A Comprehensive Fluid Dynamic and Geometric Study for an "In-Vitro" Comparison of Four Surgically Implanted Pericardial Stented Valves

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Background and aim of the study: **Many variables may affect the fluid dynamic of an implanted bioprosthesis. In-vitro studies have provided accurate data such that, when different prostheses are implanted in the same true aortic root, it should be possible to make a fair comparison. The study aim was to evaluate the fluid dynamic and geometric characteristics of the four most widely used stented pericardial bioprostheses.**

Methods: **Four types of pericardial prosthesis (Magna Ease 21, Trifecta 21, Soprano-Armonia 20, and Mitroflow 23) that fitted eight aortic roots with a native annulus diameter of 2.1 cm were implanted and tested in a mock loop.**

Results: **Energy loss and mean gradients were increased with stroke volume (SV) in all valves tested. The effective orifice area values were fairly stable across the SV intervals (p = 0.57). All hemodynamic-related indices displayed mutually consistent behaviors, with Trifecta showing the lowest hindrance to flow. Both geometric orifice area (GOA) and edge geometric orifice area (eGOA) were increased significantly as the SV increased; the Trifecta valve showed the largest eGOA value, while the Trifecta and Mitroflow provided the largest GOAs. For the Trifecta and Soprano-Armonia prostheses (and the Magna to a lesser extent), the most distal cross-section was systematically greater than the inflow area, suggesting a divergent configuration at the systolic peak.**

Conclusion: **The study results combined the fluid dynamic reproducibility of the in-vitro setting and the specificity of surgery. A quantitative comparison of the fluid dynamic performance of the different bioprostheses was feasible.**

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After aortic valve replacement, patients with small aortic annuli are at risk of high transprosthesis gradients (1,2). As these place an extra load on the left ventricle, they may have a negative impact on the patients' survival and quality of life (3-7). In order to implant a prosthesis that fits the patient's hemodynamic requirements and overcomes the inherent obstruction due to the stent, both the implantation of stentless valves and annulus enlargement have been proposed, but the results obtained have been disappointing (8,9). Pericardial stented bioprostheses have displayed excellent durability and yielded better fluid dynamic performance than porcine prostheses, especially in small aortic roots (10,11).

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Prostheses differ both in design and in their true dimensions, such as internal diameter (ID), tissue annulus diameter (TAD) and external diameter (ED) (12,13). This heterogeneity, along with the variability of the aortic root anatomy (14), makes it difficult to make a fair comparison of the hemodynamic performance of the various prostheses. In evaluating fluid dynamics, the in-vitro setting is the "gold standard", based on the high accuracy of its measurements. However, a prosthesis needs to be sutured in an aortic root that has specific anatomic characteristics, which may in turn influence the hemodynamic result. To eliminate the bias related to anatomic variability, different prostheses should be implanted in the same aortic root.

The aim of the present study was to evaluate any differences in the fluid dynamic and geometric characteristics of the four most widely used stented pericardial bioprostheses, namely the Mitroflow and

Soprano-Armonia (Sorin Group, Saluggia, Italy), the Magna Ease (Edwards Lifesciences, Irvine, CA, USA) and the Trifecta (St. Jude Medical, St. Paul, MN, USA), at different values of stroke volume (SV). Prostheses with labeled sizes that fitted porcine aortic roots with a native aortic annulus of 2.1 cm in diameter were selected and surgically implanted.

Materials and methods

ForCardio.Lab pulsatile mock loop

The ForCardio.Lab mock loop (15-17) is a computer-controlled volumetric pump able to replicate left ventricular flow waveforms; its test section is designed to house a whole aortic root unit (ARU) and it is equipped with an adjustable hydraulic. For this experimental campaign, the mock loop was equipped with a transit-time flow-meter (HT100R; Transonic System Inc., Ithaca, NY, USA), the 1″ probe of which was placed downstream of the ARU sample, and with three pressure transducers (PC140 series; Honeywell Inc., Morristown, NJ, USA). One pressure transducer was placed immediately upstream and one immediately downstream of the sample, and the third was placed at the inlet section of the hydraulic afterload part. A high-speed digital camera set at 1000 frames per second (Phantom Miro2; Vision Research, Morristown, NJ, USA) was placed downstream of the sample so as to acquire an aortic view of the working prostheses. Hydrodynamic data were acquired via an analog/digital (A/D) board (USB 6210; National Instruments, Austin, TX, USA).

Sample preparation and prosthesis sizing

Eight fresh whole swine hearts, with a native aortic annulus of 2.1 cm, were selected. Prosthesis sizing was performed by using the probes and the valve replica provided by the manufacturer for each prosthesis on the eight hearts, to select the prosthesis that fitted the annulus. The Trifecta (TRI) and Magna Ease (MG) probes that fitted had the label size of 21. For Mitroflow (MF), sizing was undertaken with the valve replica alone, as this is the only tool provided by the manufacturer, and a labeled size 23 was chosen. These three valves - the TRI, MG and MF - have the same ED (2.6 cm). For the Soprano-Armonia (SA) valve, although the probe for the size labeled 22 was able pass through the native annulus, the valve replica appeared too bulky; thus, a size 20 was chosen. The ARU samples were then harvested by including 1.5 cm of the left ventricular outflow tract (LVOT), which was rendered cylindrical by suturing the anterior mitral valve leaflet to the adjacent muscular septum. The ascending aorta was transected 0.5 cm above the sinotubular junction (STJ) and the coronary ostia were ligated. Circular Dacron meshes were sutured to the inflow and outflow to fix the aortic root samples into the housing section of the mock loop (15-17).

Experimental design

Tests were conducted at SV-values of 30 ml, 50 ml, 65 ml, and 85 ml. The systolic ejection time was set at one-third of the entire cardiac cycle, and the heart rate at 70 bpm, with a mean simulated arterial pressure of 80-104 mmHg. After housing each ARU sample in the test-section holder, the four bioprostheses were implanted in a randomized sequence. For each experimental point, data were evaluated over five consecutive simulated heart cycles.

The prostheses were implanted by means of a simple interrupted suture technique with ethylene terephthalate sutures (Ethibond 2/0). The flow rate, the pressures upstream and downstream of the aortic root, and the pressure in the afterload were acquired at a sampling rate of 200 Hz via an A/D acquisition board. Post-processing of the raw data was performed to calculate the following quantities:

- The mean systolic pressure drop (Δp_m, in mmHg) across the aortic root unit (i.e., the difference between pressures measured immediately upstream and downstream of the ARU) and averaged over the systolic interval.
- The effective orifice area (EOA, in cm^2) was calculated from the formula:

$$\mathrm{EOA(cm^2)} = \frac{Q_{rms}}{k\sqrt{\Delta p_m}}$$

where Qrms (l/min) is the square-root of the mean systolic flow rate, Δpm (in mmHg) is the mean systolic pressure drop across the sample, and k is a conversion factor (k = 3.1 to yield the EOA in cm^2).

- The geometric orifice area (GOA, in cm^2) was evaluated semi-quantitatively by means of high-speed videos as the largest cross-section opening area recorded during systole.
- The edge geometric orifice area (eGOA, in cm^2) was evaluated semi-quantitatively from the high-speed videos by tracking the free edges of the prostheses' leaflets at the systolic peak, and integrating the resulting area.
- Space efficiency = the ratio between GOA and the area calculated from the external diameter of the prosthesis.
- Performance index (Pi) = EOA/inner GOA. The inner GOA was calculated from the ID values provided by the manufacturers: TRI = 1.83 cm; MF = 1.9 cm; SA = 1.98 cm; MG = 2.0 cm.

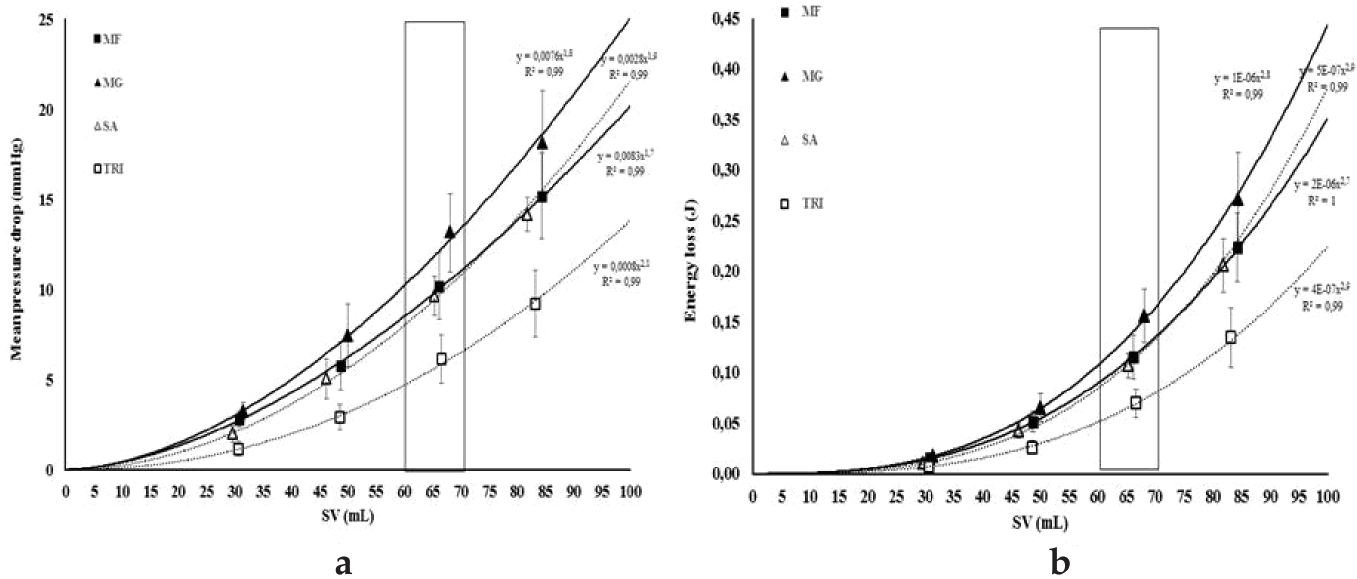

Figure 1: Relationship between (a) mean pressure drops and (b) energy loss with stroke volume (SV). Bars represent 95% confidence intervals. The rectangle represents the physiologic SV interval at rest in patients whose body size matches the sizes of the prostheses.

- Systolic energy loss: this is the energy provided by the pump that is lost when the fluid passes through the prosthesis, expressed in Joules (J).
- Systolic energy loss (%): this is the percentage of the energy provided by the pump that is lost when the fluid passes through the prosthesis.
- Coefficient of contraction (Cc) = EOA/GOA.
- Geometric area ratio = GOA/inner GOA. The inner GOA is calculated from the internal diameter of the prosthesis.

GOA and eGOA were evaluated from high-speed videos by means of a semi-automated tracking algorithm developed in Matlab (MathWorks Inc., MA, USA) (18).

Statistical analysis

Continuous variables were expressed as mean ± SD and compared by means of ANOVA for repeated measures, with Bonferroni's test used in post-hoc analysis; in the graph, the values are reported with 95% confidence intervals; a p-value <0.05 was considered statistically significant. The data were analyzed by means of Statsoft 8.2 software.

Results

None of the valves displayed any significant structural problems in any of the test sessions, the results of which are listed in Table I. Energy loss and mean pressure gradients (Fig. 1) were increased with SV in all valves tested, with TRI displaying a lower level of significance than the other prostheses. EOA values were fairly stable across the SV intervals (p = 0.57); once again, TRI showed the largest value (Table I; Fig. 2). Similar considerations are applicable for the Pi (the ratio between the EOA and inner GOA). The eGOA was increased significantly as the SV increased, with TRI providing the largest value (Table I; Fig. 3). The GOA was also increased significantly on increasing the SV, with TRI and MF providing the largest areas (Table I; Fig. 3). For the TRI and SA prostheses (and for MG to a lesser extent), the most distal cross-section was systematically greater than in the other prostheses, which suggests a divergent configuration at the systolic peak.

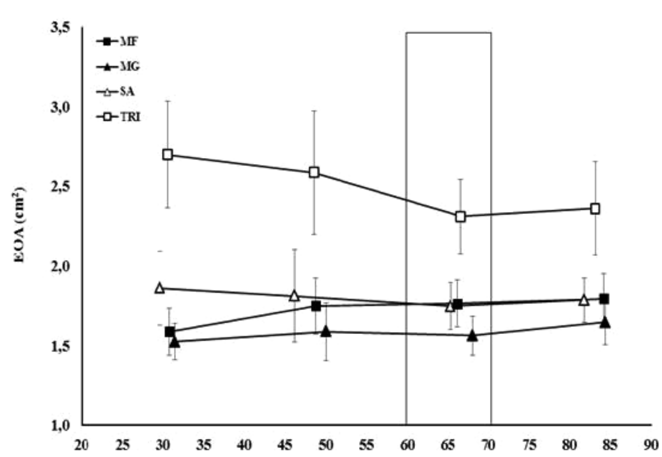

Figure 2: Relationship between effective orifice area (EOA) and stroke volume (SV). Bars represent 95% confidence intervals. The rectangle represents the physiologic SV interval at rest in patients whose body size matches the sizes of the prostheses.

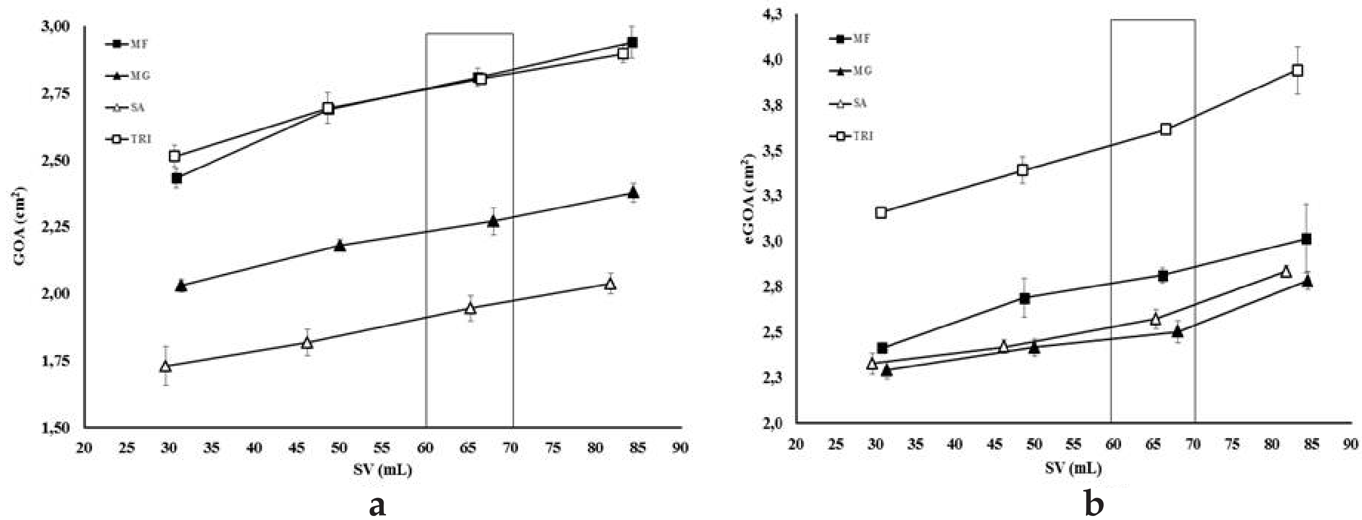

Figure 3: Relationship between (a) geometric orifice area (GOA) and (b) edge geometric orifice area (eGOA) with stroke volume (SV). Bars represent 95% confidence intervals. The rectangle represents the physiologic SV interval at rest in patients whose body size matches the sizes of the prostheses.

Discussion

Bioprostheses are the most frequently implanted valves. Among those currently in use, pericardial stented valves have shown better fluid dynamic results than porcine valves, especially in patients with small aortic annuli (10,11,19). Although durability is the main concern, the fluid dynamic performance of a bioprosthesis cannot be neglected because the residual obstruction places an extra load on the left ventricle, with detrimental effects (3-7). However, despite substantial improvements the performance of stented bioprostheses is far from that of a native valve (20).

Theoretical aspects

Interaction between the prosthesis and flow is mainly subjected to the concentrated loss of head laws. The quantity of the mechanical energy dissipated correlates well, after pressure recovery has taken place, with the pressure drop across the orifice (21,22) with a quadratic relationship with flow. Pressure drop, for a certain flow, depends on the prosthesis structural characteristics (stent design and material used), geometric properties (ID and GOA projected by the leaflets), and both inflow (LVOT/prosthesis) and outflow (prosthesis/STJ) characteristics (23). The orifice provided to the flow by the bioprosthesis is the result of an interaction between the inner GOA, calculated from the ID being the theoretical largest orifice available for the flow, and the projected GOA of the leaflets when fully opened. The flow passing through these two orifices contracts with its minimum at the level of "vena contracta". The EOA represents the actual area used by the flow, and is the term on which the pressure drop mainly depends. In contrast to Doppler, the EOA, when calculated with an invasive procedure or an in-vitro setting, is larger than the "vena contracta" because it depends on the extent of the pressure recovery (23).

Complexity of the clinical scenario

The clinical scenario is tremendously complex because the patient's anatomic and physiologic conditions impact on postoperative valve fluid dynamics. In addition, the implantation process hides several pitfalls that affect the size of prosthesis to be implanted, and is the main factor affecting fluid dynamics. The prosthesis size implanted depends on the manufacturer's sizing strategy, surgical procedure, and the patient's aortic root characteristics. The manufacturer's sizing strategy is specific to each valve brand, and implies that prostheses with different labeled sizes, but made by different manufacturers, may fit the same aortic root (12,14). The impact of the surgical procedure depends on the surgeon's aptitude and experience, as well as the suture technique adopted (24,25). Finally, the LVOT characteristics (shape and size) and annulus-prosthesis interaction may affect how smoothly/abruptly the flow lines approach and enter into the prosthesis, while the size of the STJ may also influence pressure recovery (23).

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Table I: Fluid dynamic and geometric results.

Variable	Stroke volume				Effect	p-value
	30 ml	50 ml	65 ml	85 ml		
Mean gradient (mmHg)						
MF	2.8 ± 0.64	5.8 ± 1.93	10.2 ± 2.67	15.2 ± 3.46	Valve	<0.001
MG	3.2 ± 0.65	7.4 ± 2.51	13.2 ± 3.15	18.1 ± 4.16	Time (SV)	<0.001
SA	2.0 ± 0.67	5.0 ± 1.57	9.6 ± 1.57	14.1 ± 1.34	Interaction	<0.001
TRI	1.1 ± 0.58	2.9 ± 1.02	6.1 ± 1.93	9.2 ± 2.68		
Energy loss (J)						
MF	0.015 ± 0.01	0.05 ± 0.01	0.11 ± 0.03	0.22 ± 0.05	Valve	<0.001
MG	0.018 ± 0.01	0.07 ± 0.02	016 ± 0.04	0.27 ± 0.07	Time (SV)	<0.001
SA	0.010 ± 0.01	0.04 ± 0.01	0.11 ± 0.02	0.21 ± 0.04	Interaction	<0.001
TRI	0.008 ± 0.01	0.03 ± 0.01	0.07 ± 0.02	0.14 ± 0.04		
Energy loss (%)						
MF	6.5 ± 1.42	8.7 ± 2.45	10.7 ± 2.51	13.3 ± 1.89	Valve	<0.001
MG	7.3 ± 1.41	10.8 ± 3.78	13.5 ± 3.25	15.7 ± 2.81	Time (SV)	<0.001
SA	4.6 ± 1.19	8.3 ± 2.72	10.9 ± 1.79	13.1 ± 1.38	Interaction	<0.001
TRI	2.7 ± 1.23	4.3 ± 1.59	6.6 ± 1.63	8.4 ± 1.79		
EOA (cm^2)						
MF	1.6 ± 0.22	1.8 ± 0.26	1.8 ± 0.21	1.8 ± 0.23	Valve	<0.001
MG	1.5 ± 0.17	1.6 ± 0.26	1.6 ± 0.18	1.6 ± 0.20	Time (SV)	0.57
SA	1.9 ± 0.33	1.8 ± 0.42	1.7 ± 0.21	1.8 ± 9.20	Interaction	0.13
TRI	2.7 ± 0.48	2.6 ± 0.56	2.3 ± 0.34	2.4 ± 0.42		
GOA (cm^2)						
MF	2.4 ± 0.05	2.7 ± 0.03	2.8 ± 0.05	2.9 ± 0.09	Valve	<0.001
MG	2.0 ± 0.03	2.2 ± 0.03	2.3 ± 0.07	2.4 ± 0.05	Time (SV)	<0.001
SA	1.7 ± 0.10	1.8 ± 0.07	1.9 ± 0.07	2.0 ± 0.05	Interaction	<0.001
TRI	2.5 ± 0.06	2.7 ± 0.08	2.8 ± 0.02	2.9 ± 0.04		
Edge GOA (cm^2)						
MF	2.42 ± 0.05	2.69 ± 0.03	2.81 ± 0.05	3.01 ± 0.05	Valve	<0.001
MG	2.29 ± 0.07	2.42 ± 0.07	2.50 ± 0.09	2.78 ± 0.07	Time (SV)	<0.001
SA	2.33 ± 0.08	2.42 ± 0.05	2.57 ± 0.08	2.83 ± 0.04	Interaction	<0.001
TRI	3.16 ± 0.11	3.39 ± 0.11	3.62 ± 0.04	3.95 ± 0.19		
Cc						
MF	0.67 ± 0.10	0.62 ± 0.08	0.62 ± 0.10	0.58 ± 0.08	Valve	<0.001
MG	0.75 ± 0.12	0.67 ± 0.10	0.65 ± 0.04	0.64 ± 0.07	Time (SV)	<0.001
SA	1.07 ± 0.12	0.90 ± 0.18	0.85 ± 0.10	0.85 ± 0.10	Interaction	0.203
TRI	1.05 ± 0.22	0.92 ± 0.14	0.77 ± 0.11	0.76 ± 0.10		
Performance index						
MF	0.56 ± 0.08	0.62 ± 0.09	0.62 ± 0.08	0.63 ± 0.08	Valve	<0.001
MG	0.49 ± 0.05	0.51 ± 0.08	0.50 ± 0.06	0.52 ± 0.06	Time (SV)	0.56
SA	0.61 ± 0.11	0.59 ± 0.14	0.57 ± 0.07	0.58 ± 0.07	Interaction	0.12
TRI	1.03 ± 0.18	0.98 ± 0.21	0.88 ± 0.13	0.90 ± 0.16		
Space efficiency						
MF	0.46 ± 0.01	0.51 ± 0.01	0.53 ± 0.01	0.55 ± 0.02	Valve	<0.001
MG	0.38 ± 0.01	0.41 ± 0.01	0.43 ± 0.01	0.45 ± 0.01	Time (SV)	<0.001
SA	0.30 ± 0.02	0.32 ± 0.01	0.34 ± 0.01	0.36 ± 0.01	Interaction	<0.001
TRI	0.47 ± 0.01	0.51 ± 0.02	0.52 ± 0.01	0.55 ± 0.01		
Geometric area ratio						
MF	0.86 ± 0.02	0.95 ± 0.01	0.99 ± 0.02	1.04 ± 0.03	Valve	<0.001
MG	0.65 ± 0.01	0.69 ± 0.01	0.72 ± 0.02	0.76 ± 0.02	Time (SV)	<0.001
SA	0.56 ± 0.03	0.59 ± 0.02	0.63 ± 0.02	0.66 ± 0.02	Interaction	<0.001
TRI	0.96 ± 0.02	1.02 ± 0.03	1.07 ± 0.01	1.10 ± 0.02		

Values are mean ± SD.
Cc: Coefficient of contraction; EOA: Effective orifice area; GOA: Geometric orifice area.

Interpretation of the in-vitro study

Fluid dynamic terms (energy loss, mean pressure drop and EOA)

Mean pressure drops and energy losses were increased on increasing the SV (Table I); these terms displayed strongly non-linear trends, with different patterns according to the bioprosthesis model (Fig. 1). The TRI showed the best fluid dynamic behavior in energetic terms and, accordingly, in terms of the EOA (Fig. 2) than the MF, SA and MG. Moreover, at physiologic SV values (i.e. >50 ml) the EOA values were stable for all valve models, despite a statistically significant increase in GOA. The trends of the mean pressure drops for MF, MG and SA valves were consistent with those obtained by Gerosa et al. (26) in a fully artificial experimental set-up. Moreover, at physiologic SV values the EOA values were stable for all valve models, which suggests that for these prostheses the interaction between the flow and the valve structure is well exploited over this SV range. Indeed, as the EOA is the result of hydrodynamic measurements, it should be considered an index of hydrodynamic performance, although at a first glance it might be assimilated to a geometric parameter. The EOA of the SA valve was stable across the whole SV range, while EOA values yielded by the TRI valve were higher at SV <50 ml than at SV >50 ml. This can be explained by the pliability of the leaflets, which are probably completely open at low-flow regimens. In order to obtain an EOA that is characteristic of a specific size and brand prosthesis type, the anatomy upstream and downstream of the prosthesis must be equal; this is easily achieved in vitro. Accordingly, the fact that larger standard deviations of EOA were found in the present study than by Gerosa et al. (27) can be explained by the present use of eight different ARUs, and the LVOTs and aortic roots which probably had different morphologies. As the EOA value is influenced by specific anatomic features in vivo, either the application of Gorlin's formula or the continuity equation can yield only a partial view of the performance of a specific type and size of prosthesis. This makes the EOA value relevant only for those patients in whom the prosthesis is being implanted, and is much less relevant for the type and size of prosthesis.

Geometric terms (GOA, edge GOA, geometric area ratio, space efficiency)

In all of the bioprostheses, both the GOA and eGOA were increased as the SV increased, confirming that pericardial stented valves have a reserve opening area (19,27). At each SV level, the prostheses with pericardial leaflets housed inside the stent (i.e. MG and SA) showed smaller GOAs and eGOAs than both the TRI and MF valves, in which the pericardium is outside (Table I; Fig. 3). Interestingly, while the GOAs of both TRI and MF valves were similar, the Cc proved to be lower in MF valves (confirmed by a larger pressure gradient drop and energy loss), indicating a higher flow velocity due to certain, not immediately apparent, structural characteristics. The shape assumed by the prosthesis during the ejection period played a role. Indeed, at 65 ml the TRI valve provided both GOA and eGOA values larger than the inner GOA, suggesting a divergent aperture, thus achieving the lowest gradients and energy losses, notwithstanding the smallest inner GOA. This shape better exploited the inner GOA and might probably determine less flow separation in the flow deceleration zone, resulting in a greater energy recovery due to the more gradual flow expansion and lower ratio between eGOA and STJ diameter. The MF valve opened like a cylinder, while the SA and MG valves showed a convergent-divergent shape, having the eGOA smaller than the inner GOA and larger than the GOA. This peculiar morphology could be related to the internal position of the pericardium.

Space efficiency (SE) was not related to the valve performance. This was clear on comparing the MF and TRI valves, which showed a similar SE, and also SA and MG valves; indeed, while the SA valve had the worst SE it performed better than the MG valve. It is worth noting that ID size, when considering prostheses that fit the same aortic root, is a parameter that does not affect fluid dynamic and/or geometric terms. Thus, a larger ID does not guarantee a larger GOA or a lower pressure drop. What is most important here is how much of this area is used by the flow.

Hybrid indexes (Cc and performance index)

In normally functioning bioprostheses, the Cc is expected to be >0.9 (28), but this value was found only in TRI and SA valves at SV values of 30 and 50 ml; as the SV increased, the Cc was decreased. This can be explained by the presence of the true LVOT that influences how sharply/smoothly the flow lines approach and enter into the prosthesis due to the LVOT characteristics and aortic annulus-prosthesis interaction. By contrast Pi, which describes a type of "dynamic" efficiency, seems to be fairly well related to the energy loss %. The performance appears to be specific to each valve because they differ in terms of the material used, stent design, and dimensions. The Pi showed that the TRI valve made the best use of the small area available. The MF valve also had a better Pi, notably because of the position of the pericardium outside the stent (as with the TRI valve).

Study limitations

Although all conditions to which the prostheses were exposed in the study were equal, the "implantability" characteristics of each bioprosthesis, along with the surgeon's level of experience in implanting a specific type of prosthesis, might have influenced the results. However, such biases are difficult to avoid, as they are specific to the surgical procedure. The GOA and eGOA were evaluated from a two-dimensional video, which implies that their values are planar projections of a three-dimensional area, and could be affected by experimental errors due to misalignment between the evaluation plane and the charge-coupled device sensor.

In conclusion, the study results confirmed that pericardial stented prostheses have a reserve of area, and that those in which the pericardium is housed outside the stent were more efficient. The geometric study results implied that geometrical characteristics are not parameters that can reliably predict which prosthesis will perform better than any other. The TRI valve displayed the best fluid dynamic and geometric behaviors, despite having the smallest ID.

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