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Influence of Transvalvar Pressure Gradient on Hinge Washing in Closed Mechanical Prosthetic Cardiac Valves Under Pulmonary Pressure Conditions: A Comparative In Vitro Study

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Abstract

Objective: Hinge washing is a crucial factor in the prevention of mechanical prosthetic valvar thrombosis, especially in the pulmonary valve position. The aim of this laboratory study was to determine the relationship between pressure difference and the amount of hinge washing in the closed position, using the pressures that are normal for the right ventricle and pulmonary artery. **Methods:** In an in vitro setting, four different bileaflet mechanical valves were tested for hinge washing in closed position. Based on similarity in inner diameter (range: 20.5-21.4 mm), the following valves were tested: Abbott SJM Regent size 23, Cryolife On-X size 23, LivaNova Carbomedics-R size 25, Medtronic Open Pivot (M-OP)-A size 25. Tests were carried out in a range between 3 and 100 mm Hg pressure difference, using water as a test fluid. The amount of leakage per minute through the closed valve was measured. **Results:** All four valves showed an increase in leakage with increasing transvalvar gradient, and the relationship between pressure and leakage behaves in logarithmic fashion. Leakage under normal pulmonary diastolic pressure conditions (10 mm Hg) was between 23.3% and 29.3% of the leakage under aortic diastolic pressure conditions (80 mm Hg). The Cryolife On-X valve showed the highest closed leakage volume under pulmonary conditions (10 mm Hg) 0.254 ± 0.01 (L/min), where the Medtronic M-OP showed the lowest leakage volume with 0.125 ± 0.014 (mL/min). **Conclusion:** Hinge washing is related to transvalvar pressure difference in closed position. Valve brands differed significantly from each other in the amount of hinge washing.

Keywords
mechanical heart valve, congenital heart disease, pulmonary valve replacement

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Introduction

Prosthetic valvar thrombosis is one of the most common complications of mechanical prosthetic valves in the pulmonary valvar position. In contrast, prosthetic valvar thrombosis is rare in the aortic position for which these prostheses have been designed so successfully.[1,2] For the most commonly used bileaflet valves, valvar thrombosis in most cases originates from the hinges.[3] These hinges are flushed under aortic circumstances by a pressure gradient of about 80 mm Hg between aorta and the left ventricle that produces small turbulent flows while the valve is in closed position. These small regurgitant flows through the hinges wash them free of microclots, to prevent clots from growing and subsequently embolizing.[4,5] Jun et al have demonstrated that the washout of these hinge regions during closed position appeared to be crucial under aortic conditions.[6]

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Abbreviations and Acronyms

CarboR	LivaNova Carbomedics R
IOD	inner orifice diameter
M-OP	Medtronic Open Pivot
P	pressure difference
Regent	Abbott SJM Regent
SD	standard deviation
TAD	tissue annulus diameter

The extensive research in the field of mechanical prosthetic valves has been focused on the aortic and mitral position and related physiology, because these valves are replaced most frequently.[5,7] However, patients with a congenital cardiac defect more often require replacement of the diseased or absent pulmonary valve.[8,9] In this pulmonary position, however, these very same valvar prostheses are beset by a substantial propensity for clotting, for which reason tissue valves have been popular for pulmonary valve replacement, even though their reoperation rates are high.[10,11] Recent follow-up suggests, nonetheless, that mechanical valves proved actually to be surprisingly promising for this position, despite the higher propensity for clotting.[1,2] Little is known about the flow behavior of mechanical valves in the pulmonary position under the much lower pulmonary pressures, which will result in less flow through the hinges in closed position. The precise relationship between pressure and flow has not been investigated, let alone for different brands or models. It is conceivable that these (yet unquantified) lower flows are insufficiently capable of washing the currently existing valvar hinges free of microclots and are thus causal for the higher incidence of clot formation.

The aim of this in vitro study was to determine the relationship between pressure difference and the amount of hinge washing in the closed position, using the pressures that are normal for the right ventricle and pulmonary artery. Particularly, the differences, if any, between valvar brands or models can well be relevant for the choice of pulmonary valvar mechanical prosthesis.

Materials and Methods

A static in vitro model was developed to determine accurately the relationship between pressure and the amount of hinge washing in closed position (Figure 1). The model consists of a water container, various sizes of tubing with a 25 mm diameter that were connected to the container, a customized valve holder, and a stand to keep the valve holder in place. For each valve, an individual valve holder was designed to make sure that no paravalvar leakage was possible. The model was loaded with a constant pressure that could be varied by adjusting the height of the water container. A pressure gauge connected to a Philips Intelli-Vue MP70 (Amsterdam, Netherlands) monitor was used to monitor the pressure. The regurgitant volume was determined by weighing the regurgitant water using a digital measuring scale. Testing was done with pressures ranging between 3 and 100 mm Hg, which is the average range of diastolic pressure differences over the aortic and pulmonary valves. Each measurement was done over a period of 60 seconds with the valve continuously in closed position; for each sample, the measurement was repeated nine times. We expected that the amount of hinge washing (and not the leakage *between* the leaflets and between the leaflets and the housing) was by far the most dominant part of the total regurgitant volume in this setup. To confirm this, a qualitative assessment by eye was done and photographs were taken (H.P. and T.E.).

Valvar Prostheses

Valves of four major mechanical heart valve producers were used: Medtronic Open Pivot (M-OP; Medtronic plc, Dublin, Ireland), Cryolife On-X (On-X; Cryolife Inc, Kennesaw, Georgia), LivaNova (Livanova plc, London, United Kingdom)—Carbomedics R (CarboR), and the Abbott (Abbott Laboratories, Lake Buff, Illinois) SJM Regent (Regent) valves. To make a sensible comparison, valves were selected with similar internal orifice diameters (IOD) instead of tissue annulus diameter (TAD), as according to International Standards Organization standard (ISO; Standard #5840-2: Cardiovascular Implants, Cardiac Valve Prostheses, Surgically Implanted Heart Valve Substitutes) valvar label should reflect TAD. We derived the IOD from sizes 23 and 25 from the manufacturer's specifications and, in addition, measured the IOD using a Vernier calliper. We chose prosthetic valves from these four brands so that the standard deviation (SD) of the four IOD's was as small as possible.

Statistics

Continuous data are presented as means and SDs. Spearman rank correlation coefficient was used to determine the correlation coefficient between leakage pressure. Curve fitting was used to find the best fit for relationship between pressure and valvar leakage for the four different valves. To determine differences between the four valve brands, analysis of variance testing was used. We performed a logarithmic transformation on the dependent variable leakage and the predictor variable pressure. A *P* value <.05 was considered statistically significant. For all statistical analyses, IBM SPSS Statistics version 23 was used.

Results

The IOD of the sizes 23 and 25 of the four manufacturers are shown in Table 1. We found no difference between our own IOD measurement with the Vernier calliper as compared to the diameters as supplied by the manufacturers. The mean IOD of the size 23 valves was 20.0 mm (SD: 1.6 mm) and of the 25 valves 21.9 mm (SD: 1.5 mm). The percentage range of the difference from the mean was −7.6% to + 6.9% for the size 23 valves and −6.5% to +6.7% for the size 25 valves. When we chose valves, irrespective of their label, to have the least SD, the mean IOD was 21.0 mm (SD: 0.45 mm). The percentage

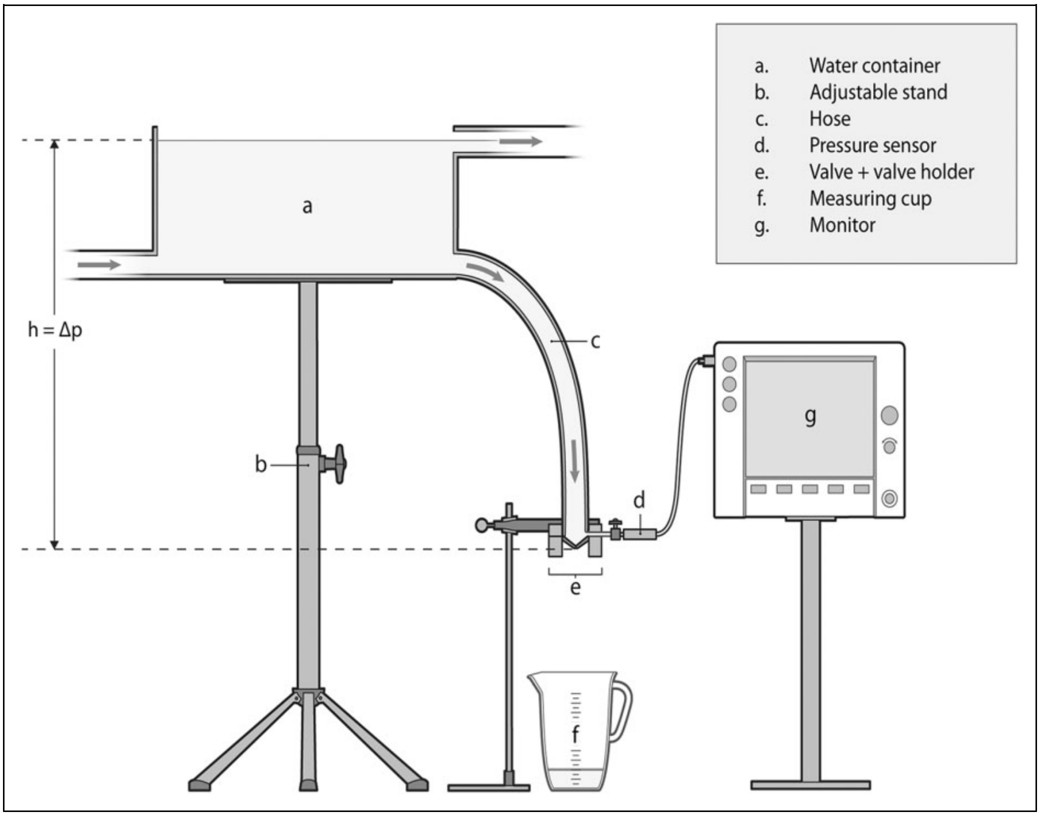


Figure 1. Test setup.

Table 1. Internal Orifice Diameter in Millimeters.[a]

Valve Label	23	25	Chosen Size	Choice
Medtronic M-OP	18.8 (−6.1%)	20.8 (−5.1%)	25	20.8 (−1.1%)
Cryolife On-X	21.4 (+6.9%)	23.4 (+6.7%)	23	21.4 (+1.8%)
Sorin/carbomedics R	18.5 (−7.6%)	20.5 (−6.5%)	25	20.5 (−2.5%)
St. Jude regent	21.4 (+6.9%)	23.0 (+4.9%)	23	21.4 (+1.8%)
Mean	20.0	22.0		21.0
Standard deviation	1.6	1.5		0.45

Abbreviations: IOD, internal orifice diameter; M-OP, Medtronic Open Pivot.
[a] Given IOD by the manufacturer and the deviation from the mean in percentage.

range of the difference from the mean then diminished to −2.5% to +1.8%. This led us to the choice of the following valves in our experiments: M-OP size 25, On-X size 23, CarboR size 25, Regent size 23.[12–15]

The leakage through the hinges was by far the largest of the entire regurgitant volume as could clearly be distinguished by direct observation (Figure 2). However, as the regurgitating fluid mixes right after having passed the valve, we found it impossible to separate these streams so as to make a reliable quantitative distinction between the two elements of regurgitation. There seemed not to be an obvious difference between the valves, so that the total regurgitant volume seems to allow for a realistic comparison between the hinge washing of the valves.

As expected, regurgitant volume (leakage) was positively correlated with pressure, $\rho = 0.93$, $P < .001$; all four valves showed an increase in leakage with increasing pressure (Figure 3). The increase in leakage volume was linear in the test pressure range from 3 to 10 mm Hg, with higher pressures the leakage increased in logarithmic fashion. The difference in leakage between 3 and 5 mm Hg pressure tests was not statistically significant. All valves differed significantly on mean leakage volumes ($P < .001$). The CarboR had 6.7% less leakage as compared to the On-X valve as reference, because it has the most leakage. The leakage of the Regent and M-OP valves was 60.4% and 53.8% less, respectively. In the high-pressure test area, the On-X and CarboR valve showed much higher leakage volumes at 80 mm Hg than the Regent and the M-OP valve: The On-X and the CarboR-valves show, respectively, a leakage of 596 ± 7 mL/min and 495 ± 30 mL/min, compared to 305 ± 13 L/min and 337 ± 33 mL/min for the Regent and

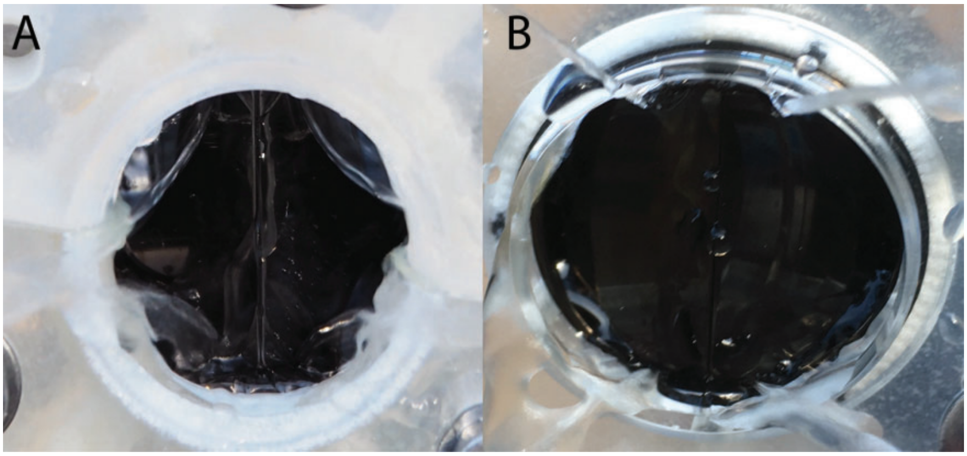
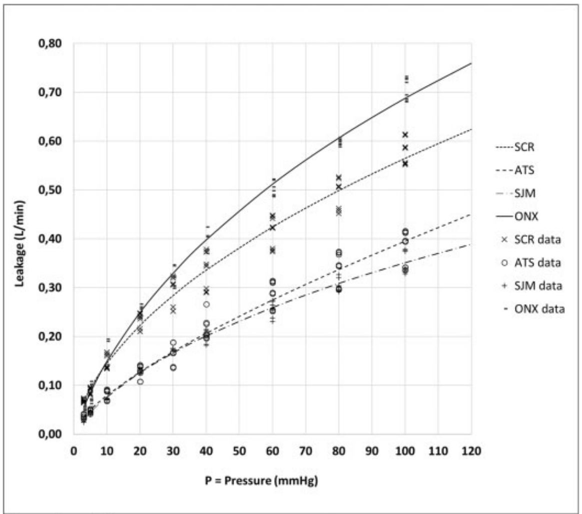


Figure 2. Image of valve leakage in closed position. A = Cryolife On-X size 23, B = Abbott SJM Regent size 23.



Regression coefficients

	SCR	ATS	SJM	ONX
Constant	-3.49	-3.81	-3.87	-3.37
B	0.63	`0.60	0.59	0.64
R^2	1.0	2.0	1.0	1.0

Figure 3. Valve leakage in the closed position, $\text{Leakage}=e^{\left(C+B\times\ln(p)\right)}$. M-OP, Medtronic Open Pivot-A size 25; ONX, Cryolife On-X size 23; SCR, LivaNova Carbomedics R-reduced size 25; SJM, Abbott SJM Regent size 23.

the M-OP valve. In the low-pressure test area, the On-X and CarboR valve showed higher leakage, respectively, 77 ± 21 mL/min and 90 ± 6 mL/min at 5 mm Hg, than the Regent and the M-OP, respectively, leaking 44 ± 3 and 48 ± 4 L/min at 5 mm Hg.

The leakage under pulmonary pressure (10 mm Hg) was 23.3% of that in the aortic pressure (80 mm Hg) for the Regent valve, 24.3% for the M-OP valve, 27.7% for the On-X valve, and 29.3% for the CarboR valve. In the most leaking On-X valve, the corresponding leakage dropped from 596 to 165 mL/min, which is a 72.3% decrease. In the least leaking Regent valve, the leakage volume flow decreased from 347 to 71 mL/min, which is 79.5% less. The proportional difference in hinge leakage between the Regent and On-X valves then differs from 347/596 = 58.2% at 80 mm Hg versus 71/165 = 43.0% at 10 mm Hg.

Several regression models were tested to find the best relationship between pressure p and valve leakage; the following model provided the highest coefficient of determination (R^2) for the relationship between pressure and leakage.

$$\text{Leakage}=e^{\left(C+B\times\ln(p)\right)},$$

p = pressure difference (mm Hg)

In Figure 3, the regression function and the regression parameters are shown, values for C and B can be found in Figure 3. Figure 4 shows a detailed figure of the low-pressure circumstances.

Discussion

This study has quantified the logarithmic relationship between pressure and regurgitant hinge flow in four major brands of mechanical valvar prostheses. In addition, we have demonstrated that there is considerable difference in hinge leakage between these four brands of aortic cardiac valvar prostheses. The relationship between pressure and leakage is logarithmic at pressures over 10 mm Hg and may be virtually linear at lower pressures. This implies that the leakage flow at pressures over 10 mm Hg is most likely diminished by turbulence, because a laminar flow would have yielded a linear relationship according to the Hagen-Poiseuille law. In addition to the quantification of the flow–pressure relationship, the location of the leakage flow occurs predominantly through the hinges. These hinges allow for a complex shape of the channel through which the water flowed, this shape being an element we did not investigate in this study. This means that the flow at lower, diastolic

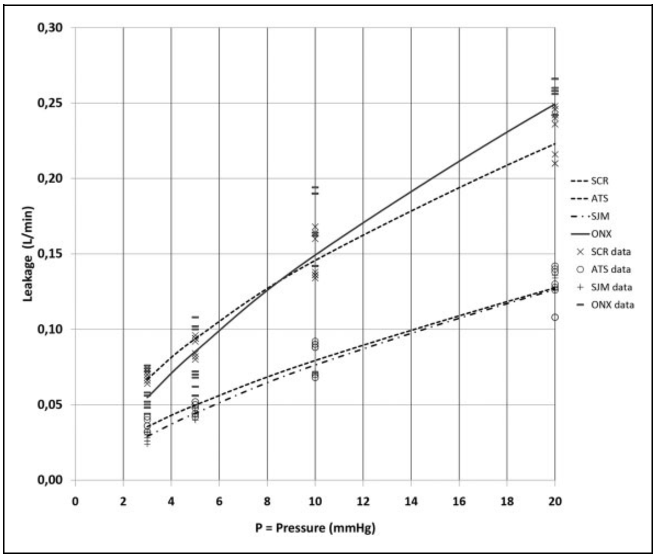


Figure 4. Detailed valve leakage in closed position up to 20 mm Hg. $\text{Leakage} = e^{\left(C + B \times \ln(p)\right)}$. M-OP, Medtronic Open Pivot-A size 25; ONX, Cryolife On-X size 23; SCR, LivaNova Carbomedics R-reduced size 25; SJM, Abbott SJM Regent size 23.

pulmonary pressure range is not turbulent and behaves according to the Hagen-Poiseuille law.

The amount of hinge leakage of these mechanical valvar prostheses under 10 mm Hg was about a quarter of the amount under 80 mm Hg. Obviously, these valves have not been designed for these low pressures. Furthermore, we have shown for the first time, to the best of our knowledge, that there is a substantial difference in this respect between valvar brands. Unknown is whether this difference plays a role in a possible difference between brands in the propensity for clot formation under pulmonary pressures.

The fact that we used water as test fluid means that the regurgitation of blood will be less than our measurements indicate, as the viscosity of blood is three to four times higher than the viscosity of water. Blood viscosity, however, is not a static factor as it is a so-called “non-Newtonian fluid.” Being non-Newtonian means that viscosity increases when shear rate goes down with lower flow (through lower pressure), thus with decreased vessel (channel) diameter such as a hinge. Nonetheless, we can think of no argument why the comparison between the valves would not be valid, because the magnitude of the non-Newtonian phenomena is limited. In addition, a pressure gradient of 10 mm Hg coincides with a Doppler velocity of about 1.6 m/s, where turbulence does not play a role. Thus, the regurgitant flow through the hinges is laminar in the pulmonary pressures. Furthermore, the viscosity conundrum cannot be solved using a water/glycerol mixture to mimic blood viscosity, because water/glycerol does not possess this “non-Newtonian” property. Instead, as the viscosity is three to four times higher than that of water/glycerol, the flow will proportionally decrease, in accordance to Poiseuille law. Turbulence ensued with increasing pressure above 10 mm Hg, leading to nonlinear increasing resistance, but did so for all tested valves in the same fashion. Arguably, the testing should have been done with blood; however, blood is a prohibitively inconvenient test fluid and would not have an advantage, particularly for pulmonary pressures. Thus, both water/glycerol and blood were not used, because in our conviction, the results reflect effective differences between aortic and pulmonary position.

Although the vast majority of the leakage flow is due to hinge leakage, the design of the bileaflet valves also includes some additional leakage flow through the so-called “B-datum gap” (the point where the two leaflets touch each other in closed position) and the periphery gaps (minor gap between the leaflets and the housing).[4] Although we could not quantify these different areas of leakage, our observation also confirms that the vast majority of the leakage occurred through the hinges. We are not aware of data quantifying the difference between these two areas of leakage. It is important to recognize that these values are all measurements over a continuous period of one minute, where the average adult heart beats 70 times per minute at rest. During one heartbeat, the valve is closed during approximately two-thirds of a cardiac cycle, which means that the average leakage per minute has to be divided by approximately 47 to obtain the value per heartbeat.

In this study, we focussed on hinge washing in mechanical prosthetic valves, and it must be noted that hinge washing can only have one valvar design characteristic of several that may influence valvar thrombosis.[4] An important influence on the formation of valvar thrombosis is the intrinsic hemodynamic properties of the valvar design.[16–18] Since valvar thrombosis is a highly complex phenomenon, there are other factors that could play a role in the development of a thrombosed valve. Nonetheless, hinge washing may play an important role in thrombus formation, and because it is quantifiable, it became the parameter of interest in this study.

Although similar research has not yet been published, Bottio et al did an in vitro comparison with four different valvar brands that are suitable for the replacement of a systemic atrioventricular valve (mitral and tricuspid) in children.[19] Of the four valves they tested, the On-X and the Regent valves coincide with the group of valves we tested. In contrast to our setup, they compared the valvar leakage under pulsatile conditions in a closed system, where pressures varied from 120 to 80 mm Hg, whereas for the pulmonary position, we focus on much lower pressure circumstances. The size of the valves they used varied from 18 to 19 mm; however, for the pulmonary position, these small sizes are hardly ever used. Although the setup is different from our study, they also found a higher average closed leakage volume for the On-X as compared to the Regent valve, which is in line with our results.

Jun et al have shown that the “hinge gap width” of mechanical valves is essential for thrombus formation. For aortic valves, a larger hinge gap width was associated with increased shear stresses and increased washout.[6] For the pulmonary position, the optimal hinge geometry might very well differ from the aortic position, most likely creating more washout potential. Our previous clinical research was underpowered to determine differences between brands.[1] The average rate of valvar thrombosis in the pulmonary position for all valve models was about 1.7% per patient year.

Limitations

Limitation of this study is that we compared single samples of four different cardiac valves, not considering the possibility of relevant differences between samples of the same size and valvar make. We have not found publications elaborating on the tolerance that the manufacturers allow in their production series, while the manufacturers themselves are not transparent about this feature. Furthermore, in this setup, we could not quantify the difference between regurgitant flow through the hinges and flow in between the leaflets and the housing, although visual observation indicated the majority of regurgitant flow to originate from the hinges.

Another potential limitation of our study was the usage of water for our experiments, as valve leakage and clot formation are influence by fluid viscosity. Testing our research question with blood is prohibitively complicated. For discovering the basic principles of leakage in mechanical valves and the basic differences between valves, water was an exceedingly convenient and theoretically acceptable test fluid,[19] with the additional advantage of being freely available.

Conclusion

Hinge washing has been shown to be related to the fluid pressure applied in closed position. Remarkable differences have been noticed between the different valve brands under pulmonary conditions. With the outcome of this research, we aim to provide knowledge that could be of use in selection of prosthetic valves for pulmonary valvar positions.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: H.P. and T.E. own rights to a patent for a mechanical valve design for the pulmonary position (US: 2018/14929A1; EU: 16718495.1-1664; China: 173605PCT-CN).

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Note

Standard #5840-2: Cardiovascular Implants, Cardiac Valve Prostheses, Surgically Implanted Heart Valve Substitutes.

References

1. Pragt H, van Melle JP, Javadikasgari H, et al. Mechanical valves in the pulmonary position: an international retrospective analysis. *J Thorac Cardiovasc Surg*. 2017;154(4): 1371-1378.e1.
2. Meuris B, Verbeken E, Flameng W. Mechanical valve thrombosis in a chronic animal model: differences between monoleaflet and bileaflet valves. *J Heart Valve Dis*. 2005;14(1): 96-104.
3. Scharfschwerdt M, Thomschke M, Sievers HH. In-vitro localization of initial flow-induced thrombus formation in bileaflet mechanical heart valves. *ASAIO J*. 2009;55(1): 19-23.
4. Dasi LP, Simon HA, Sucosky P, Yoganathan AP. Fluid mechanics of artificial heart valves. *Clin Exp Pharmacol Physiol*. 2009;36(2): 225-237.
5. Simon HA, Leo HL, Carberry J, Yoganathan AP. Comparison of the hinge flow fields of two bileaflet mechanical heart valves under aortic and mitral conditions. *Ann Biomed Eng*. 2004; 32(12): 1607-1617.
6. Jun BH, Saikrishnan N, Arjunon S, Min Yun B, Yoganathan AP. Effect of hinge gap width of a St. Jude medical bileaflet mechanical heart valve on blood damage potential—an in vitro micro particle image velocimetry study. *J Biomech Eng*. 2014;136(9): 091008.
7. Simon HA, Ge L, Sotiropoulos F, Yoganathan AP. Simulation of the three-dimensional hinge flow fields of a bileaflet mechanical heart valve under aortic conditions. *Ann Biomed Eng*.2010;38(3): 841-853.
8. Moons P, Bovijn L, Budts W, Belmans A, Gewillig M. Temporal trends in survival to adulthood among patients born with congenital heart disease from 1970 to 1992 in Belgium. *Circulation*. 2010;122(22): 2264-2272.
9. Baumgartner H, Bonhoeffer P, Groot NMD, et al. ESC Guidelines for the management of grown-up congenital heart disease (new version 2010). *Eur Heart J*. 2010;31(23): 2915-2957.
10. Henaine R, Roubertie F, Vergnat M, Ninet J. Valve replacement in children: a challenge for a whole life. *Arch Cardiovasc Dis*. 2012;105(10): 517-528.
11. Lee C, Park CS, Lee CH, et al. Durability of bioprosthetic valves in the pulmonary position: long-term follow-up of 181 implants in patients with congenital heart disease. *J Thorac Cardiovasc Surg*. 2011;142(2): 351-358.
12. Gebruiksaanwijzing. *SJM Regent Mechanische Hartklep (Dutch)*. St Paul, MN: St Jude Medical; 2009.
13. M-OP Medical. *Medtronic Open Pivotheart Valve, Instruction for Use*. Plymouth, MN: Medtronic M-OP Medical; 2012.
14. Sorin Biomedica Cardio S.r.L. *Carbomedics Prosthetic Heart Valve Instruction for Use*. Saluggia, Italy: Sorin Biomedica Cardio S.r.L; 2009.
15. On_x Prosthetic Heart Valve. *Instruction for Use*. Austin, TX: On-X Life Techologies; 2002.
16. Yoganathan AP, He Z, Casey Jones S. Fluid mechanics of heart valves. *Annu Rev Biomed Eng*. 2004;6: 331-362.
17. Govindarajan V, Udaykumar HS, Chandran KB. Flow dynamic comparison between recessed hinge and open pivot bi-leaflet heart valve designs. *J Mech Med Biol*. 2009;9(2): 161-176.
18. Travis BR, Marzec UM, Leo HL, et al. Bileaflet aortic valve prosthesis pivot geometry influences platelet secretion and anionic phospholipid exposure. *Ann Biomed Eng*. 2001;29(8): 657-664.
19. Bottio T, Lin CD, Lika A, et al. In vitro comparison of different mechanical prostheses suitable for replacement of the systemic atrioventricular valve in children. *J Thorac Cardiovasc Surg*. 2012;143(3): 558-568.