Review Article

Patient-Prosthesis Mismatch and Strategies to Prevent It During Aortic Valve Replacement

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Aortic valve replacement (AVR) is the well established treatment for patients with severe aortic valvular stenosis (AVS). It decreases (or eliminates) the pressure gradient between the left ventricle and ascending aorta and consequently leads to a gradual regress of left ventricular (LV) hypertrophy.[1,2] LV hypertrophy caused by severe aortic valve stenosis is associated with a high risk of sudden death, congestive heart failure, and stroke.[1] On the other hand, incomplete regression of LV hypertrophy after AVR has been shown to significantly reduce 10-year survival.[2-4] The concept of prosthesis-patient mismatch (PPM) was first introduced by Rahimtoola in 1978 as the situation in which "the effective prosthetic valve area, after insertion into the patient, is less than that of a normal human valve".[5] In other words, PPM is deemed to occur when the effective orifice area of the implanted prosthetic valve is too small in relation to the patient's body size, despite normal prosthesis function, resulting in an abnormally high postoperative pressure gradient.[6-8] By this definition, nearly all patients receiving a prosthetic aortic valve will have some degree of PPM, as the sewing ring, struts and leaflets of prostheses produce a relative obstruction to blood flow.[1,9] Although some authors claim that PPM is a rarely observed phenomenon without relevant clinical implications,[10-12] many others have argued that it occurs frequently and has important clinical consequences.[8,13-16] We reviewed the international bibliography and in this report we focus on the aetiology, pathophysiology and prevention of PPM.

Aetiology of PPM

The phenomenon of PPM is mainly attributed to two main reasons. First, patients with aortic valve disease frequently exhibit annulus calcification and fibrosis as well as LV hypertrophy, and these pathological processes can reduce the size of the aortic annulus.[1,3] In these situations a small prosthesis—in relation to the patient's body surface area (BSA)—should be implantated.[8] Second, because the stented prosthesis is inserted within the aorta and has its own annulus, the effective orifice area (EOA) after implantation is necessarily smaller than that of a normal native valve.[1,2] In fact, it has been shown that the EOA available for blood flow represents only 40% to 70% of the total area occupied by the valve.[17] However, the stentless valves without a fixed annulus alleviate this problem, and they generally provide a larger valve EOA in relation to the patient's BSA, as compared with stented

bioprostheses.[18-21] The EOA is a physiological parameter that represents the minimal cross-sectional area of the trans-prosthetic blood flow jet, and is easily measured by Doppler echocardiography. The only parameter that has been validated to identify PPM is the 'indexed' EOA, that is, the EOA of the prosthesis divided by the patient's BSA (indexed EOA = EOA/BSA).[7,22-24] Reference values for EOA data exist for each type and size of prosthesis, and they should ideally be derived from *in vivo* rather than *in vitro* values.[8,14]

Internal geometric area (IGA) is another anatomical parameter calculated from the static measurement of the internal diameter of the prosthesis. Unfortunately, IGA measurement varies from one type of prosthesis to the other, while the ratio between the EOA and the geometric area also varies widely from one type and/or size of prosthesis to another.[10,14,25] Notably, although these measurements are reproducible without significant variability, they have consistently been shown to be unrelated to either postoperative gradients[26] or clinical outcomes.[10,12,27-29] In fact, Koch et al[29] reported identical values for indexed IGA in patients with stented pericardial valves and patients with homografts, whereas peak and mean pressure gradients were twice as high in the former as in the latter. In addition, they found no relation between the indexed IGA and the clinical outcome of functional recovery after surgery.

Generally, haemodynamic compromise occurs when the indexed EOA of the prosthetic valve is calculated to be less than 75% of the native EOA, leading to high postoperative transvalvular gradients and reduced regression of left ventricular hypertrophy.[8] According to the commonly used definition, valve PPM is characterized as *severe* for indexed EOA ≤0.6 cm^2/m^2, *moderate* for values 0.6-0.85 cm^2/m^2, and *mild* for values >0.85 or 90 cm^2/m^2.[13,18,30-33] Interestingly, after AVR severe PPM occurs in 2-11% of patients, moderate PPM in 20-70%,[23] while after a mechanical implantation the incidence of significant mismatch may reach 60%.[34]

Prediction of PPM

Intraoperatively, a measured small prosthesis size is a widely recognized aetiological factor for postoperatively observed PPM. Consequently, a small valve implanted in the aortic position – generally prosthetic valves sized <20-21 mm (for an adult) – tend to have much higher gradients.[35-37] Factors that may predict PPM preoperatively are as follows: larger BSA, high BMI, older age, smaller prosthesis size, and valvular stenosis as the predominant lesion before the operation.[38-40] It is observed that PPM occurs more frequently in patients with stenotic native valves and in older patients. This is consistent with the overall concept, because patients with stenotic native valves generally have a smaller valvular annulus than those with regurgitant valves,[41] while calcific aortic stenosis is by far the most prevalent lesion in older patients undergoing AVR.[8]

Pathophysiologic consequences of PPM

It has been shown that PPM has a significant impact on important clinical outcomes, such as freedom from heart failure, LV mass regression and late survival, and that this impact is highly modulated by the functional status of the LV before surgery.[8,13,42,43] The temptation to conclude that PPM is an important consideration only in patients with impaired LV function and can almost be dismissed as irrelevant in patients with normal function should, however, be avoided.[6] The impact of PPM on clinical outcomes might well be at least as important as that of LV function.[6,44] It has been reported that a small decrease in indexed EOA may correspond to a large increase in transvalvular pressure gradient,[5,7,8,18,38] to less regression of LV hypertrophy, and to decreased survival after AVR.[42,43,45] Indeed, the extent of postoperative LV mass regression has been shown to be highly dependent on the type and size of prostheses used for valve replacement, as well as on their haemodynamic performance.[43,46,47] According to Pibarot et al,[40] in patients with PPM and an indexed EOA ≤0.85 cm^2/m^2 the trans-prosthetic gradient was found to be 22 ± 8 mm Hg, compared with 15 ± 6 mm Hg in patients without PPM. In addition, cardiac index, which was similar in patients with and without mismatch up to three years after the operation, decreased significantly thereafter only in patients with mismatch (-0.54 ± 0.32 vs. -0.17 ± 0.49 $L/min/m^2$, p=0.04). Although the deterioration in valve EOA was similar in both groups, during follow up the mean gradient increased significantly (6 ± 6 vs. 1 ± 1 mmHg) only in patients with PPM. The greatest postoperative deteriorations in cardiac index and gradients were seen in the patients with the most severe PPM (i.e. with an indexed EOA ≤0.65 cm^2/m^2).[8,40]

Influence on LV mass and function

As has been reported in many studies, there is a strong interaction between PPM and depressed LV function with regard to early mortality after AVR, and such an interaction also exists in relation to late mortality, heart failure, and LV mass regression.[14] The interaction between LV dysfunction and PPM is consistent with the concept that the increased LV afterload caused by PPM is less well tolerated in a poorly functioning ventricle than in a normal ventricle. Avoidance of PPM in patients with preoperative LV systolic dysfunction is, therefore, an important priority.[7] Regarding the expected LV mass regression after AVR, Barner et al[48] demonstrated that it is better in patients with a prosthesis size >21 mm (21%) than in patients with a prosthesis size ≤21 mm (8%). Nishimura et al[42] found that the mean wall thickness of the LV after AVR was directly related to the pressure gradient across the aortic prosthetic valve. In a recent study of 1103 patients with a bioprosthesis, Del Rizzo et al[49] found a strong relation between the indexed EOA and the extent of LV mass regression. At three years after the operation, the LV mass index had decreased by 23%, on average, in patients whose indexed EOA was >0.8 cm^2/m^2, as compared with 4.5% in patients with an indexed EOA <0.8 cm^2/m^2. In contrast, no difference was noted between the patients with an indexed EOA between 0.8 and 1.0 cm^2/m^2 and those with an indexed EOA >1.0 cm^2/m^2 (-24% vs. -22%).

Influence on physical capacity

Postoperative improvement of the patient's physical capacity is an important objective of AVR, because it directly influences the patient's symptomatic status, quality of life and rate of reemployment.[2,50] In addition, poor physical capacity is associated with a higher rate of late mortality after valve replacement.[4] De Carlo et al[51] reported that, among patients with a 21 mm St. Jude mechanical valve, those with a BSA >1.70 m^2 had significantly lower exercise tolerance than those with a BSA <1.70 m^2. Furthermore, the indexed valve EOA was an independent predictor of exercise tolerance variables. On the other hand, recent studies of patients with bioprosthetic aortic valves showed that maximal exercise capacity, as estimated by maximal workload, peak oxygen consumption or anaerobic threshold, is similar when patients with an indexed EOA ≤0.85 and >0.85 cm^2/m^2 are compared.[8,31]

Influence on operative mortality

According to Blais et al,[14] the impact of PPM was found to increase exponentially in relation to the degree of severity, to the extent that even patients with normal LV function were found to have a significant increase in early mortality when faced with severe PPM. PPM associated with increased operative mortality after AVR, particularly when combined with LV dysfunction,[14] can be predicted at the time of surgery and measures can be taken to avoid severe PPM.[26] These measures include performing an aortic annulus enlargement procedure,[52,53] or choosing a prosthesis with a larger effective orifice area—although such techniques may increase the complexity of the procedure and the operative mortality.[9]

Multi-centre data collected from 701 consecutive patients undergoing AVR showed that 30-day mortality was higher in those with PPM than in those without PPM (15.2% vs. 3.4%). Severe PPM was associated with increased early mortality by a factor of five to six times.[9,54,55] Blais et al,[14] in a similar study, found that severe PPM was associated with an 11.4-fold and 12.6-fold increase in early and late mortality by univariate and multivariate analysis, respectively.[14] In another study of patients after AVR using bioprostheses, Rao et al showed that early mortality was higher in those with an indexed EOA ≤0.75 cm^2/m^2 (7.9% vs. 4.6%).[56] Given that the LV is most vulnerable during the early postoperative period, it is intuitive to think that the increased afterload posed by PPM may be particularly deleterious and may lead to excess mortality during this period.[9] In contrast to this, three other studies found no difference in early mortality with PPM.[10,30,57] Concerning the early 30-day morbidity (stroke, prolonged ventilation, new renal failure, prolonged post-operative stay, prolonged ICU stay or readmission) among patients with severe PPM after AVR, one study found no association.[9]

Influence on late survival

Previous short- and intermediate-term survival analyses have not consistently identified PPM as an independent predictor of adverse outcomes.[10,12] It is therefore agreed that severe PPM increases early mortality, whereas its effect on late results is less clear. Clinically, severe PPM appears to be associated with a higher incidence of late symptoms of heart failure and less regression of LV hypertrophy, as deter-

mined by means of echocardiographic analysis.[44,58,57] Recently, an analysis from the Mayo Clinic identified severe PPM as an independent predictor of long term mortality in patients with small aortic valve prostheses.[13] However, it is important to note that only patients with small valves (19 and 21 mm) were included in that study. The study also excluded all short-term deaths, which might have biased the results because short-term mortality is higher in patients with moderate or severe PPM.[13] However, several studies have shown that PPM was associated with an increased risk of late mortality[13,34,44,59,60] and the greatest mortality risk was observed in patients with pre-existing LV systolic dysfunction.[14,44]

Although most,[11,14,59,61] but not all,[30] studies showed an impact of PPM on early mortality, the importance of PPM for long-term survival is still unclear. Indeed, some authors[56,58,59] did identify mismatch as a significant risk factor for reduced long-term survival, but others did not support this finding.[10-12,30] Among 469 adult patients who underwent mechanical AVR for aortic stenosis and were followed for a mean period of 7.9 years (interquartile range 5.0-10.0 years) the degree of PPM was minimal in 57%, moderate in 39%, and severe in only 4% of patients.[34] Seventy-five percent of severe PPM cases occurred after implantation of smaller (i.e. 19 and 21 mm) mechanical aortic valves. This severe mismatch occurred in 11% of all patients who received 19 or 21 mm mechanical valves. Twelve-year survival was 77% in patients with minimal mismatch, 63% in those with moderate mismatch, and only 47% in those with severe mismatch.[34] Another study of 533 patients who underwent AVR concerned the relationship between the measured EOA within 10 days after operation and the follow up for a mean follow-up time of 4.7 ± 2.2 years.[45] According to that measurement, moderate and severe PPM were observed in 52% and 28% of the patients, respectively. The adjusted survival rates at 5 and 7 years were 81 ± 4% and 65 ± 9% for patients with severe prosthesis-patient mismatch, 83 ± 3% and 69 ± 6% for patients with moderate mismatch, and 90 ± 4% and 87 ± 7% for patients with mild mismatch at discharge, respectively. Notably, the main decrease in survival was observed after 5 years. In another study involving 2576 pts undergoing AVR who were followed for a mean follow-up of 4.8 ± 3.4 years (median 4.3 years; maximum 14 years), the patients were divided in 3 groups according to PPM severity: non-significant (67%), moderate (31%), and severe (2%).[60] The total late survival was 79 ± 1% at 5 years and 59 ± 2% at 10 years. For patients with severe PPM, 5-year survival (74 ± 8%) and 10-year survival (40 ± 10%) were significantly lower than for patients with non-significant PPM (84 ± 1% and 61 ± 2%, respectively). There was also a trend towards lower survival in the severe PPM group when compared with the moderate PPM group (5-year survival: 81 ± 2%; 10-year survival: 57 ± 3%) and in the moderate PPM group when compared with the non-significant PPM group. Freedom from cardiovascular-related death was 92 ± 1% at 5 years and 79 ± 2% at 10 years in the whole series, and was significantly lower in patients with severe PPM (5-year: 78 ± 7%; 10-year: 50 ± 11%) than in those with moderate PPM (5-year: 90 ± 1%; 10-year: 77 ± 3%) and in those with non-significant PPM (5-year: 93 ± 1%; 10-year: 81 ± 2%). Notably, severe PPM was more significant for patients >70 years-old, with BMI <30 kg/m^2 and with LV ejection fraction (LVEF) <50%.[60]

Risk factors for operative and late mortality

Several factors, including age, BMI, and preoperative LV functional status, may potentially influence the effect of PPM and the postoperative outcome.[60,62] Some other risk factors could be advanced age, elevated preoperative serum creatinine, elevated mean pulmonary artery pressure, emergent intervention and a long total bypass time. Severe PPM was not associated with stroke, prolonged ventilation, new renal failure, prolonged postoperative stay, prolonged ICU stay or readmission within 30 days, by univariate or multivariate analysis.[9] One study[60] has shown that PPM reduces survival in patients with a BMI less than 30 kg/m^2, but not in those who are obese (BMI ≥30 kg/m^2). This finding is most likely related to the fact that the use of the body surface area for normalisation of EOA may overestimate the prevalence and severity of PPM in obese patients.[60]

According to some reports, severe PPM has a significant negative effect on late survival in younger patients.[60,62] This finding might be related to the fact that younger patients have higher cardiac output requirements. They certainly have higher basal metabolic rates and are generally more physically active. Also, because they have a longer life expectancy, younger patients are exposed to the risk of PPM for a longer period of time.[11] A possible explanation for the late effect of PPM on survival could be that patients with PPM undergoing long-term biopros-

thetic valve degeneration or development of pannus have less EOA "reserve" and will therefore develop severe stenosis of their valves more rapidly than patients without PPM undergoing the same processes. Also, older patients might be more likely to die from other causes before this process has any impact.[11,60] Moderate-to-severe PPM (indexed EOA ≤0.85 cm^2/m^2) was also an independent predictor of late mortality in patients with a preoperative LVEF <50%, but not in patients with preserved LV systolic function.[60] Previous studies[14] have shown increased early mortality in patients with a combination of moderate PPM and LV dysfunction, as well as in all patients with severe PPM, irrespective of LV function. Studies from other laboratories[44,63] have also demonstrated that the impact of moderate PPM on mid-term mortality is more important in patients with pre-existing LV dysfunction than in those with preserved LV function.

According to one study,[34] patient variables more commonly associated with greater degrees of mismatch included hypertension, increasing age, and higher BSA. Female sex was associated with more severe mismatch; however, this association is probably substantially confounded by the smaller prosthetic valve sizes often used in female patients. No significant differences were found in other domains at baseline. Age greater than 65 years was an independent risk factor for long-term mortality. Because the population is ageing, the incidence of degenerative aortic valve disease continues to grow, and the potential adverse effect of PPM on long-term survival in the elderly population is of increasing concern. However, there was no interaction between age and PPM. Instead, PPM predicted long-term mortality regardless of patient age.[34] Moderate or severe mismatch was most likely to occur in patients with larger BSA, older age, and smaller prosthesis size. The patients with substantial mismatch had significantly worse long-term outcomes than those with minimal mismatch.[34]

Therapeutic strategies

Prediction of mismatch at the time of surgery seems to be the optimal way to avoid PPM after AVR. Moderate PPM should be avoided in young patients (less than 65 years old), in patients who present with preoperative LV dysfunction or severe LV hypertrophy, as well as in physically active individuals.[7]

To avoid PPM, an algorithm has been suggested which can easily be applied in the operating room, according to the literature:[8]

- Step 1. Calculate the patient's BSA from weight and height using the equation or the chart, proposed by Dubois:[64]

$$BSA = weight^{0.425} \times height^{0.725} \times 0.007184$$

- Step 2. Ensure an indexed EOA >0.85, >0.80 or >0.75 cm^2/m^2, given the patient's BSA as calculated in step 1. The choice between 0.85, 0.80 and 0.75 cm^2/m^2 is based on the minimal requirement for a given patient, with the knowledge that 0.85 cm^2/m^2 or higher is the optimal value for better blood flow.[8]
- Step 3. Select the type and size of valve that has reference values for EOA greater than or equal to the minimal EOA value obtained in step 2.[8]

The reference values for EOA should therefore be readily available in the operating room to determine whether a particular prosthesis meets the requirements to avoid PPM. If not, the insertion of a larger prosthesis size or that of a different type with a better haemodynamic performance should be considered.[8]

However, strategies to avoid or reduce the severity of PPM should be individualised and should take into account multiple variables, such as age, BMI, lifestyle, LV function, LV hypertrophy, and the use of concomitant procedures.[2,3,15] For example, if moderate PPM is expected to occur in an elderly, sedentary patient with normal LV function, the benefits of doing an alternate procedure to avoid PPM might be estimated to be outweighed by the inherent risks or disadvantages of doing such a procedure. Prevention of PPM becomes an important consideration in a young, athletic individual, or if the patient has evidence of impaired LV function or severe LV hypertrophy. It has been emphasised that implantation of a small prosthesis does not necessarily result in PPM, and can be perfectly adequate in a patient with a small body size.[7] In the case of an anticipated PPM, alternate procedures may be included: a) aortic annulus enlargement[14,52] to accommodate a larger size of the same prosthesis model;[8,60] b) insertion of a prosthesis with a better haemodynamic performance, such as a stentless bioprosthesis;[8,60,65] c) implantation of a new generation stented or bileaflet mechanical prosthesis implanted in a supra-annular position;[60,66-68] d) homografts;[8,14] or e) performance of a Ross operation.[69] However, a considerable number of patients have also had mismatch after stentless valve implantation, even after full root replacement—although some of these cases are attributed

to technical reasons relating to the implantation procedure.[70]

Despite over 30 years of investigations and clinical applications, the ideal aortic valve substitute remains elusive. Although conventional stented bioprostheses avoid the hazards of embolisation and anticoagulation, the rigid stent design increases the likelihood of late structural failure and reoperation.[71] Furthermore, the obstructive nature of the stent leads to a non-physiological flow pattern and residual pressure gradient,[72] which—particularly in small valves—may have an important bearing on postoperative left ventricular mass regression and function, with an adverse clinical outcome.[73,74] It has therefore been suggested by many studies that, in patients with a measured aortic annulus diameter of 19 mm or smaller, prostheses with the largest actual orifice area provided by the manufacturer,[75,76] or other types of valve prostheses—i.e. stentless porcine,[43,77-80] aortic homograft,[81] or pulmonary autograft[42,82]—should be considered.

Aortic root replacement

In order to avoid PPM, patients could undergo an aortic root enlargement procedure.[83] The insertion of a larger prosthesis may require enlargement of the aortic root,[84] but the increased operative risk must be taken under consideration.[83] Some groups have successfully reduced the occurrence of PPM using aortic root enlargement, without any increase in operative risk.[52] Preoperative calculation of the projected indexed EOA can likewise be used to avoid the unwarranted use of aggressive procedures such as aortic root enlargement. The importance of these considerations becomes particularly evident in Asian patients, who often have a small aortic root. This characteristic is, however, often counterbalanced by the reduced cardiac output requirement inherent to small body size.[85] In this patient population, therefore, the implantation of a small prosthesis with a good haemodynamic performance often provides a valve EOA that is large enough to accommodate their cardiac output requirements.[7]

Prosthesis with better haemodynamic performance

It is known that, for any aortic annulus size, haemodynamic performance can vary widely from prosthesis to prosthesis. Indeed, haemodynamic performance is generally superior, and thus the prevalence and severity of PPM lower, in newer vs. older generations of prostheses, in mechanical vs. stented bioprosthetic valves, in supra-annular vs. intra-annular stented bioprostheses, and in stentless vs. stented bioprosthetic valves.[37,52,86]

Stentless valves

Lower rates of severe PPM were observed after insertion of stentless valves than after the use of stented biological valves.[87] The advent of stentless bioprostheses represents a major advance, because these prostheses generally have a much better haemodynamic performance than stented bioprostheses, both at rest and during exercise.[19,65,88-91] Another option is the stentless aortic xenograft, which was first introduced into the clinical arena by Binet and associates[91] in 1965. Despite excellent initial results, early enthusiasm waned because of premature structural deterioration as a consequence of the poor preservation methods. This concept of using the aortic root as a physiological stent for the valve prosthesis was revived by David et al[92] in 1987, when they initiated a new trial using a stentless porcine aortic valve. Indeed, stentless bioprostheses provide a larger EOA in relation to the patient's BSA, resulting in a larger indexed EOA and a lower gradient.[65]

The superior haemodynamic performance of stentless valves is due to the fact that, size for size, their EOA is generally larger than that of stented valves. Moreover, for the stentless valves, a larger prosthesis can be inserted in a smaller annulus.[20,65,93,94] Several studies have demonstrated that AVR with a stentless bioprosthesis is associated with a greater decrease in transvalvular gradient and LV wall stress, as well as with more complete regression of LV hypertrophy, compared with stented valves.[18,43,95] Stentless porcine valves were developed to help alleviate the problem of PPM by providing a larger EOA, thus improving flow through the valve and consequently LV function.[96] Nonetheless, the EOA of stentless valves remains somewhat smaller than that of the corresponding native valve, because they are usually implanted using techniques requiring insertion of the prosthesis within the patient's aorta.[8]

However, the implantation of stentless valves is more complex than for stented valves, requiring longer cardiopulmonary bypass and ischaemic times.[97] A study was conducted in 95 patients who underwent AVR with the Freestyle aortic root prosthesis. The 30-day mortality rate was 3 ± 2% (in-hospital mortal-

ity rate 2 ± 2%), with no death being directly valve-related, while the 1- and 5-year actuarial estimates of freedom from valve-related morbidity and mortality were 82 ± 4% and 79 ± 4%, respectively.[98] This prospective analysis demonstrated that the Freestyle stentless valve can be implanted safely with excellent mid-term clinical results. It has superb haemodynamics in terms of residual transvalvular pressure gradient, EOA, and regression of LV hypertrophy. It is a valuable alternative for those with a small aortic root, particularly in the elderly patient. The question of durability compared with conventional stented bioprostheses remains unanswered and requires longer follow up.[98] It was recommended that patients receive aspirin, 80 to 325 mg/d, for the first 12 postoperative weeks.[1] This study shows that the use of stentless valves for AVR in patients with aortic stenosis is associated with a similar degree of LV mass regression to a stented valve. Both valves provide regression of LV mass to within the normal range, but AVR with a stentless valve is associated with a significantly greater increase in EOA index and lower transvalvular velocities than a stented valve.[1]

The implantation of a stentless valve is more demanding than for a stented valve, and this is reflected by longer cardiopulmonary bypass and cross-clamp times. Some reports have shown higher hospital mortality with stentless valves than with stented valves,[99,100] but long-term mortality may be lower with stentless valves.[101] Both valves improved functional capacity, as measured by NHYA class and quality of life, but there was no difference between the 2 valve types. Similarly, 6-minute walking distance was significantly improved in both groups, and there were no differences between valve types.[1] In a case-matched study, Casali et al[102] showed a lower risk of cardiac death (77 ± 7% versus 90 ± 4%) and freedom from valve-related death (78 ± 7% versus 91 ± 4%) after 3 years in stentless versus stented patients, respectively.

Homografts

Other alternatives also include aortic homografts[103,104] or pulmonary autografts (Ross procedure),[105-108] which provide an indexed EOA similar to that of the normal native aortic valve. Although the aortic homograft, first introduced by Ross[109] in 1962, is an excellent alternative to the stented biologic prosthesis in terms of performance,[110,111] its clinical use is severely curtailed by its limited availability.

Conclusions

PPM is a risk factor in patients who undergo AVR and is associated with poor haemodynamic and symptomatic status. In patients with PPM, mortality and cardiac events are frequent. Every effort should be made to avoid severe PPM in all patients, especially in young patients who are physically active. However, PPM may be avoided by using newer generation prostheses, stentless valves or homografts, performing the Ross procedure, or carrying out aortic annulus enlargement.

References

1. Perez de Arenaza D, Lees B, Flather M, et al. Randomized comparison of stentless versus stented valves for aortic stenosis: effects on left ventricular mass. Circulation 2005; 112; 2696-2702.
2. Treasure T, Holmes L. Measuring the quality of life. J Heart Valve Dis. 1995; 4: 337-338.
3. Lund O, Kristensen LH, Baandrup U, et al. Myocardial structure as a determinant of pre- and postoperative ventricular function and long-term prognosis after valve replacement for aortic stenosis. Eur Heart J. 1998; 19: 1099-1108.
4. Bortolotti U, Milano A, Mossuto E, Mazzaro E, Thiene G, Casarotto D. Early and late outcome after reoperation for prosthetic valve dysfuntion: analysis of 549 patients during a 26-year period. J Heart Valve Dis. 1994; 3: 81-87.
5. Rahimtoola SH. The problem of valve prosthesis-patient mismatch. Circulation. 1978; 58: 20-24.
6. Dumesnil JG, Pibarot P. Prosthesis-patient mismatch and clinical outcomes: the evidence continues to accumulate. J Thorac Cardiovasc Surg. 2006; 131: 952-955.
7. Pibarot P, Dumesnil J. The relevance of prosthesis-patient mismatch after aortic valve replacement. Nat Clin Pract Cardiovasc Med. 2008; 5: 764-765.
8. Pibarot P, Dumesnil JG. Hemodynamic and clinical impact of prosthesis-patient mismatch in the aortic valve position and its prevention. J Am Coll Cardiol. 2000; 36: 1131-1141.
9. Yap CH, Mohajeri M, Yii M. Prosthesis-patient mismatch is associated with higher operative mortality following aortic valve replacement. Heart Lung Circ. 2007; 16: 260-264.
10. Medalion B, Blackstone EH, Lytle BW, White J, Arnold JH, Cosgrove DM. Aortic valve replacement: is valve size important? J Thorac Cardiovasc Surg. 2000; 119: 963-974.
11. Blackstone EH, Cosgrove DM, Jamieson WRE, et al. Prosthesis size and long-term survival after aortic valve replacement. J Thorac Cardiovasc Surg. 2003; 126: 783-796.
12. Hanayama N, Christakis GT, Mallidi HR, et al. Patient prosthesis mismatch is rare after aortic valve replacement: valve size may be irrelevant. Ann Thorac Surg. 2002; 73: 1822-1829.
13. Mohty D, Mohty-Echahidi D, Malouf JF, et al. Impact of prosthesis-patient mismatch on long-term survival in patients with small St Jude Medical mechanical prostheses in the aor-

tic position. Circulation. 2006; 113: 420-426.
14. Blais C, Dumesnil JG, Baillot R, Simard S, Doyle D, Pibarot P. Impact of valve prosthesis-patient mismatch on short-term mortality after aortic valve replacement. Circulation. 2003; 108: 983-988.
15. Botzenhardt F, Eichinger WB, Bleiziffer S, et al. Hemodynamic comparison of bioprostheses for complete supra-annular position in patients with small aortic annulus. J Am Coll Cardiol. 2005; 45: 2054-2060.
16. Milano A.D, De Carlo M, Mecozzi G, et al. Clinical outcome in patients with 19-mm and 21-mm St. Jude aortic prostheses: comparison at long-term follow-up. Ann Thorac Surg. 2002; 73: 37-43.
17. Carrel T, Zingg U, Jenni R, Aeschbacher B, Turina MI. Early in vivo experience with the Hemodynamic Plus St. Jude Medical heart valves in patients with narrowed aortic annulus. Ann Thorac Surg. 1996; 61: 1418-1422.
18. Pibarot P, Dumesnil JG, Jobin J, Cartier P, Honos G, Durand LG. Hemodynamic and physical performance during maximal exercise in patients with an aortic bioprosthetic valve: comparison of stentless versus stented bioprostheses. J Am Coll Cardiol. 1999; 34: 1609-1617.
19. Eriksson MJ, Rosfors S, Rådegran K, Brodin LA. Effects of exercise on Doppler-derived pressure difference, valve resistance, and effective orifice area in different aortic valve prostheses of similar size. Am J Cardiol. 1999; 83: 619-22, A10.
20. Walther T, Falk V, Langebartels G, et al. Prospectively randomized evaluation of stentless versus conventional biological aortic valves: impact on early regression of left ventricular hypertrophy. Circulation. 1999; 100(19 Suppl): II6-10.
21. Yun KL, Jamieson WR, Khonsari S, Burr LH, Munro AI, Sintek CF. Prosthesis-patient mismatch: hemodynamic comparison of stented and stentless aortic valves. Semin Thorac Cardiovasc Surg. 1999; 11(4 Suppl 1): 98-102.
22. Dumesnil JG, Honos GN, Lemieux M, Beauchemin J. Validation and applications of indexed aortic prosthetic valve areas calculated by Doppler echocardiography. J Am Coll Cardiol. 1990; 16: 637-643.
23. Pibarot P, Dumesnil JG. Prosthesis-patient mismatch: definition, clinical impact, and prevention. Heart. 2006; 92: 1022-1029.
24. Bleiziffer S, Eichinger WB, Hettich I, et al. Prediction of valve prosthesis-patient mismatch prior to aortic valve replacement: which is the best method? Heart. 2007; 93: 615-620.
25. Muneretto C, Bisleri G, Negri A, Manfredi J. The concept of patient-prosthesis mismatch. J Heart Valve Dis. 2004; 13 Suppl 1: S59-62.
26. Pibarot P, Dumesnil JG, Cartier PC, Métras J, Lemieux MD. Patient-prosthesis mismatch can be predicted at the time of operation. Ann Thorac Surg. 2001; 71: S265-268.
27. Knez I, Rienmüller R, Maier R, et al. Left ventricular architecture after valve replacement due to critical aortic stenosis: an approach to dis-/qualify the myth of valve prosthesis-patient mismatch? Eur J Cardiothorac Surg. 2001; 19: 797-805.
28. Freed DH, Tam JW, Moon MC, Harding GEJ, Ahmad E, Pascoe EA. Nineteen-millimeter prosthetic aortic valves allow normalization of left ventricular mass in elderly women. Ann Thorac Surg. 2002; 74: 2022-2025.
29. Koch CG, Khandwala F, Estafanous FG, Loop FD, Blackstone EH. Impact of prosthesis-patient size on functional recovery after aortic valve replacement. Circulation. 2005; 111: 3221-3229.
30. Howell NJ, Keogh BE, Barnet V, et al. Patient-prosthesis mismatch does not affect survival following aortic valve replacement. Eur J Cardiothorac Surg. 2006; 30: 10-14.
31. Pibarot P, Dumesnil JG, Jobin J, Lemieux M, Honos G, Durand LG. Usefulness of the indexed effective orifice area at rest in predicting an increase in gradient during maximum exercise in patients with a bioprosthesis in the aortic valve position. Am J Cardiol. 1999; 83: 542-546.
32. Rahimtoola SH. Perspective on valvular heart disease: an update. J Am Coll Cardiol. 1989; 14: 1-23.
33. Bonow RO, Carabello B, de Leon AC, et al. Guidelines for the management of patients with valvular heart disease: executive summary. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Management of Patients with Valvular Heart Disease). Circulation. 1998; 98: 1949-1984.
34. Kohsaka S, Mohan S, Virani S, et al. Prosthesis-patient mismatch affects long-term survival after mechanical valve replacement. J Thorac Cardiovasc Surg. 2008; 135: 1076-1080.
35. Bojar RM, Rastegar H, Payne DD, Mack CA, Schwartz SL. Clinical and hemodynamic performance of the 19-mm Carpenter-Edwards porcine bioprosthesis. Ann Thorac Surg. 1993; 56: 1141-1147.
36. Ihlen H, Mølstad P, Simonsen S, et al. Hemodynamic evaluation of the CarboMedics prosthetic heart valve in the aortic position: comparison of noninvasive and invasive techniques. Am Heart J. 1992; 123: 151-159.
37. Kallis P, Sneddon JF, Simpson IA, Fung A, Pepper JR, Smith EE. Clinical and hemodynamic evaluation of the 19-mm Carpentier-Edwards supraannular aortic valve. Ann Thorac Surg. 1992; 54: 1182-1185.
38. Dumesnil JG, Yoganathan AP. Valve prosthesis hemodynamics and the problem of high transprosthetic pressure gradients. Eur J Cardiothorac Surg. 1992; 6 Suppl 1: S34-37.
39. Pibarot P, Honos GN, Durand LG, Dumesnil JG. The effect of prosthesis-patient mismatch on aortic bioprosthetic valve hemodynamic performance and patient clinical status. Can J Cardiol. 1996; 12: 379-387.
40. Pibarot P, Dumesnil JG, Lemieux M, Cartier P, Métras J, Durand LG. Impact of prosthesis-patient mismatch on hemodynamic and symptomatic status, morbidity and mortality after aortic valve replacement with a bioprosthetic heart valve. J Heart Valve Dis. 1998; 7: 211-218.
41. Pantely G, Morton M, Rahimtoola SH. Effects of successful, uncomplicated valve replacement on ventricular hypertrophy, volume, and performance in aortic stenosis and in aortic incompetence. J Thorac Cardiovasc Surg. 1978; 75: 383-391.
42. Nishimura RA, Pieroni DR, Bierman FZ, et al. Second natural history study of congenital heart defects. Aortic stenosis: echocardiography. Circulation. 1993; 87(2 Suppl): I66-72
43. Jin XY, Zhang ZM, Gibson DG, Yacoub MH, Pepper JR. Effects of valve substitute on changes in left ventricular func-

tion and hypertrophy after aortic valve replacement. Ann Thorac Surg. 1996; 62: 683-690.
44. Ruel M, Al-Faleh H, Kulik A, Chan KL, Mesana TG, Burwash IG. Prosthesis-patient mismatch after aortic valve replacement predominantly affects patients with preexisting left ventricular dysfunction: effect on survival, freedom from heart failure, and left ventricular mass regression. J Thorac Cardiovasc Surg. 2006; 131: 1036-1044.
45. Florath I, Albert A, Rosendahl U, Ennker IC, Ennker J. Impact of valve prosthesis-patient mismatch estimated by echocardiographic-determined effective orifice area on long-term outcome after aortic valve replacement. Am Heart J. 2008; 155: 1135-1142.
46. Sim EK, Orszulak TA, Schaff HV, Shub C. Influence of prosthesis size on change in left ventricular mass following aortic valve replacement. Eur J Cardiothorac Surg. 1994; 8: 293-297.
47. González-Juanatey JR, García-Acuña JM, Vega Fernandez M, et al. Influence of the size of aortic valve prostheses on hemodynamics and change in left ventricular mass: implications for the surgical management of aortic stenosis. J Thorac Cardiovasc Surg. 1996; 112: 273-280.
48. Barner HB, Labovitz AJ, Fiore AC. Prosthetic valves for the small aortic root. J Card Surg. 1994; 9(2 Suppl): 154-157.
49. Del Rizzo DF, Abdoh A, Cartier P, Doty D, Westaby S. Factors affecting left ventricular mass regression after aortic valve replacement with stentless valves. Semin Thorac Cardiovasc Surg. 1999; 11(4 Suppl 1): 114-120.
50. Foster C, Oldridge NB, Dion W, et al. Time course of recovery during cardiac rehabilitation. J Cardiopulmon Rehabil. 1995; 15: 209-215.
51. De Carlo M, Milano A, Musumeci G, et al. Cardiopulmonary exercise testing in patients with 21mm St. Jude Medical aortic prosthesis. J Heart Valve Dis. 1999; 8: 522-529.
52. Castro LJ, Arcidi JM, Fisher AL, Gaudiani VA. Routine enlargement of the small aortic root: a preventive strategy to minimize mismatch. Ann Thorac Surg. 2002; 74: 31-6; discussion 36.
53. Sommers KE, David TE. Aortic valve replacement with patch enlargement of the aortic annulus. Ann Thorac Surg. 1997; 63: 1608-1612.
54. Rankin JS, Hammill BG, Ferguson TB, et al. Determinants of operative mortality in valvular heart surgery. J Thorac Cardiovasc Surg. 2006; 131: 547-557.
55. Jamieson WR, Edwards FH, Schwartz M, Bero JW, Clark RE, Grover FL. Risk stratification for cardiac valve replacement. National Cardiac Surgery Database. Database Committee of The Society of Thoracic Surgeons. Ann Thorac Surg. 1999; 67: 943-951.
56. Rao V, Jamieson WR, Ivanov J, Armstrong S, David TE. Prosthesis-patient mismatch affects survival after aortic valve replacement. Circulation. 2000; 102(19 Suppl 3): III5-9.
57. Ruel M, Rubens FD, Masters RG, et al. Late incidence and predictors of persistent or recurrent heart failure in patients with aortic prosthetic valves. J Thorac Cardiovasc Surg. 2004; 127: 149-159.
58. Tasca G, Mhagna Z, Perotti S, et al. Impact of prosthesis-patient mismatch on cardiac events and midterm mortality after aortic valve replacement in patients with pure aortic stenosis. Circulation. 2006; 113: 570-576.
59. Walther T, Rastan A, Falk V, et al. Patient prosthesis mismatch affects short- and long-term outcomes after aortic valve replacement. Eur J Cardiothorac Surg. 2006; 30: 15-19.
60. Mohty D, Dumesnil JG, Echahidi N, et al. Impact of prosthesis-patient mismatch on long-term survival after aortic valve replacement: influence of age, obesity, and left ventricular dysfunction. J Am Coll Cardiol. 2009; 53: 39-47.
61. Bridges CR, O'Brien SM, Cleveland JC, et al. Association between indices of prosthesis internal orifice size and operative mortality after isolated aortic valve replacement. J Thorac Cardiovasc Surg. 2007; 133: 1012-1021.
62. Moon MR, Pasque MK, Munfakh NA, et al. Prosthesis-patient mismatch after aortic valve replacement: impact of age and body size on late survival. Ann Thorac Surg. 2006; 81: 481-488.
63. Kulik A, Burwash IG, Kapila V, Mesana TG, Ruel M. Long-term outcomes after valve replacement for low-gradient aortic stenosis: Impact of prosthesis-patient mismatch. Circulation. 2006; 114(1 Suppl): I553-558.
64. Dubois E.F: Metabolism in Health and Disease. Philadelphia: Lea & Febiger, 1936.
65. Dumesnil JG, LeBlanc MH, Cartier PC, et al. Hemodynamic features of the freestyle aortic bioprosthesis compared with stented bioprosthesis. Ann Thorac Surg. 1998; 66: S130-133.
66. Botzenhardt F, Eichinger WB, Guenzinger R, et al. Hemodynamic performance and incidence of patient-prosthesis mismatch of the complete supraannular perimount magna bioprosthesis in the aortic position. Thorac Cardiovasc Surg. 2005; 53: 226-230.
67. Bach DS, Sakwa MP, Goldbach M, Petracek MR, Emery RW, Mohr FW. Hemodynamics and early clinical performance of the St. Jude Medical Regent mechanical aortic valve. Ann Thorac Surg. 2002; 74: 2003-2009.
68. Chambers J, Ely JL. Early postoperative echocardiographic hemodynamic performance of the On-X prosthetic heart valve: a multicenter study. J Heart Valve Dis. 1998; 7: 569-573.
69. Laforest I, Dumesnil JG, Briand M, Cartier PC, Pibarot P. Hemodynamic performance at rest and during exercise after aortic valve replacement: comparison of pulmonary autografts versus aortic homografts. Circulation. 2002; 106: I57-I62.
70. Albert A, Florath I, Rosendahl U, et al. Effect of surgeon on transprosthetic gradients after aortic valve replacement with Freestyle stentless bioprosthesis and its consequences: a follow-up study in 587 patients. J Cardiothorac Surg. 2007; 2: 40.
71. Jamieson WR. Modern cardiac valve devices: bioprostheses and mechanical prostheses: state of the art. J Card Surg. 1993; 8: 89-98.
72. Barratt-Boyes BG, Christie GW. What is the best bioprosthetic operation for the small aortic root?: allograft, autograft, porcine, pericardial? Stented or unstented? J Card Surg. 1994; 9: 158-164.
73. Jaffe WM, Coverdale HA, Roche AH, Whitlock RM, Neutze

JM, Barratt-Boyes BG. Rest and exercise hemodynamics of 20 to 23 mm allograft, Medtronic Intact (porcine), and St. Jude Medical valves in the aortic position. J Thorac Cardiovasc Surg. 1990; 100: 167-174.
74. Galloway AC, Colvin SB, Grossi EA, et al. Ten-year experience with aortic valve replacement in 482 patients of 70 years of age or older: operative risk and long-term results. Ann Thorac Surg. 1990; 49: 84-91.
75. Hunziker PR, Spöndlin B, Hediger S, Burckhardt D, Brett W, Buser P. Long-term follow-up and dobutamine stress echocardiography of 19-mm prosthetic heart valves. Echocardiography. 1998; 15: 617-624.
76. Gelsomino S, Morocutti G, Da Col P, et al. Early in vivo hemodynamic results after aortic valve replacement with the St Jude Medical Regent mechanical heart valve in patients with pure aortic stenosis. J Card Surg. 2003; 18: 125-132.
77. Marcus RH, Heinrich RS, Bednarz J, et al. Assessment of small-diameter aortic mechanical prostheses: physiological relevance of the Doppler gradient, utility of flow augmentation, and limitations of orifice area estimation. Circulation. 1998; 98: 866-872.
78. Silberman S, Shaheen J, Fink D, et al. Comparison of exercise hemodynamics among nonstented aortic bioprostheses, mechanical valves, and normal native aortic valves. J Card Surg. 1998; 13: 412-416.
79. Morsy S, Zahran M, Usama M, Elkhashab K, Abdel-Aziz I. Hemodynamic performance of stentless porcine bioprosthesis and mechanical bileaflet prosthesis using dobutamine stress echocardiography. Semin Thorac Cardiovasc Surg. 2001; 13: 129-135.
80. Kitamura M, Satoh M, Hachida M, Endo M, Hashimoto A, Koyanagi H. Aortic valve replacement in small aortic annulus with or without annular enlargement. J Heart Valve Dis. 1996; 5 Suppl 3: S289-293.
81. Jaffe WM, Coverdale HA, Roche AH, Brandt PW, Ormiston JA, Barratt-Boyes BG. Doppler echocardiography in the assessment of the homograft aortic valve. Am J Cardiol. 1989; 63: 1466-1470.
82. David TE, Feindel CM, Bos J, Sun Z, Scully HE, Rakowski H. Aortic valve replacement with a stentless porcine aortic valve. A six-year experience. J Thorac Cardiovasc Surg. 1994; 108: 1030-1036.
83. Niinami H, Aomi S, Tomioka H, Nakano K, Koyanagi H. A comparison of the in vivo performance of the 19-mm St. Jude Hemodynamic Plus and 21-mm standard valve. Ann Thorac Surg. 2002; 74: 1120-1124.
84. Nakano S, Matsuda H, Shimazaki Y, et al. An appraisal of patch enlargement of the small aortic annulus in 33 patients undergoing aortic valve replacement. Eur J Cardiothorac Surg. 1992; 6: 347-349.
85. Dumesnil JG, Pibarot P. Invited commentary. Ann Thorac Surg. 2008; 85: 1308-1309.
86. Roedler S, Moritz A, Wutte M, Hoda R, Wolner E. The CarboMedics "top hat" supraannular prosthesis in the small aortic root. J Card Surg. 1995; 10: 198-204.
87. Kunadian B, Vijayalakshmi K, Thornley AR, et al. Meta-analysis of valve hemodynamics and left ventricular mass regression for stentless versus stented aortic valves. Ann Thorac Surg. 2007; 84: 73-78.
88. Westaby S, Amarasena N, Long V, et al. Time-related hemodynamic changes after aortic replacement with the freestyle stentless xenograft. Ann Thorac Surg. 1995; 60: 1633-1638.
89. Eriksson MJ, Brodin LA, Dellgren GN, Rådegran K. Rest and exercise hemodynamics of an extended stentless aortic bioprosthesis. J Heart Valve Dis. 1997; 6: 653-660.
90. Cartier PC, Dumesnil JG, Métras J, et al. Clinical and hemodynamic performance of the Freestyle aortic root bioprosthesis. Ann Thorac Surg. 1999; 67: 345-349.
91. Binet JP, Duran CG, Carpenter A, Langlois J. Heterologous aortic valve transplantation. Lancet. 1965; 2: 1275.
92. David TE, Pollick C, Bos J. Aortic valve replacement with stentless porcine aortic bioprosthesis. J Thorac Cardiovasc Surg. 1990; 99: 113-118.
93. Del Rizzo DF, Goldman BS, Joyner CP, Sever J, Fremes SE, Christakis GT. Initial clinical experience with the Toronto stentless porcine valve. J Cardiac Surg. 1994; 9: 379-385.
94. Westaby S, Amarasena N, Ormerod O, Amarasena GA, Pillai R. Aortic valve replacement with the Freestyle stentless xenograft. Ann Thorac Surg. 1995; 60(2 Suppl): S422-427.
95. Pibarot P, Dumesnil JG, Leblanc MH, Cartier P, Métras J. Changes in left ventricular mass and function after aortic valve replacement: a comparison between stentless and stented bioprosthetic valves. J Am Soc Echocardiogr. 1999; 12: 981-987.
96. Collinson J, Henein M, Flather M, Pepper JR, Gibson DG. Valve replacement for aortic stenosis in patients with poor left ventricular function: comparison of early changes with stented and stentless valves. Circulation. 1999; 100: II1-5.
97. Kon ND, Westaby S, Amarasena N, Pillai R, Cordell AR. Comparison of implantation techniques using freestyle stentless porcine aortic valve. Ann Thorac Surg. 1995; 59: 857-862.
98. Yun KL, Sintek CF, Fletcher AD, et al. Aortic valve replacement with the Freestyle stentless bioprosthesis: five-year experience. Circulation 1999; 100(19 Suppl): II17-23.
99. Jin XY, Pepper JR. Do stentless valves make a difference? Eur J Cardiothorac Surg. 2002; 22: 95-100.
100. Kappetein AP, Braun J, Baur LH, et al. Outcome and follow-up of aortic valve replacement with the freestyle stentless bioprosthesis. Ann Thorac Surg. 2001; 71: 601-607.
101. Luciani GB, Casali G, Auriemma S, Santini F, Mazzucco A. Survival after stentless and stented xenograft aortic valve replacement: a concurrent, controlled trial. Ann Thorac Surg. 2002; 74: 1443-1449.
102. Casali G, Auriemma S, Santini F, Mazzucco A, Luciani GB. Survival after stentless and stented xenograft aortic valve replacement: a concurrent, case-match trial. Ital Heart J. 2004; 5: 282-289.
103. Ross D. Homograft replacement of the aortic valve. Br J Surg. 1967; 54: 842-843.
104. O'Brien MF, McGiffin DC, Stafford EG, et al. Allograft aortic valve replacement: long-term comparative clinical analysis of the viable cryopreserved and antibiotic 4°C stored valves. J Card Surg. 1991; 6: 534-543.
105. Ross DN. Replacement of aortic and mitral valves with a pul-

monary autograft. Lancet. 1967; 2: 956-958.
106. Elkins RC, Santangelo K, Stelzer P, Randolph JD, Knott-Craig CJ. Pulmonary autograft replacement of the aortic valve: an evolution of technique. J Card Surg. 1992; 7: 108-116.
107. Kouchoukos NT, Dávila-Román VG, Spray TL, Murphy SF, Perrillo JB. Replacement of the aortic root with a pulmonary autograft in children and young adults with aortic-valve disease. N Engl J Med. 1994; 330: 1-6.
108. Elkins RC. Pulmonary autograft—the optimal substitute for the aortic valve? N Engl J Med. 1994; 330: 59-60.
109. Ross DN. Homograft replacement of the aortic valve. Lancet. 1962; 2: 487.
110. Bodnar E, Wain WH, Martelli V, Ross DN. Long term performance of 580 homograft and autograft valves used for aortic valve replacement. Thorac Cardiovasc Surg. 1979; 27: 31-38.
111. Kirklin JK, Smith D, Novick W, et al. Long-term function of cryopreserved aortic homografts. A ten-year study. J Thorac Cardiovasc Surg. 1993; 106: 154-165.