presence of the Valsalva sinuses when aortic compliance is ensured. In contrast, the hybrid-Valsalva and hybrid-straight configurations were tested without forcing compliant behavior on the constructs (by filling with saline solution the housing aortic chamber). The rationale for this second setting was to investigate the behavior of the valve in the presence of differently shaped commercial grafts. A dedicated software control system was used to drive and control the mock circulatory system (ViviTest, ViVitro Systems). This allowed us to obtain and analyze the physiologic flow and pressure waveforms within the in vitro simulator. Technically, the analog aortic, ventricular, and mitral pressure signals were acquired using 3 pressure transducers (Utah Medical Products, Salt Lake City, Utah). The volumetric flow rates in the aortic and mitral positions were acquired using an electromagnetic flow meter system incorporating Carolina Medical probes (Carolina Medical Electronics, East Bend, NC). A sample rate of 500 Hz was considered appropriate. Analog signals were acquired using a 12-bit analog I/O resolution A/D board (KPCI-3101; Keithley Instruments, Cleveland, Ohio). The hydrodynamic performance of the assembled models of aortic root and valve was evaluated in terms of the aortic transvalvular pressure decrease and the effective orifice area (EOA), calculated using the well-established Gorlin formula, where Q is the volumetric aortic flow rate. Data are presented as the mean ± standard deviation, as obtained, for each simulated flow rate, from 3 independent experimental sessions.

RESULTS

The pressure decrease across the valve and EOA at each CO value is shown in Figure 3 and 4 for the silicon and hybrid configurations, respectively.

Pressure Decrease

In both silicon root configurations (Figure 3, *Left*), the pressure decreases across the valve were comparable at a CO of 2, 3.5, and 5 L/min (2.57 ± 0.41, 2.05 ± 0.50, and 2.10 mm Hg ± 0.60 mm Hg vs 1.32 ± 0.34, 1.51 ± 0.68, and 2.65 mm Hg ± 0.44 mm Hg, respectively). However, when the CO was increased to 7 L/min, the pressure decrease markedly increased in the silicon roots without sinuses (7.90 mm Hg ± 1.77 mm Hg) but not in the roots with sinuses (2.87 mm Hg ± 0.53 mm Hg). Similarly, in both hybrid root configurations (Figure 3, *Right*) the pressure decreases were comparable at 2, 3.5, and 5 L/min (1.20 ± 0.47, 1.26 ± 0.21, and 1.83 mm Hg ± 0.15 mm Hg vs 1.09 ± 0.03, 1.63 ± 0.12, and 4.16 mm Hg ± 0.37 mm Hg, respectively). Also, for the hybrid root configurations, when the CO was increased to 7 L/min, the pressure decrease remained low in the presence of sinuses (2.42 mm Hg ± 0.5 mm Hg) but markedly increased in the absence of sinuses (11 mm Hg ± 0.1 mm Hg).

Effective Orifice Area

Paralleling the results in pressure decrease, the EOA was comparable in all 4 root configurations at lower CO, but they were significantly larger at 7 L/min only in both configurations with sinuses (5.13 ± 0.5 and 5.47 ± 0.5 for the silicon and hybrid root, respectively; Figure 4).

DISCUSSION

The 3 anatomic pouches located immediately above the aortic valve were described in the 17th century by the Italian anatomist Antonio Maria Pini, who termed them the ‘‘Valsalva,’’ from the location of his grandfather’s family castle. Although from that day onward, they have always been termed the ‘‘sinuses of Valsalva,’’ it was Leonardo da Vinci, who many years before had described, depicted, and explained in detail their shape and function. The greatness of Leonardo da Vinci in understanding the anatomy of the aortic valve has been celebrated by Robicsek[6] in a historical article. Recently, we have also reported how much Leonardo da Vinci had understood the modern concepts of the function of the aortic valve—from the generation of vortices and their importance in smooth valve closure, to the cusp’s surface of coaptation, to a stunning description of leaflet histology.[7] In the modern era, the experiments of Bellhouse and Bellhouse[8] in the early 1970s methodically demonstrated the role of the sinuses in generating vortices to prevent the leaflet from affecting the aortic wall and in regulating aortic valve closure. All subsequent studies have always focused on the role played by the sinuses during the diastolic phase[9] and even more so after various types of valve-sparing procedures entered the surgical arena. In the past 10 years, a large number of studies have demonstrated the problem related to a lack of sinuses of Valsalva or, in contrast, the benefit of their reconstruction during surgery of the aortic root.[10,11] All studies, whether in vitro[12] or with the use of transesophageal echocardiography[1,2] or contrast phase magnetic resonance imaging,[13] have invariably shown the positive effect of the sinuses in regulating leaflet dynamics during the cardiac cycle and even in modulating coronary flow.[14] However, very little has been reported on the role played by the sinuses, if any, during systole. Because the sinuses are located on the aortic side, very similar to an extension of the aortic leaflet into the aortic wall, their role has always been considered almost exclusively in diastole. The function of the sinuses in systole has always been considered marginal, and most studies considered the cusp motion during the cardiac cycle, just as an increase in valve opening velocity is reported every time the aortic root is reconstructed in the absence of the sinuses.[1,2] In this experimental setting, we were able to show how the sinuses of Valsalva are also important in modulating the relative obstruction of flow present in the outflow tract of the left ventricle every time an increase in CO is present.