A heart valve substitute

M. S. Valiathan

Materials science and biomedical engineering come together in the making of an artificial heart valve.

Valves of the heart

Not every heart needs valves. The heart of an earthworm has no valves and is none the worse for it. So long as the demand for oxygen was small and the pressure to separate lung and body circulations less insistent, the heart could manage to pump without valves. The picture however changed with the emergence of a four-chambered heart where a muscle wall completely separated the right- and left-side chambers. This was imperative for survival because the demands on the heart had increased manifold over the millennia. The pumping chamber on the right was now obliged to ferry venous blood to the lung against a resistance of 200 dynes sec^{-1} cm^{-1} (ref. 1), whereas the chamber on the left was called upon to eject an equal volume to the entire body against a resistance of 1150 dynes sec^{-1} cm^{-1} (ref. 1). Within the chambers of the heart, the streams of blue blood *en route* to the lung and red blood to the organs of the body had not only to remain apart, they also had to move forward lest any reversal of flow should unbalance the right- and left-side circulations. Valves were the answer which evolution supplied to ensure the forward flow of blood in the heart. But they are more than mere one-way check valves.

Four in number, two inflow or atrioventricular valves regulate the filling of the ventricular pumps while two others or semilunar valves guard the outflow openings. Together they maintain the forward flow of blood; guard openings whose dimensions change during the cardiac cycle; and open and close 100,000 times a day in the highly reactive medium of blood. But, in structure and design, the inflow and outflow valves could not be more different. The inflow valves have either two or three leaflets which guard kidney-shaped openings. When the heart fills and the pumping chambers relax, their intracavitary pressure drops below that of the filling chambers and causes the passive opening of the inflow valves (Figure 1). When the ventricular pumps eject, the pressure in the chambers rises sharply with instant closure of the inflow valves and opening of the outflow valves (Figure 2). The ballooning of the thin leaflets of the inflow valves into the filling chambers during ejection is prevented by chords which tether the leaflets to muscular projections on the interior of the pumping chambers. Thread-like, the chords are immensely strong. At the height of ventricular ejection, the tensile stress at the point of attachment of a chord to the

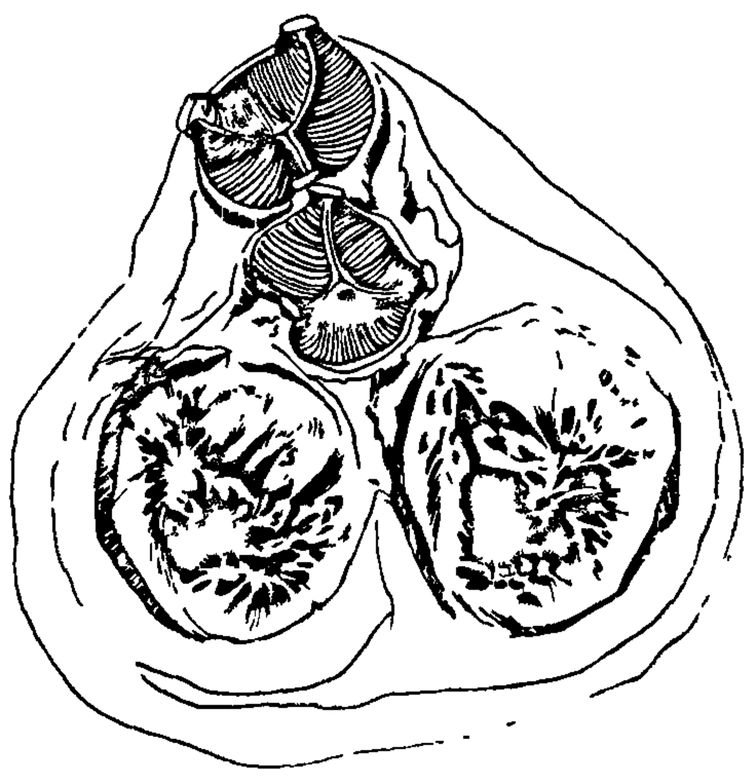

Figure 1. Heart valves during filling; inflow valves open, outflow valves closed.

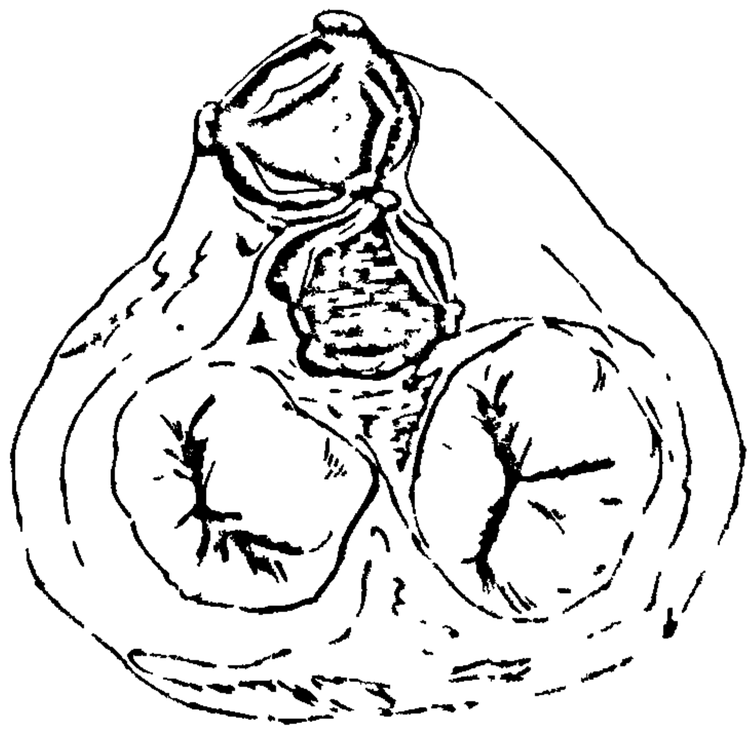

Figure 2. Heart valves during ejection; inflow valves closed, outflow valves open.

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leaflet has been estimated[1] to be 17,280 psi. The competence of the inflow valves owes as much to the integrity of the leaflets and their peripheral attachments as to the intactness of the chords and their muscular connections. In contrast, the outflow valves are trileaflet in design and guard an opening which is roughly circular and less susceptible to dimensional changes than the inflow valves. Thanks to their edges which constitute six radii, the leaflets open fully to the circumference, which would be impossible if the valve had two or four leaflets (Figure 3). Their scallopped attachment ensures that the leaflets remain fully closed when the ejection is over and filling begins. Seldom have form and function found a fuller union than in the mechanism of the valves of the heart. No wonder Leonardo da Vinci tried to capture their magic through innumerable drawings.

Replacement of heart valves

For all the masterly design and function, heart valves, alas, are prone to the assault of disease, the commonest of which is rheumatic fever. Claiming deprived children and adolescents as its usual victims, rheumatic fever 'licks the joints and bites the heart' in the course of a prolonged illness. The recurrent attacks of disease devastate the valve mechanism which may fail to open or close fully and may no longer maintain the unidirectional flow of blood (Figure 4). Burdened by additional work, the heart eventually fails when its large reserves of function run out. The enormity of the problem of rheumatic valve disease is apparent from a survey conducted by the Indian Council of Medical Research which put the children and adolescents at risk at five per 1000 in India. When the valve is damaged beyond repair, there is no alternative to its replacement, which may be needed by no less than 20,000 patients a year. This figure may indeed be an underestimate as

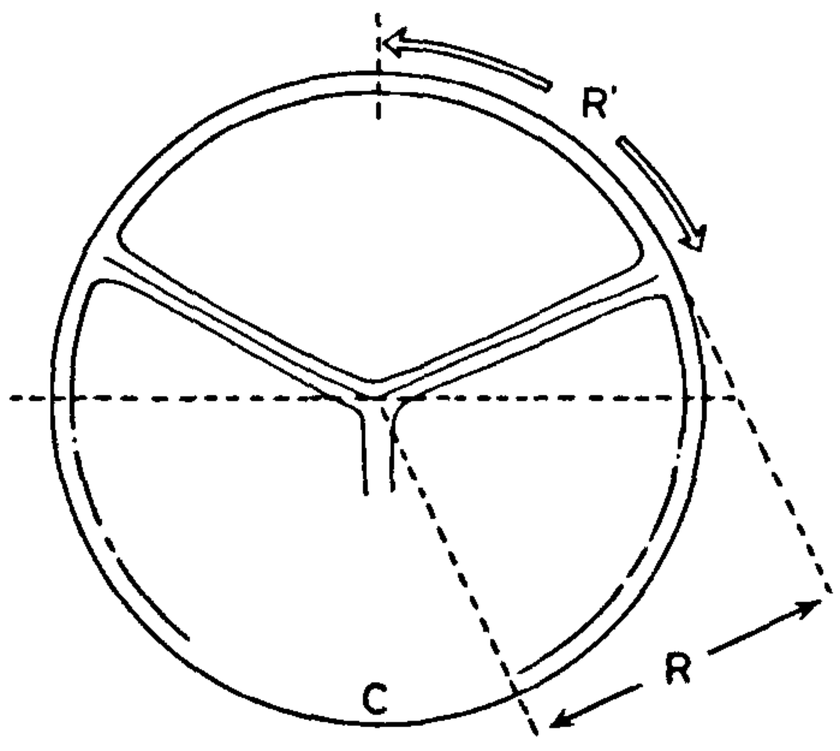

Figure 3. Outflow valve, trileaflet design.

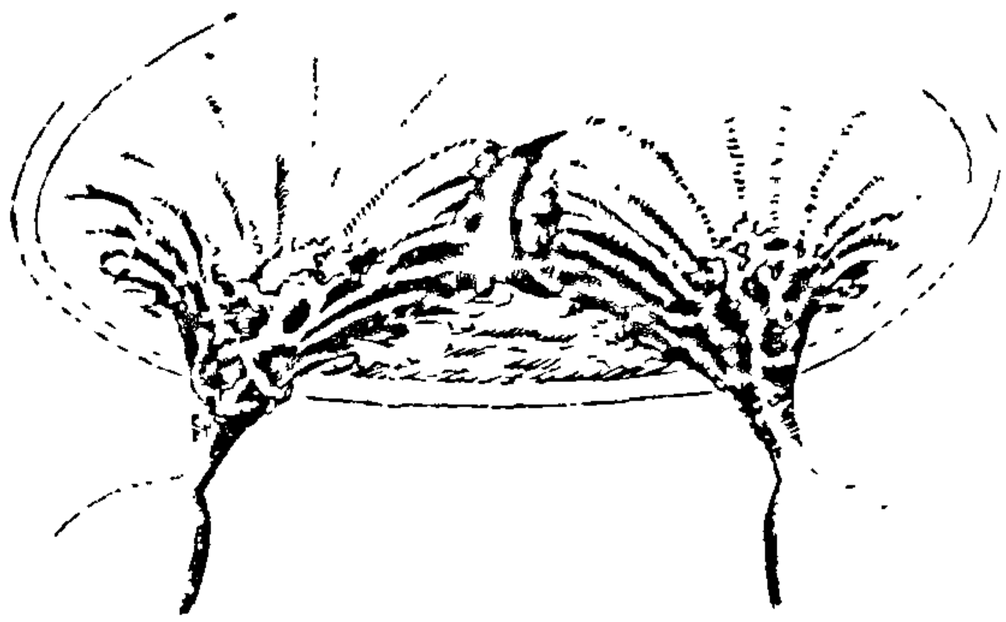

Figure 4. Mitral valve, chords fused and distorted with a narrowed orifice.

Sree Chitra Tirunal Institute alone has 3000 patients awaiting valve replacement at the present time.

Replacement of diseased valves is by no means a new concept. It was exactly forty years ago, and that too before the advent of the heart–lung machine, that Hufnagel[3] startled the surgical world by placing a lucite ball valve in the descending thoracic aorta and gave relief to a patient with severe aortic insufficiency. Noisy and bulky, the caged ball valve of Hufnagel nevertheless proved that a man-made valve could remain and function effectively for many years in the cardiovascular system. The decades following Hufnagel saw the rise and fall of innumerable valve designs which came to litter the field of cardiac surgery. There were as many valve models as there were surgeons. The Baxter Museum, in fact, lists over 300 valve models which appeared, vanished and occasionally endured during those prolific years.

The Chitra valve

A serious effort to develop a mechanical valve began at the Sree Chitra Tirunal Institute a decade ago when it became clear that supply of foreign valves was impossible for the great majority of Indian patients thanks to the high cost of import[4,5]. However, like others who sought to develop heart valves, our group soon discovered that the course of valve development never ran smooth. Shortcuts there were none, and each group appeared condemned to learn from its own experience, including mistakes in the choice of materials, fabrication of components and the use of test methods. The Chitra valve which successfully entered clinical trial in December 1990 was, in fact, the third in a series of candidate valves which were developed and tested according to an international protocol (Figure 5).

The International Standard readily acknowledges that there is no ideal heart valve substitute[1]. All it does is to specify types of tests, methods of testing, requirements of test apparatus and the reporting of

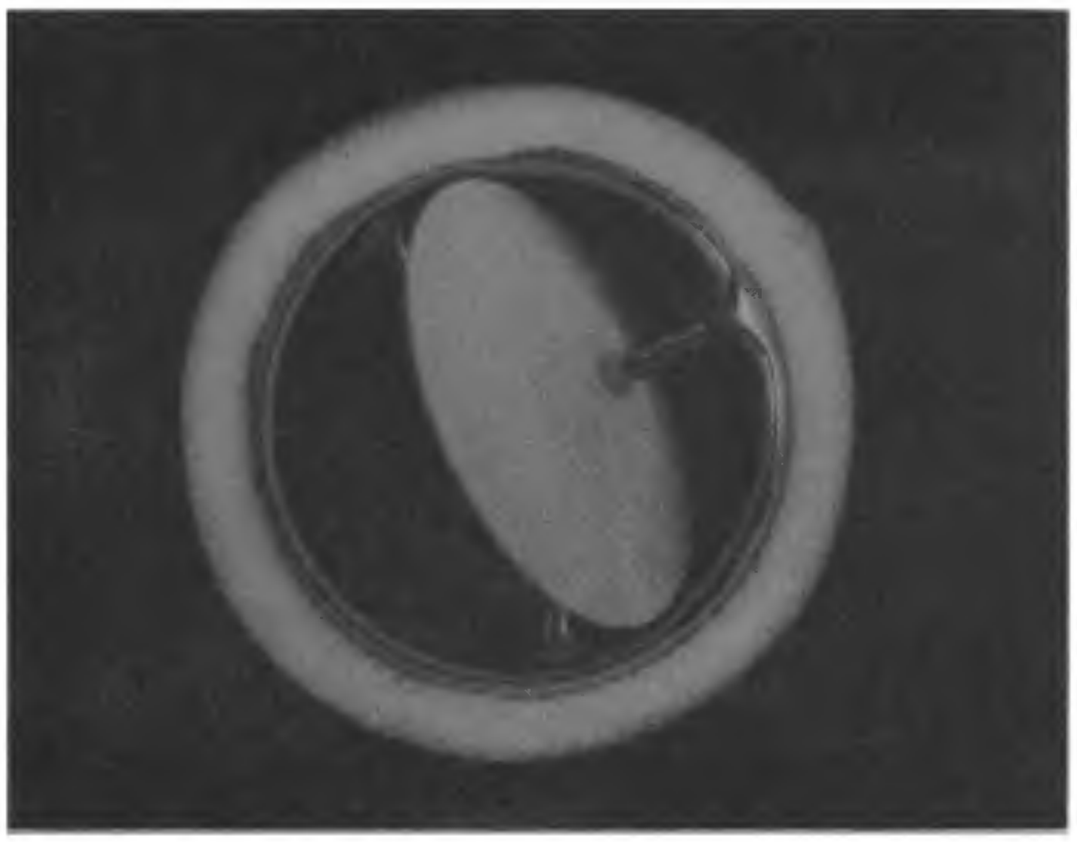

Figure 5. The Chitra valve.

data. It covers, apart from basic material testing for mechanical, physical, chemical and biocompatibility characteristics, important hydraulic and fatigue characteristics of the valve substitute. The areas with which the International Standard is concerned are those which facilitate quality assurance and aid the surgeon in the choice of a valve substitute. Incomplete in several areas, the standard is admittedly still evolving.

Candidate materials

A valve substitute has three parts, viz. the housing, the occluder and a sewing ring, which call for different mechanical properties. The materials used in the Chitra valve as it graduated from model 1 to model 3 are listed in Table 1.

The materials problem in model 1 was basically the hygroscopic property of polyacetal and a consequent dimensional change in the disc during autoclaving. Though the change was reversible, polyacetal was abandoned abroad in the construction of heart valve substitutes and its continued use would have been unacceptable in India. As the technology of pyrolitic carbon coating, which upgraded valve discs abroad, was unavailable in India, an alternative material was found in single-crystal sapphire, which combined desirable properties such as hardness, inertness, biocompatibility and excellent surface smoothness. The change in the disc material dictated a corresponding change in the mating material of the cage, which was switched to Haynes alloy with a coating of titanium nitride. Though the second model passed the series of hydraulic and durability tests flawlessly over a two-year period, its demise occurred to our chagrin when two sapphire discs fractured in sheep after several weeks of implantation of the valve. The search for a better substitute began immediately and culminated in the third model which has a cage made of Haynes alloy and disc made from ultra-high-molecular-weight polyethylene. The unchanging component in all the three models was the sewing ring of polyester cloth.

All the three materials in model 3 have been used in the fabrication of surgical implants such as joint prostheses and vascular grafts and known for their safety and durability for many years. However, the application of ultra-high-molecular-weight polyethylene in the construction of a heart valve substitute did represent a new approach. The characteristics and testing of materials used in model 3 have been reported in detail elsewhere[6].

Fabrication techniques

Not surprisingly the techniques of fabrication of the valve components from model 1 to model 3 parallelled the changes in candidate materials (Table 2).

In model 1, the initial setback came when the struts of the electron-beam-welded cage fractured after a mere 100,000 cycles against the requirement of 360 million cycles. Failure analysis by scanning electron microscopy and other methods at the National Aeronautical Laboratory showed the cause of the fracture to be weld embrittlement, which underlined the inherent vulnerability of welded components in the blood stream. The problem of the cage in model 1 was also compounded by the absorption of moisture by the polyacetal disc. These difficulties were overcome in model 2 by introducing an all-integral cage of Haynes alloy and a disc of single-crystal sapphire. The Haynes alloy blank was initially subjected to CNC wire-cut and electric discharge machining followed by CNC machining (Government Toolroom and Training Centre, Bangalore), multistage operations for finishing, and coating with TiN. For the disc, coins of required thickness were sliced from boules of single-crystal sapphire and then ground and polished to shape using diamond-coated

Table 1. Materials used in various models of the Chitra artificial heart valve.

Model	Housing	Occluder	Sewing ring
1	Titanium	Polyacetal	Polyester
2	Haynes alloy with TiN coating	Sapphire	Polyester
3	Haynes alloy	UHMW-PE	Polyester

Table 2. Techniques of fabrication of materials used in the Chitra heart valve

Model	Cage	Disc	Sewing ring
1	Electron beam-welded struts	Machining	Knitted
2	All integral cage TiN coating	Single crystal sapphire	Knitted
3	All-integral cage	Cryomachining	Knitted

tools by the manufacturer. When the fracture of the sapphire disc led to the introduction of model 3, the coating of TiN on the Haynes alloy cage was dispensed with and the disc machined from rods of ultra-high-molecular-weight polyethylene under cryogenic conditions. Thermal polishing of the disc was accomplished in a three-piece stainless steel die using controlled heating and cooling cycles even as a compressive load was applied. Following annealing, the flash generated during thermal polishing was removed with a polished formed tool under cryogenic conditions again. The sewing ring was made from knitted polyester fabric in all the three models.

Design features

The series of changes in materials and fabrication technique did not affect the design, which remained unchanged over the years of development. The basic features of the design included an opening angle of 70° for the disc, which was non-seating and had a taper and well on the outflow side to accommodate the minor strut. A sewing ring fitted snugly into the concavity of the ring of the metallic housing (Figure 6).

Performance tests

The performance of a heart valve substitute is gauged in terms of hydraulics, durability and long-term function in an animal model. A pulse duplicator consisting of a model of the left heart with an appropriately designed actuator system is employed to measure the pressure drop across test valves and to estimate regurgitant volumes on closure. The experimental set-up also serves to record flow patterns during the opening and closing phases of the valve. As the International Standard does not specify performance standards, the hydraulic data of the Chitra valve were compared with those of standard disc Bjork–Shiley valves, of which more than 200,000 have been used in patients over the years. The comparison was made between valves of identical diameter under identical conditions and the Chitra model was shown to be marginally superior in all hydraulic parameters, including pressure drop, regurgitant volume, effective orifice area, energy loss and performance index. Figures 7, 8, 9 illustrate, for example, the comparative performance of the Chitra and Bjork–Shiley models of 23-mm size in the aortic position for pressure drop and regurgitant volume.

The International Standard requires a candidate valve to cross a minimum of 380 million cycles without mechanical failure in an accelerated wear tester, which corresponds to 10 years of durability in a patient. The wear tester must also operate under controlled conditions with reference to temperature, pressure, chemical composition and specific gravity of the perfusing fluid, speed of cycles and regular measurement of wear. Designed and built in our laboratories, the accelerated test equipment was as much a challenge to itself as to the candidate valve. The Chitra valve model 3 passed the fatigue test and the wear was shown to be comparable to that of the Bjork–Shiley valve which features LTI carbon and stellite 21 as its

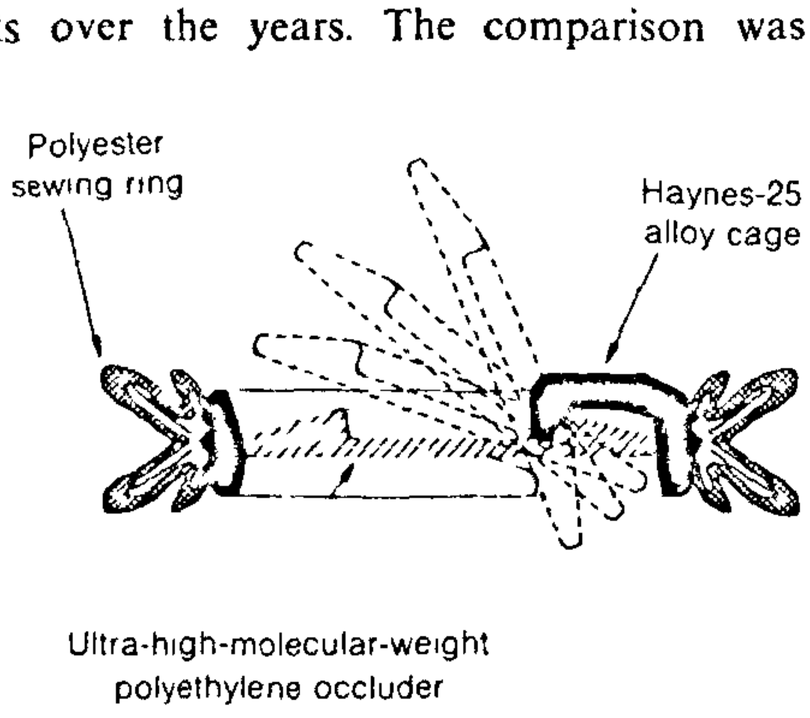

Figure 6. Design features of the Chitra valve.

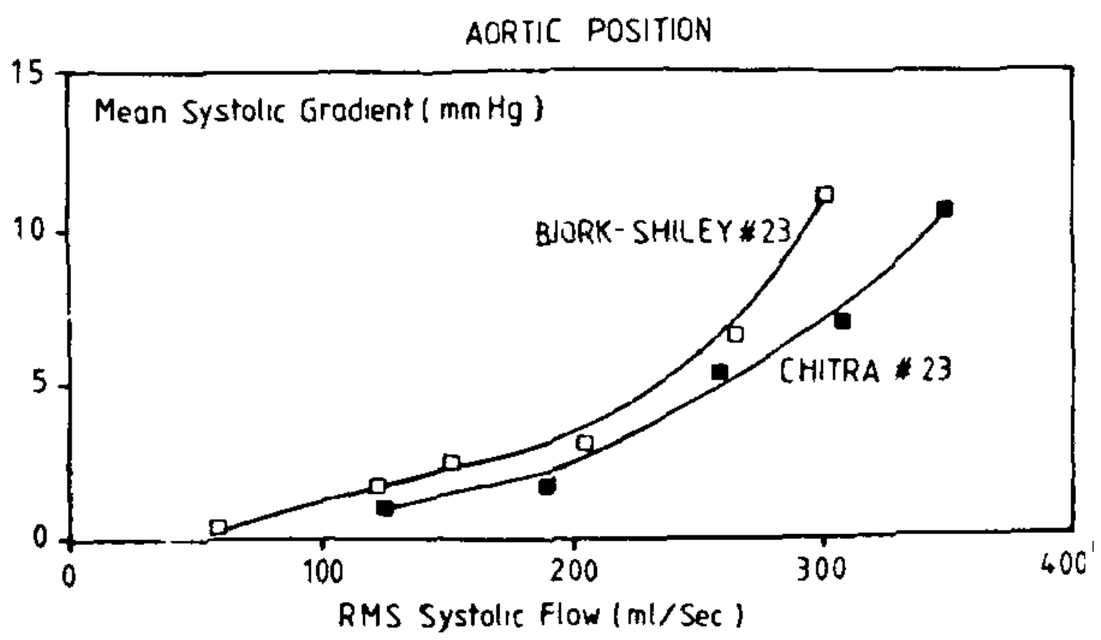

Figure 7. Pressure drop (mean flow), Chitra and Bjork–Shiley valves, aortic 23 mm (RMS, root mean square).

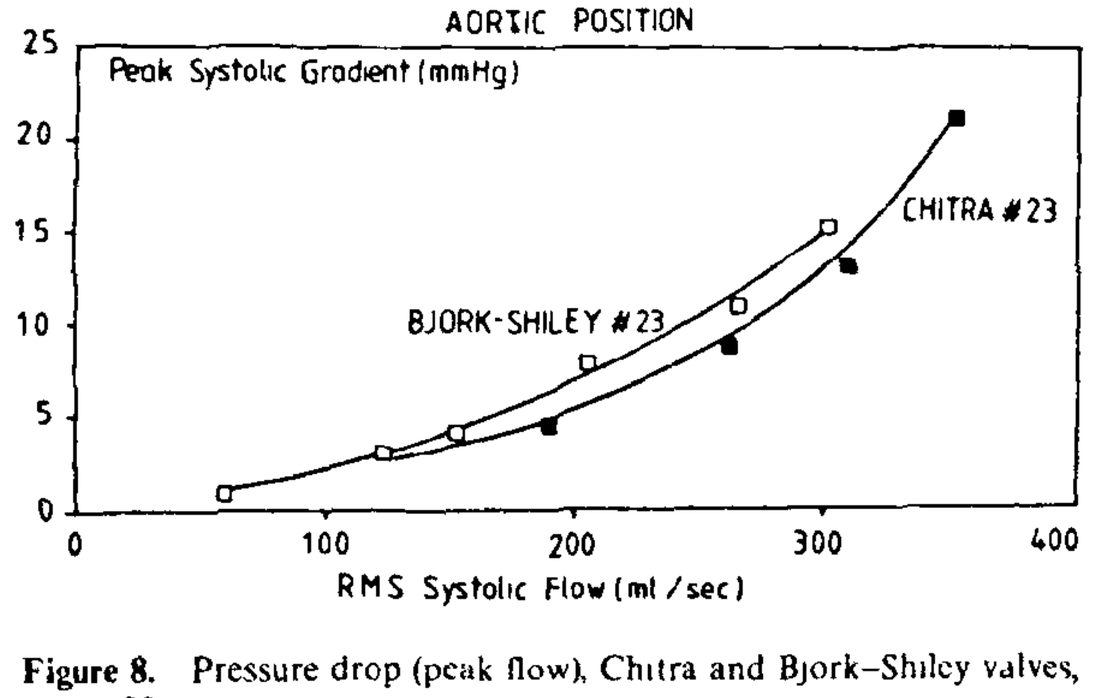

Figure 8. Pressure drop (peak flow), Chitra and Bjork–Shiley valves, aortic 23 mm.

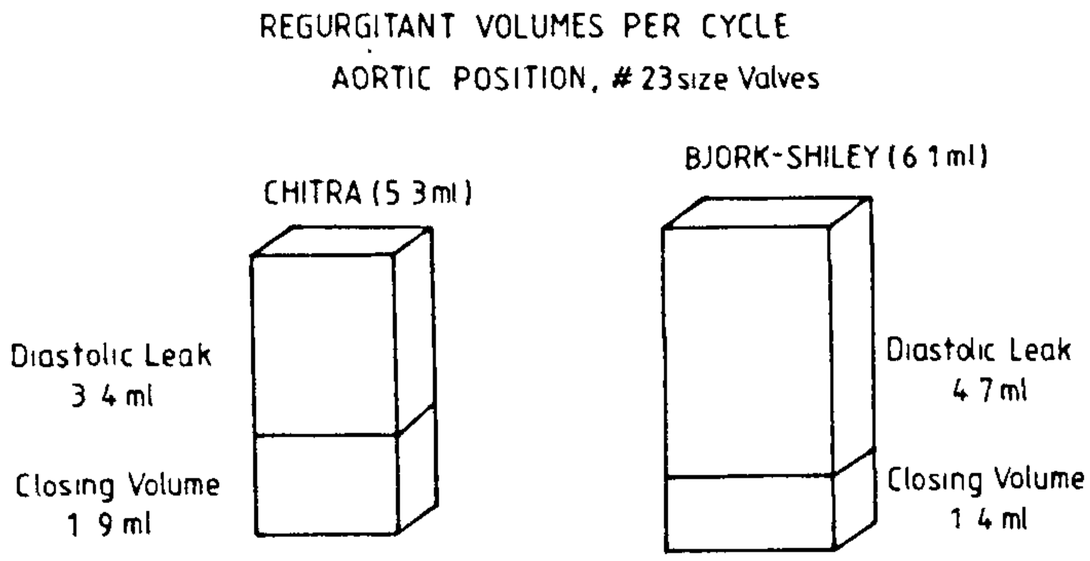

Figure 9. Regurgitant volumes, Chitra and Bjork–Shiley valves, aortic 23 mm.

component materials (Figure 10). This was followed by its insertion in the mitral position of sheep under heart–lung bypass and the careful monitoring of the animals for six months. The upstream and downstream pressures in relation to the valve, its healing characteristics, status of viscera, and the evidence of damage to blood were assessed at the time of the elective termination of the animal trial. The Chitra valve showed smooth healing, good hydraulic function and no evidence of blood or organ damage in these experiments.

Clinical trial

Given the data on component materials and performance *in vitro* and *in vivo*, the Ethics Committee of the institute approved the clinical trial of the valve on the basis of informed consent from patients. The trial began in December 1990 and has accounted for the placement of over thirty Chitra valves in the mitral and aortic positions with excellent valve function and benefit to the consecutive series of patients. Echocardiography after several months of implantation in patients confirmed the predicted functions of the valve in terms of the opening angle of the disc, effective orifice area, regurgitant leak and pressure drop. The clinical trial at the Sree Chitra Tirunal Institute will be followed by a larger, multicentric trial in the country during 1992. The production of valves for the multicentric trial will induct industry in the endeavour and supply the hitherto missing link in the technological chain of valve development.

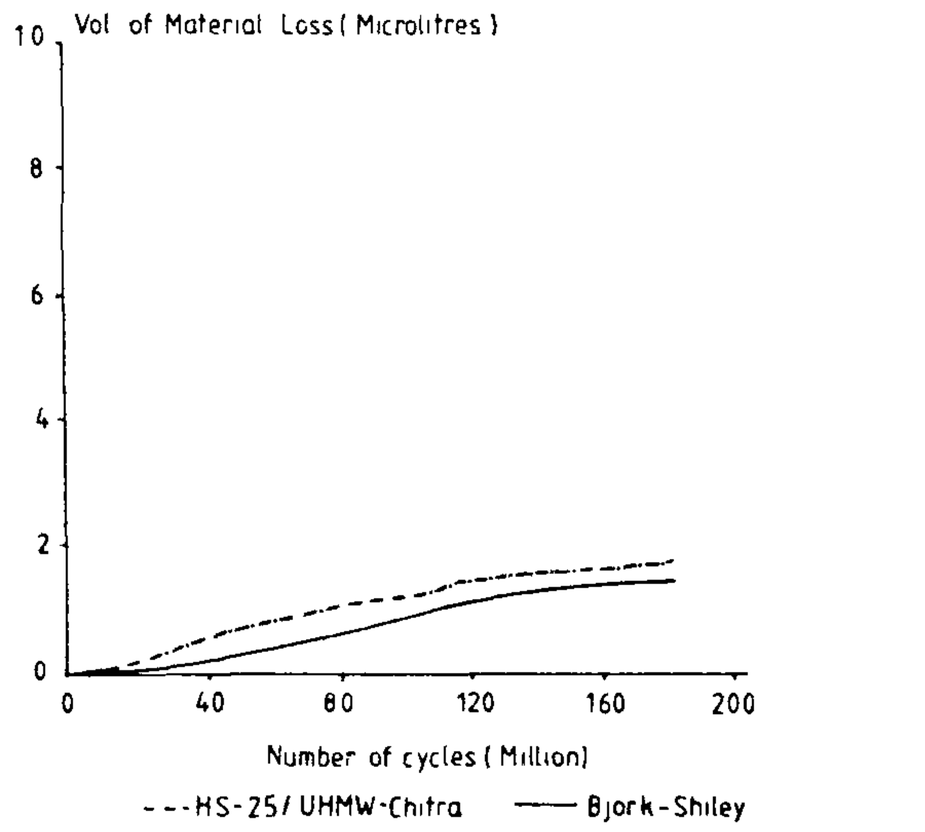

Figure 10. Wear of candidate materials. Note similar wear in Chitra and Bjork–Shiley valves.

The true significance of the Chitra valve lies in the triumphant demonstration that the technology of heart valve substitutes, an oligopoly of rich nations, could be mastered by Indian scientists, and the home base strengthened for rapid advances in devices technology. Their achievement has rekindled new hope for thousands of patients who are priced out of valve replacement therapy today. While no substitute can begin to approach the natural valve in elegance or function, it does offer a fresh lease on life to patients whose valves have been wrecked by disease. Haunted by offsprings of destruction, saddened by handiwork that silences the spring, technology in some part has redeemed itself by developing heart valve substitutes and forging one more weapon in man's battle against disease.

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