REVIEW

Analysis of prosthetic cardiac devices: a guide for the practising pathologist

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Pathologists all over the world increasingly encounter prosthetic cardiac devices. A good evaluation of these devices is a valuable source of information, which can contribute to patient care and the appreciation and understanding of the pathobiology involved in the changes occurring between the host and the implanted prosthetic device. This article summarises the considerations underlying the analysis of prosthetic devices (particularly prosthetic heart valves), including the identification of the devices, the major morphological features of the devices, their modes of failure, and some technical details about evaluation and pitfalls.

Prosthetic cardiac devices improve survival and greatly increase the quality of life in most patients.[1] Despite considerable advances in the technology behind prosthetic devices, these devices are still far from perfect, and ongoing changes continue to be made in an effort to enhance their function, effectiveness, and life expectancy.[2] Detailed evaluation of explanted devices (failed or still functional) can contribute to the future care of patients needing these devices, in addition to establishing the mechanisms of change and the pathobiology of failure of these devices. Many of these devices are still not ''perfect''. In the case of new devices (new coronary and aortic stents) or modifications to devices that have been in use for some time, we suggest that the device should be referred to colleagues with the facilities and interest necessary for detailed analysis, or to the manufacturers, who will probably conduct a thorough and exhaustive analysis. Ongoing evaluation will also help to define the structural features of those devices that are most important and which are most beneficial to the host. Understanding these features may help to predict the modifications needed in the future development of these devices, in an effort to improve their safety and durability. We present a brief summary of the approach to the analysis of prosthetic cardiovascular devices, followed by a more detailed description and analysis of different devices.

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''Detailed evaluation of explanted devices (failed or still functional) can contribute to the future care of patients needing these devices, in addition to establishing the mechanisms of change and the pathobiology of failure of these devices''

We will emphasise the following: (1) the objectives of evaluation, (2) the techniques of evaluation, and (3) the use of technical and other data in the necropsy/surgical pathology evaluation of prosthetic devices in individual patients.

Because prosthetic heart valves (PHVs) have been in use for a considerably longer period than most other devices, a more detailed analysis of these is presented.

Objectives of the analysis of prosthetic cardiac devices

The pathologist at the surgical pathology bench today often sees prosthetic cardiovascular devices that surgeons have explanted, or they may be seen at the time of necropsy (table 1). The detailed and complete examination of these devices can provide invaluable information. The collected information should include the following: (1) the type of device used and its manufacturer; (2) documentation of the types of changes seen in the device, such as structural deterioration, calcification, or pannus overgrowth; and (3) correlation of the morphological features in the explanted device with the clinical features, to provide a basis for an explanation of dysfunction—that is, occlusion, stenosis, or incompetence, or device failure. In any one patient, the determination of the cause of failure may contribute to subsequent management, particularly when (1) a diagnosis of infection (infective endocarditis in the case of PHVs) is made, which would necessitate a course of appropriate antibiotic treatment for the microorganism seen; (2) the presence of a thrombus is noted on a prosthetic device, which might convince the surgeon of the need to initiate immediate anticoagulant treatment.

The analysis of a series of explanted devices will allow the rates and modes of failure to be defined, and the specific modes of failure of particular devices to be characterised. The clinical pathological examination and analysis of explanted devices, either new devices or modified devices, allows correlations and the compilation of data based on human experience, often far different than that obtained from the initial animal studies. The analyses also allow the biocompatibility of the host and the materials composing the device to be defined. In some instances, the establishment of timeframes of

Abbreviations: BHV, bioprosthetic heart valve; MHV, mechanical heart valve; PHV, prosthetic heart valve

Table 1 Prosthetic cardiovascular devices

Cardiac	Vascular
(1) Prosthetic heart valves	(1) Synthetic grafts
Bioprosthesis	Dacron
Mechanical prosthesis	PTFE
Bentall grafts (conduit with prosthesis)	
(2) Annuloplasty rings	(2) Tissue patches (pericardial)
(3) Synthetic sutures	(3) Synthetic patches
For bypass grafts	
For artificial chordae tendineae	(4) Vascular stents
(4) Pacemaker leads	(5) Endovascular devices
(5) Defibrillator leads	
(6) Tissue patches	
(7) Ventricular assist devices (rare)	
(8) Artificial hearts (rare)	

occurrence of pathological evidence of failure allows a correlation to be made with abnormalities noted on clinical investigation (such as echocardiography, computerised tomographic scan, or magnetic resonance imaging), and helps decide the time and situations in which intervention is warranted.

In addition, the observed failure modes and mechanisms help in the development of improved and new devices. Although relatively few devices are obtained before failure, when they are obtained at necropsy or at heart transplant, these devices do allow the establishment of morphological features at intermediate timeframes, before the development of overt failure. One may then speculate on the rate of progression of changes and the clinical and pathological features of devices that have functioned well, and obtain some idea of the sites where problems, such as failure modes, may arise, including the sites at which thrombus may be initiated.

> "The observed failure modes and mechanisms help in the development of improved and new devices"

Knowledge of these findings can help a pathologist involved in the examination of devices from preclinical animal studies (for example, materials implanted in large animals), and can also provide expert evidence in medical legal cases related to device failure. In many, if not most, countries where devices are implanted, the state often has rules and regulations pertaining to the reporting of device related clinical problems and complications. In the USA, this is specified in the Safe Medical Devices Act of 1990 (PL101–619),[3] and in Canada is mandated by the health protection branch of the Federal Ministry of Health and in the UK by the equivalent section at the Ministry of Health. In many jurisdictions, the law requires the reporting of device related deaths, serious illnesses, and injuries, by all health care personnel aware of the same, to the appropriate authorities or the manufacturers or both, depending on the nature of the incident. Any pathologist who makes this initial discovery of harm or damage relatable to a medical device malfunction should initiate this reporting process.

The reporting of findings in prosthetic cardiovascular devices necessitates some knowledge about the devices, their identifying features, and the established and potential failure modes of those devices used under particular circumstances at particular sites. Knowledge of the clinical data is usually helpful in making appropriate clinical–pathological correlations. In each situation, several generic types and many models of prosthetic devices have been used, and in some situations continue to be used.[4 5] Many have long since been

1. Demographic/relevant clinical data

2. Photography: all surfaces

3. Radiology, of all devises to
- (i) Confirm presence (or absence) and extent of calcification
- (ii) Identify the device
- (iii) Determine device integrity – exclude fractures of metal struts
- (iv) Examine endovascular stents (need multiplane *x* rays)

4. Dimensions: external and internal

5. Gross description: special emphasis on
- (i) Appearance, normal/abnormal
- (ii) Presence of thrombus/blood
- (iii) Host tissue (pannus), extent
- (iv) Vegetation(s): colour, size, site, fixation, friability
- (v) Mechanical valves:
  - (a) Note asymmetry
  - (b) Irregularity
  - (c) Cracks and fractures
  - (d) Mobility of components
- (vi) Tissue valves
  - (a) Shape
  - (b) Colour
  - (c) Location
  - (d) Calcific deposits
  - (e) Cusp tears
  - (f) Mobility of the cusps
  - (g) Appearance of commissural regions
- (vii) Stents or tube grafts
  - (a) Lumen size
  - (b) Presence of thrombus
  - (c) Degree of stenosis of lumen

6. Tissues for histology
- (i) Common stains
  - (a) Stain for microorganisms
  - (b) Stain for connective tissue
  - (c) Stain for calcium
- (ii) Mechanical valves
  - (a) Vegetations
  - (b) Pannus and underlying sewing cuff
- (iii) Tissue valves
  - (a) Parts of cuspal tissue (longitudinal sections)
  - (b) Porcine aortic commissural region
  - (c) Any tissue adherent to device
  - (d) Thrombus of any age (note location)

Figure 1 Gross examination of prosthetic heart devices: essential steps.

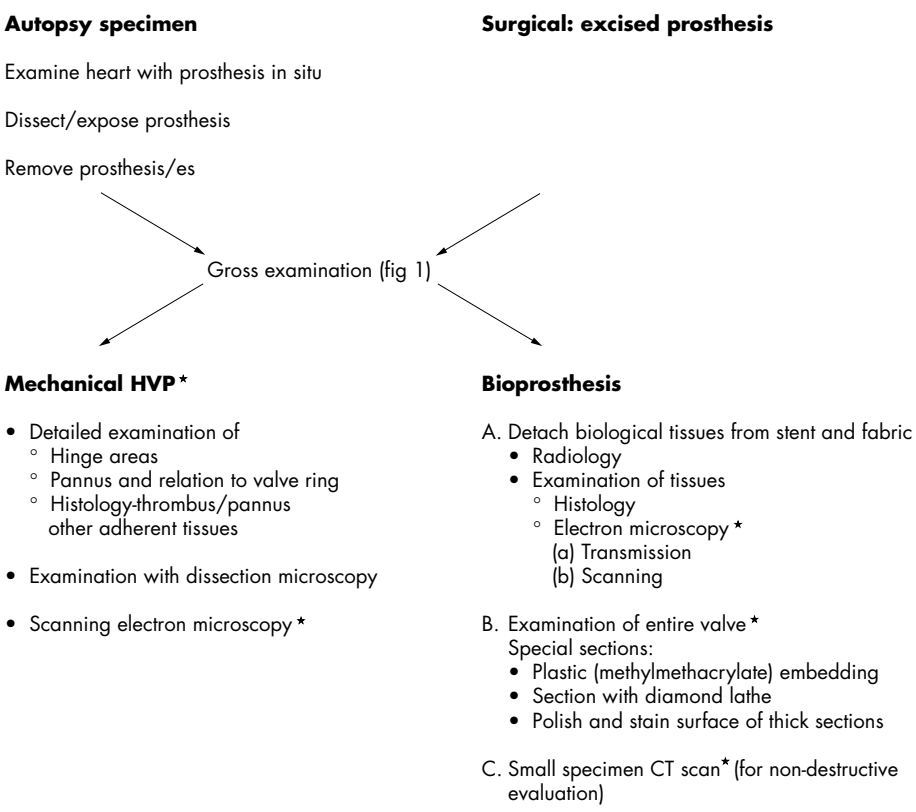

Figure 2 Detailed examination of prosthetic heart valves. *For special investigations only. Adapted from Schoen.[2] CT, computed tomography.

replaced by newer devices, which are now more widely in use. However, many pathologists will continue to encounter the ''obsolete'' devices. Therefore, it is essential to have some knowledge of the structure and pathology of these older devices, in addition to those that are currently implanted.

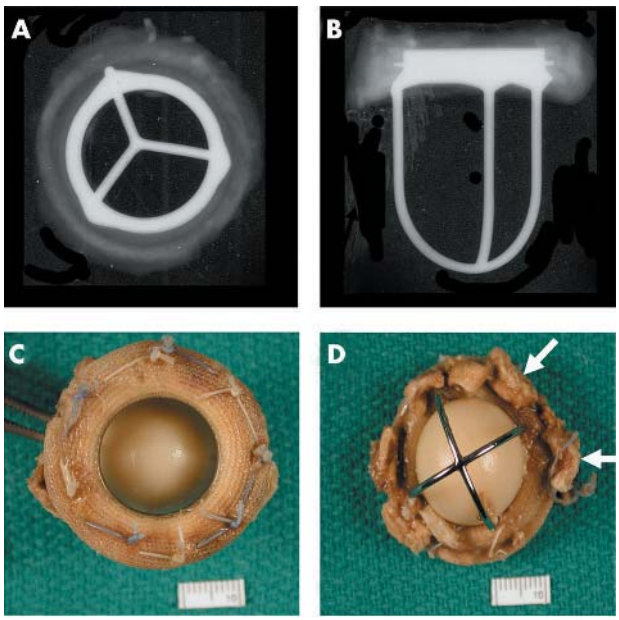

Figure 3 (A) Anteroposterior and (B) lateral *x* rays of a Starr-Edwards mechanical valve (Model 1000) shows the intact ''three leg cage''. (C) Flow surface and (D) non-flow surface of a ''four leg cage'' Starr-Edwards (Model 6400) valve. The struts are intact and the occluder (or poppet) has a pale yellow/brown colour. The non-flow surface shows tissue (arrows) still adherent to the sewing cuff.

At any institution where considerable numbers of cardiovascular devices are implanted and explanted, it is worthwhile to establish a protocol for the analysis of these devices, in consultation with the physicians who implanted/explanted the device. Later analysis of these data is considerably easier when a protocol is followed, and allows better identification of complications, tissue biomaterials, and patient device interactions. The protocol should include pathological examinations such as gross and dissecting microscopic examination, specimen photography, radiology, and histological analysis (figs 1, 2). Other methods of analysis, such as embedding the devices in different synthetic materials (for example, methylmethacrylate) and electron microscopy, require equipment usually available in biomaterials research facilities or at the manufacturer's own facilities. The principles of examination of explanted cardiovascular devices have been reported previously.[2] Contemporary cardiovascular devices are numerous and a brief listing is offered in table 1. The general approach to all of these explanted devices should be the same (fig 1). The devices to be discussed in this paper will include PHVs and endovascular devices (table 1). Figure 1 shows the general protocol to be followed in the examination of explanted prosthetic cardiovascular devices. Other similar protocols are also available.[4–8]

''At any institution where considerable numbers of cardiovascular devices are implanted and explanted, it is worthwhile to establish a protocol for the analysis of these devices''

Prosthetic heart valves

PHVs may be mechanical (MHV) (figs 3–7) or biological (BHV) (figs 8-11).[4 5 9 10] All PHVs have a passive mode of functioning, opening and closing are responses to pressure and flow changes within the heart. MHVs are made of

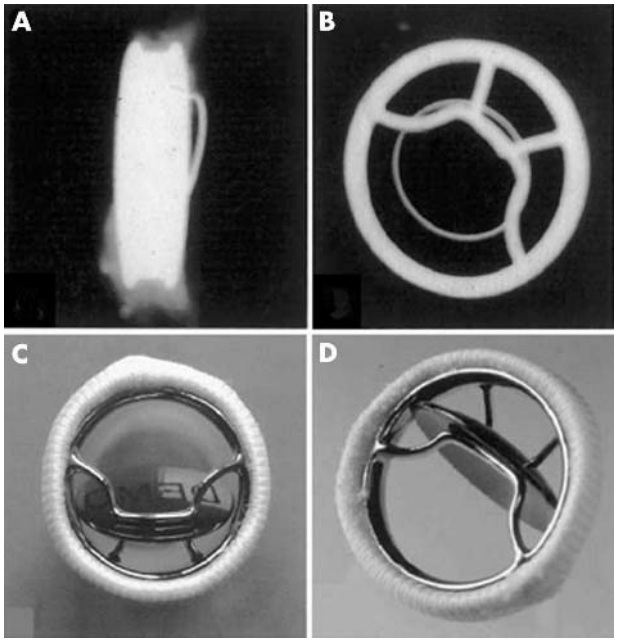

Figure 4 Bjork-Shiley concavo-convex valve. (A) *x* Ray of profile (lateral) view and (B) anteroposterior view showing the large (inflow) strut and the small (outflow) strut. Gross appearance of the valve; (C) valve partially closed with the disc in the oblique position and (D) valve open (disc or occluder is nearly vertical).

non-physiological materials with a mobile occluder, which is usually made of fairly rigid materials. BHVs are in reality a combination of tissue and synthetic biomaterials, with the tissue itself being flexible, and today made up largely of porcine aortic valves or bovine pericardium. The appearance and functioning of tissue valves is generally similar to native heart valves. The major types of cardiac valvular replacement devices that are used fairly widely are: caged ball devices (for example, Starr-Edwards ball in cage prosthesis; fig 3); the caged disc prosthesis (for example, the Beall valve); tilting disc valves (for example, Bjork-Shiley valves; figs 4, 5); bileaflet tilting disc valves (for example, St Jude Medical valves; figs 6, 7); tissue valves (for example, Medtronic (or Hancock) porcine valves, Carpentier-Edwards (porcine or pericardial) valves; figs 8–11); and other similar devices and stentless tissue valves. Prosthetic heart valves have many complications. It is useful to be aware of these when examining a heart with a prosthetic valve in place (fig 12).

MECHANICAL HEART VALVE PROSTHESES

These are prosthetic heart valves that are made entirely of synthetic materials. These devices have thrombogenic potential and patients who have these devices implanted have to be maintained on lifelong anticoagulants. These devices have three major parts, namely: (1) the occluder—this may be a ball (or poppet), a disc, or a hemidisc; (2) the superstructure, which holds the occluder in place, generally with a cage-like appearance; and (3) the valve base or housing with a fabric sewing ring.[11]

Although numerous MHV prostheses have been designed and used over the years, among the most widely used have been the Starr-Edwards ball in cage valve (fig 3), the Bjork-Shiley valve (figs 4, 5), the Medtronic Hall tilting disc valve, the St Jude Medical bileaflet valve (fig 7), and the CarboMedics bileaflet valve (fig 6). The ball in cage valve, among the first MHVs to be used, is still manufactured and sold in some regions of the world—although only in small numbers (Edwards Life Sciences, personal communication,

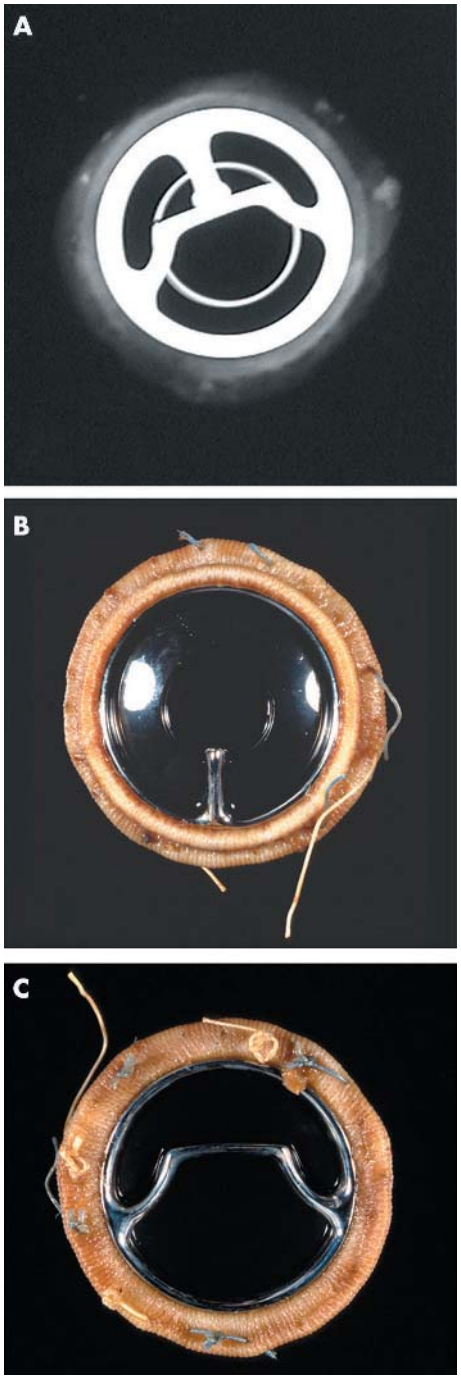

Figure 5 (A) *x* Ray (anteroposterior) of a Bjork-Shiley Monostrut valve. (B) Outflow surface showing the single outflow strut and (C) inflow surface of the Bjork-Shiley monostrut valve. The struts and the disc are intact.

2004). However, the disc in cage valves, which had a biconvex disk, are no longer available. MHVs are constructed largely of either pure titanium (for example, the Medtronic Hall valve) or chromium cobalt alloys (for example, the Starr-Edwards and the Bjork-Shiley valves), or of graphite. The leaflets of bileaflet valves are made of graphite coated with pyrolytic carbon, which provides a smooth, strong, fatigue resistant, and highly thromboresistant surface. All PHVs have a fabric sewing ring and a stent. The sewing ring allows the surgeon to anchor the valve in place at the valve site and the valve stent or housing is for anchoring the tissue or the

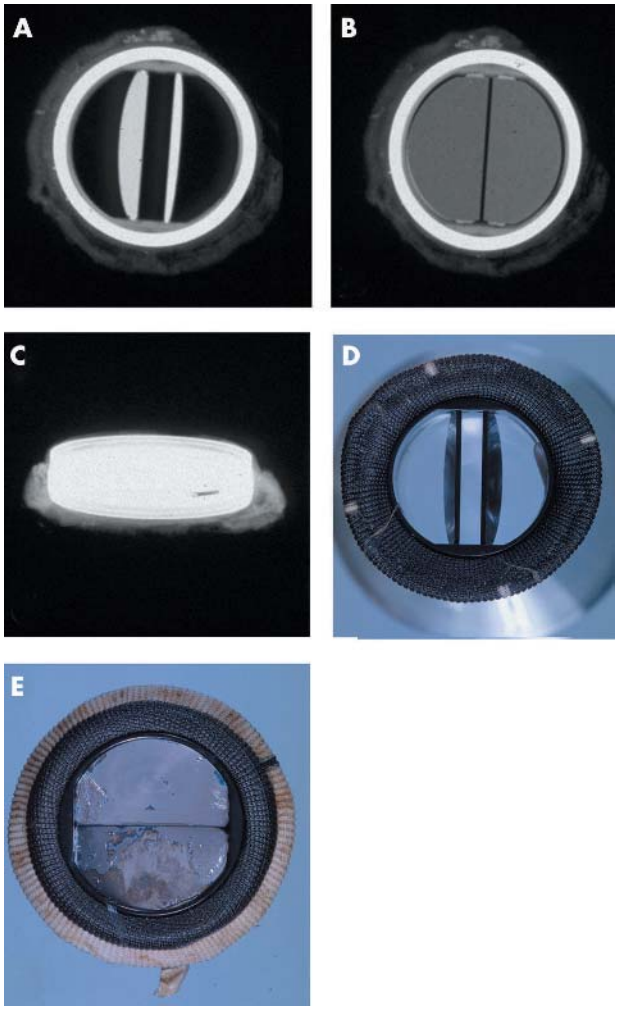

Figure 6 (A–C) *x* Rays of a Carbomedics bileaflet valve prosthesis with the discs open, discs closed, and profile of the prosthesis, respectively; *x* rays also show the radio opaque prosthesis housing. (D) The flow surface (discs open) and (E) the non-flow surface of the Carbomedics bileaflet prosthesis. The flow and non-flow surfaces of the sewing cuff are carbon coated (black).

mechanical parts of the valve. Both cause some degree of obstruction at the valve orifice, and in many instances, this is a condition that they were meant to treat.

> ''Today, autografts (the patient's own pulmonary valve), are excised and grafted into the aortic root, and a homograft placed in the pulmonary site''

Bioprosthetic heart valves (BHVs) (figs 8–11), or tissue valves (or xenografts) as they are commonly called, look very much like native aortic valves except that the implanted valve is attached to a prosthetic frame, making its commissural and infracommissural regions more rigid.[6] BHVs are of two main categories: (1) heterografts or xenografts, such as porcine aortic valves or bovine pericardial valves; and (2) homografts or allografts, such as aortic or pulmonic valves primarily from human cadavers. These may both have the aortic or pulmonic arterial tissues attached to them as a conduit. Among the newest types of BHVs are autografts. In the past, these autografts were made of fascia latta or native pericardium. Today, autografts (the patient's own pulmonary valve), are excised and grafted into the aortic root, and a homograft placed in the pulmonary site.

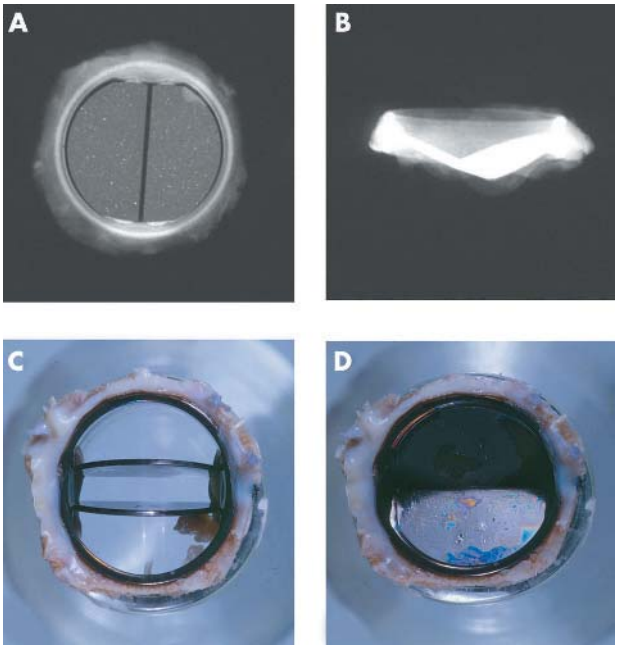

Figure 7 (A, B) *x* Rays of the flow surface and profile of the St Jude Medical bileaflet prosthesis. Views of a St Jude Medical bileaflet prosthesis with (C) the leaflets open and (D) the leaflets closed. A thick layer of grey/white pannus is seen on the flow and the non-flow surfaces of the sewing ring.

Xenografts are made from aldehyde preserved animal tissues, which are cleaned, sized, and mounted on a fabric covered prosthetic frame or stent.[4 7 8] The preservative for these tissues is glutaraldehyde. Different manufacturers use varying strengths of glutaraldehyde. The prosthetic frame is made up of posts or struts and the intervening valve ring. Pericardial bioprostheses have also been fairly widely used and in this type of BHV the cusps are made of three pieces of glutaraldehyde treated bovine parietal pericardium. This is

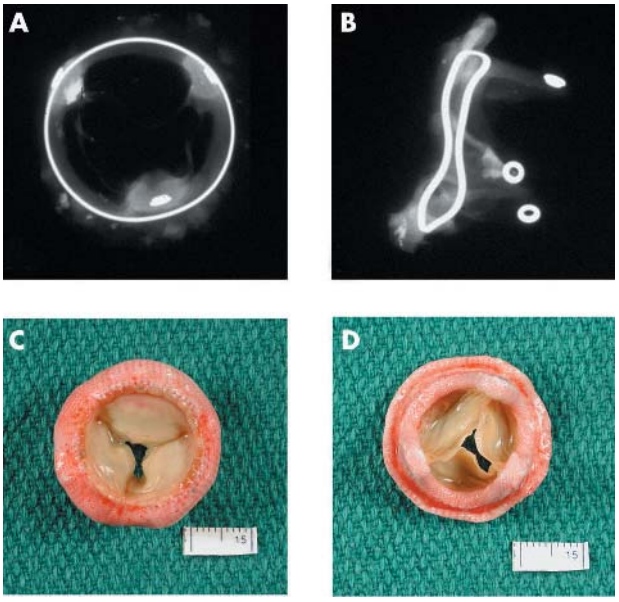

Figure 8 (A, B) Anteroposterior and lateral *x* rays of a Hancock porcine valve show a radio opaque valve ring and small eyelets in each of the stent posts. (C) The flow surface and (D) the non-flow surface of the porcine valve. The cusps are soft, pliable, and intact.

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