

Review Article

Degeneration of Biological Heart Valve Prosthesis: Review of Pathophysiological Mechanisms, Current Interventions and Future Perspectives

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Abstract

The aim of this review is to review the main pathophysiological mechanisms of bioprosthesis' degeneration, the current interventions, either conventional or transcatheter therapies, and the future perspectives of bioengineering tissues in the degeneration of the bioprosthesis. Bioprosthesis are primarily used in valve replacements, both because they eliminate the need for oral anticoagulation and because of the specific profile of patients with valvular heart disease (elderly with higher risks of bleeding due to oral anticoagulation with warfarin, mandatory on mechanical heart valve prosthesis). However, bioprosthesis have limited durability and degeneration occurs due to the following factors: the bioprosthetic's heterologous tissue shows throughout time deposition of crystals of calcium phosphate, favored by the remnants of dead cells and fibrous structures of the tissue, resulting in dystrophic calcification; mechanical factors, since the assembly and design of the bioprosthesis favors greater shear stress on the heterologous pericardial leaflets, compared to the native valve; and also to factors related to the patient, such as hypertension, left ventricular hypertrophy and patient-prosthesis mismatch (which enhances shear stress), and age (under 60 years of age), rheumatic diseases, excessive calcium excretion and up-regulation of angiotensin-converting enzyme activity (which enhances formation of crystals of calcium phosphate). In this context, conventional reoperation for degenerated bioprosthesis is indicated; still, reoperation, especially in older patients with comorbidities, can add significant surgical risk. Transcatheter therapy (valve-in-valve and sequential valve-in-valve) emerges as recent, expanding and a viable alternative, in which a transcatheter valve is implanted within a degenerated bioprosthesis. Additionally, biological tissue engineering may enable longer-lasting bioprosthesis in the future. Tissue derived from autologous cells or pluripotent cells with decellularized xenogenic tissues may represent greater durability for bioprostheses, but require further researches and does not solve the main problem: the inexorable process of bioprosthesis' degeneration.

Keywords

Heterograft Bioprosthesis, Xenograft Bioprosthesis, Physiopathology, Transcatheter Valve Implantation, Heart Valves

1. Introduction

Nowadays, there are two heart valve prosthesis types available: mechanical or biological (or bioprosthesis). Me-

chanical heart valve prosthesis are made essentially of two pivoting discs of pyrolytic carbon. On the other hand, conven-

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tional bioprosthesis are made of a flexible plastic frame in which cusps of heterologous tissue (usually porcine or bovine pericardium) are mounted. It is worth noting that transcatheter valves are conceptually bioprosthesis as well; however, the cusps of heterologous tissue are mounted in a metallic alloy stent. The [figure 1](#) shows a conventional bioprosthesis and a transcatheter valve.

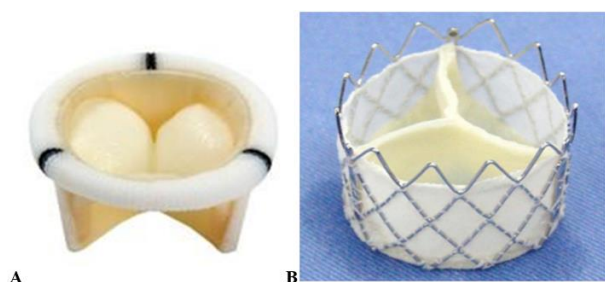


Figure 1. A. Braile conventional bioprosthesis. B. Braile Inovare transcatheter valve.

Apart from the long-term durability of mechanical heart valves, there are considerable advantages of bioprosthesis, specifically regarding biocompatibility and the abdication of oral anticoagulation by warfarin, with the respective drawbacks and risks. However, biological heart valve prosthesis degenerate, throughout some pathophysiological pathways, both by patient-related contributing factors, as well as the heterologous tissue of the bioprosthesis, requiring reoperation. Unfortunately, reoperation can add significant surgical risk. In this context, valve-in-valve emerges as an alternative for patients with higher surgical risk for reoperation of degenerated bioprosthesis, with great perspectives, even for sequential procedures. Additionally, in the near future tissue engineering can arise techniques such as decellularized xenogenic tissues for cell seeding or direct implantation, which may lead to a bioprosthesis with lower rate of degeneration. Thus, aims of this review relies on describing the main pathophysiological mechanisms of bioprosthesis' degeneration, the current interventions for degenerated bioprosthesis, either conventional surgery or transcatheter therapies, and also the future perspectives of bioengineering tissues.

Presently, due to the population profile with valvular heart disease, and the consequent risk of coumarin anticoagulation in this population, the use of bioprosthesis in valve replacements is gaining prominence. A practical proof of this is that is estimated that in the United States, between 2007 and 2011, 63.6% of prosthetic valve devices were made of bovine pericardium (an increase of 100% compared to the period from 1998 to 2001) [1, 2]. An important factor that justifies this data is the average age of patients with valvopathy: usually older, in which warfarin anticoagulation can imply considerable bleeding risk.

2. Degeneration of Bioprosthesis

It is well known that bioprosthetic valves have limited durability, despite the advantage of not requiring anticoagulation therapy. The primary factor limiting the longevity of bioprosthesis is structural valve degeneration, followed by endocarditis, paravalvular leak, thrombosis, among others [3-7].

A major pathophysiological mechanism of structural degeneration in bioprosthetic valves is dystrophic calcification of the cusps, which are typically made from heterologous pericardium [5, 8]. This is a passive process, not regulated by the host's cells, in which calcium phosphate crystals form in the remnants of dead cells and fibrous structures of the bioprosthesis [9, 10]. The cells preserved by glutaraldehyde fixation, following protein degeneration, mitochondrial dysfunction, and residual activity of alkaline phosphatase, allow for inorganic phosphate accumulation [9, 11, 12].

However, the calcification process may be influenced by factors related to the patient with a bioprosthesis, most notably the age of the patient at the time of implantation - especially those under 60 years of age. This may be partially explained by the higher calcium metabolism observed in younger individuals. Additional mechanisms of bioprosthesis degeneration are similar to those that predispose native valves to stenosis, such as: lipid deposition; upregulation of angiotensin-converting enzyme activity; autoimmune degeneration related to heterologous pericardium, with infiltration of macrophages and lymphocytes T, as observed in rheumatic disease; excessive calcium excretion by the patient, such as chronic kidney disease; hyperparathyroidism and parathyroid tumors (conditions that alter calcium metabolism) [8-10].

Another physiopathological process of considerable importance in bioprosthesis degeneration is mechanical degeneration. Due to continuous biomechanical stress, bioprosthetic valves - unlike native valves - are more susceptible to hemodynamic forces (shear stress or shear force). Repetitive, long-term stress on the heterologous pericardial cusps leads to collagen damage and loss of glycosaminoglycans from the extracellular matrix, exacerbated by glutaraldehyde treatment, which impairs regenerative capacity and elastic recoil. This results in retraction of the leaflets, formation of discontinuities on their surface, and ultimately facilitates calcific and mechanical degeneration, including leaflet tearing [8-10, 13].

In addition to these factors, patient-related hydrodynamic issues also contribute to bioprosthesis degeneration, particularly systemic arterial hypertension and left ventricular hypertrophy (associated with chronic stress on the valve leaflets due to incomplete diastolic closure). Such conditions are common in patients receiving bioprosthesis [9-11]. The disproportion between the valve area and the patient's body surface area (patient-prosthesis mismatch) at the time of implantation is also a significant factor [14-17].

The [Figure 2](#) summarizes the pathophysiological mechanisms aforementioned, and the [Figure 3](#) shows a degenerated bioprosthesis.

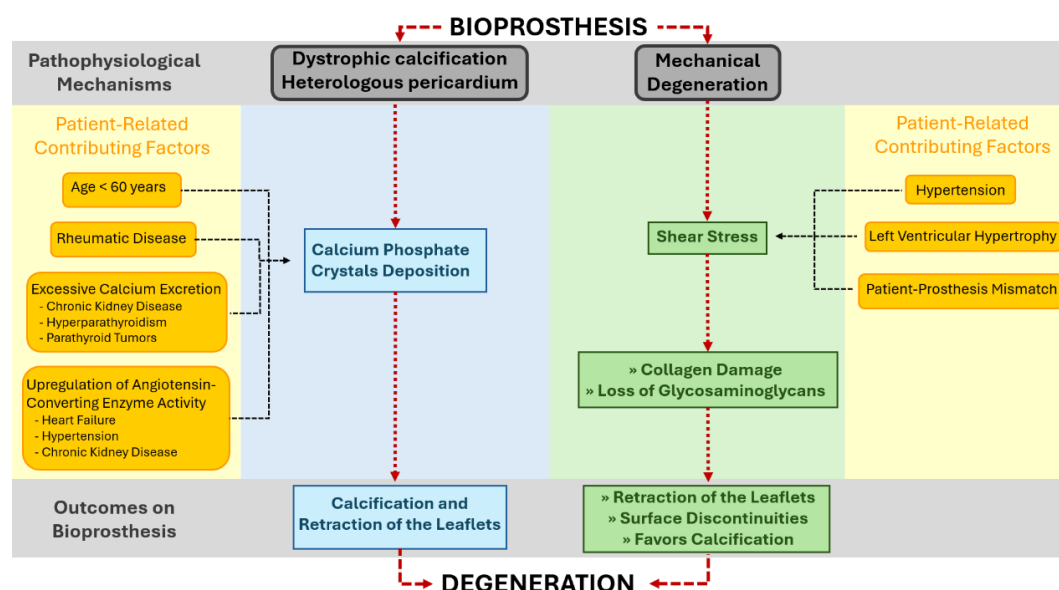


Figure 2. Diagram illustrating the pathophysiological mechanisms involved in the degeneration of bioprosthesis.



Figure 3. Bioprosthesis with intense degeneration, highlighting calcification of the cusps. Extracted from Kostyunin et al 2020.

Currently, conventional bioprosthesis offer longer durability, largely due to the improved treatment of heterologous tissues and enhanced processing techniques that better preserve the pericardial extracellular matrix. Additionally, anti-calcification agents and cryopreservation techniques have contributed to this improvement. In general, even with substantial valve degeneration, there is no significant dysfunction of the bioprosthesis until after the 10th year post-implantation [8, 10, 15].

3. Interventions: Conventional Reoperation and Transcatheter Procedures

In general, conventional bioprosthesis degeneration requires reoperation, with thoracotomy and cardiopulmonary

bypass, which has a significant higher surgical risk than the first surgery (up to 8%). It is the gold-standard to treat degenerated bioprosthesis [1].

However, in this century, the development and widespread adoption of transcatheter valves therapy has garnered attention. Although these valves are also made from heterologous pericardium, like conventional bioprosthesis, their implantation via transcatheter allows for individualized treatment in higher surgical risk patients. *In vitro* hemodynamic studies have identified higher shear stress in transcatheter bioprosthesis compared to surgical ones. Moreover, the mispositioning of these valves may lead to uneven stress on the leaflets. This results in leaflet crimping and greater early fiber damage in the heterologous pericardium. However, clinical data evaluating long-term durability of transcatheter valves, particularly in 10-year follow-up cohorts, show durability comparable to conventional bioprosthesis [16-21].

Since 2002, when Cribier described the first-in-human transcatheter valve implantation in the aortic position [22], there was widespread use of transcatheter valves not only for the treatment of aortic valve stenosis, but also for degenerated conventional bioprosthesis has started (known as "valve-in-valve"), which the first in human implantation was performed by Wenaweser in 2007 [23]. Moreover, it comes from 2016 the first report of sequential valve-in-valve implantation in a degenerated transcatheter valve previously implanted in a bioprosthesis, by Leung et al. [24]. Figure 4 shows a valve-in-valve and a sequential valve-in-valve set applied for in vitro study.

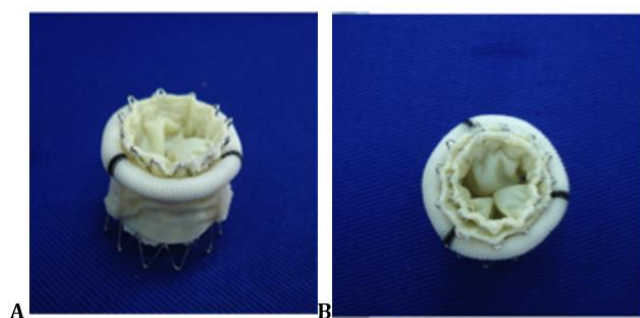


Figure 4. A. A set of a Braile conventional bioprosthesis and a Braile Inovare transcatheter valve. B. The implantation of another Braile Inovare transcatheter valve inside the set shown in A.

The in vitro research on valve-in-valve and sequential valve-in-valve with a Brazilian transcatheter valve and Brazilian bioprosthesis [25] provide valuable insights for the clinical application of the valve-in-valve procedure, considering the different combinations of bioprosthesis sizes and transcatheter valves, and allows a great reflection about alternatives to bioprosthesis degeneration reoperation. Moreover, the possibility of sequential valve-in-valve may even impact on the choice of valve prosthesis at the time of the first procedure, favoring the choice of bioprosthesis.

As the durability of transcatheter valve resembles conventional bioprosthesis, it is possible to figure out that a patient can have sequential valve-in-valve implants throughout life. Nevertheless, patient-prosthesis-mismatch plays an important role, especially in valve-in-valve, determining if the procedure is feasible. Despite a normally functioning valve prosthesis, if the area and respective transvalvular gradient resulting after valve implantation are restrictive, in relation to the patient's body surface, a disproportion between patient and prosthesis is configured as patient-prosthesis mismatch.

For instance, accordingly to the aforementioned study, a patient with a 25 mm size bioprosthesis can have sequential implantation of two transcatheter valves in valve-in-valve modality, with safe hydrodynamic parameters. In practical terms, and with certain extrapolations regarding valve durability, this patient may be free of conventional reoperation up to 30 years after valve replacement with a conventional bioprosthesis.

4. Future Perspectives

Transcatheter therapy and valve-in-valve is a current reality in consolidation and expansion. Though, it does not solve the main problem: the inexorable process of bioprosthesis' degeneration.

Ongoing researches have shown promising early results regarding bioprosthesis made from tissue derived from autologous cells, which may in the future offer greater durability. Nevertheless, this would not eliminate the inevitable degenerative process of bioprosthesis, as mechanical factors would still persist in this potential type of bioprosthesis [26].

In this sense, tissue engineering using pluripotent stem cells is a possible solution to replace tissues or organs with compromised function and has proven to be a good alternative for improving bioprosthesis [27]. Considered challenges leading to bioprosthesis degradation are fibrous tissue growth, prosthesis obstruction by thrombi, and the patient's immune system reactions [28].

To address these, some techniques have been applied in tissue engineering such as decellularized xenogenic tissues for cell seeding or direct implantation, which induce tissue regeneration when used in vitro and serve as scaffolds for cell colonization; constructs containing polymerized extracellular matrix and entrapped cells — collagen, elastin, hyaluronic acid, fibronectin, and fibrin — that promote cell adhesion, reduce smooth muscle cell migration and proliferation, induce angiogenesis, and increase elastic fiber synthesis; and degradable synthetic scaffolds pre-seeded with cells, creating a high surface-area-to-volume ratio in three-dimensional structures, increasing adhesion and growth, although triggering some inflammatory processes [28].

However, there are still many limitations and developments to be improved for the use and advancement in the field of tissue engineering. Thus, studies, tests, and laboratory analysis are essential for preparing bioartificial prostheses with autologous components using tissue engineering. It should be emphasized that bioprosthesis degradation can be reduced or even postponed but is still an inevitable factor [8].

5. Conclusions

Bioprosthesis are an effective option for heart valve replacement and are often chosen over mechanical prostheses, particularly because they do not require anticoagulation. However, they are subject to the inevitable process of degeneration, based on mechanical factors and dystrophic calcification of the leaflets, and with contributing factors related to the patient.

The gold-standard treatment for degenerated bioprosthesis is reoperation, with thoracotomy and cardiopulmonary bypass. The implication of reoperation is an increase in surgical risk; in this context, transcatheter therapy in the valve-in-valve modality is an alternative for reoperation in patients with higher surgical risk, and the possibility of sequential procedures can mitigate a drawback of conventional bioprosthesis — the need of reoperation — reducing the procedure risks. Yet, there are restrictions for performing valve-in-valve (or sequential valve-in-valve): the transcatheter valve is made of heterologous pericardium, and like bioprostheses, has limited durability; moreover, there is dependence on the size of the conventional bioprosthesis implanted: valve-in-valve in smaller bioprosthesis can lead to patient-prosthesis mismatch.

Biological tissue engineering has a good chance of reducing, but not eliminating, the degeneration of bioprosthesis. Associating enhanced biomaterials, decellularization techniques, progressively better anticalcification of tissues, and improvements on prosthesis design, in order to reduce shear

stress, can lead to longer-lasting bioprosthesis or transcatheter valves, reducing the number of interventions.

Thus, there are currently interventions for degenerated bioprosthesis, and the options can be individualized to the patient: either conventional prosthesis replacement with thoracotomy and cardiopulmonary bypass, or valve-in-valve for patients with high surgical risk. And tissue engineering can positively contribute to mitigate the inevitable process of bioprosthetic degeneration.

Author Contributions

Caio Cesar Cardoso: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing

Ana Luiza Boucault Peres: Data curation, Formal Analysis, Investigation, Writing – original draft, Writing – review & editing

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

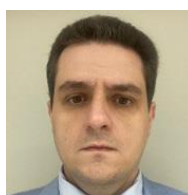
The authors declare no conflicts of interest.

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Biography



Caio Cesar Cardoso is a physician graduated from the Faculty of Medical Sciences of Santa Casa de Sao Paulo. General Surgeon from the Irmandade of Santa Casa de Misericórdia de Sao Paulo and Cardiovascular Surgeon from the Federal University of Sao Paulo. Has professional Master's Degree in New Technologies and Healthcare from the Federal University of Sao Paulo and doctorate in Cardiology from the Federal University of Sao Paulo. Works as professor of Medicine at the School of Medical Sciences of Santa Casa de Sao Paulo, physician in charge of the Cardiac Implantable Electronic Devices Outpatient Clinic of the Irmandade of Santa Casa de Misericórdia de Sao Paulo, head of the Cardiovascular Surgery Department at the Adventist Hospital of Sao Paulo and Cardiovascular Surgeon at Stella Maris Hospital. Also is an Associate Editor of Journal of Cardiology and Cardiovascular Research.



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Research Fields

Caio Cesar Cardoso: cardiovascular surgery, transcatheter valves, valve-in-valve, bioprosthesis, heart valve prosthesis

Ana Luiza Boucault Peres: medicine, heart valve prosthesis