Influence of bileaflet prosthetic mitral valve orientation on left ventricular flow—an experimental in vivo magnetic resonance imaging study

H. Mächler\textsuperscript{a,\*}, M. Perthel\textsuperscript{b}, G. Reiter\textsuperscript{c}, U. Reiter\textsuperscript{c}, M. Zink\textsuperscript{d}, P. Bergmann\textsuperscript{a}, A. Waltensdorfer\textsuperscript{d}, J. Laas\textsuperscript{b}

\textsuperscript{a}Division of Cardiac Surgery, University Medical Center, Medical University, A-8036 Graz, Austria

\textsuperscript{b}Division of Cardiac Surgery, Bad Bevensen, Germany

\textsuperscript{c}Division of Radiology, University Medical Center, Medical University, A-8036 Graz, Austria

\textsuperscript{d}Division of Anesthesiology, University Medical Center, Medical University, A-8036 Graz, Austria

Received 13 January 2004; received in revised form 7 June 2004; accepted 7 June 2004; Available online 20 August 2004

Abstract

Objective: Orientation-related bileaflet mechanical valve flow and velocity studies in the downstream area are limited in mitral valve replacement studies. Methods: In five sheep, ventricular blood flow was visualized prior to the implantation of a mitral Edwards Mira Bileaflet Mechanical Valve Model 9600. The implant orientation was either anatomic, with a 45° rotation, or anti-anatomic, with a 90° rotation. Sheep were positioned within an 1.5 T field strength MR scanner (Magnetom Sonata; Siemens) to assess time-dependent three-dimensional blood flow velocities displayed as color-encoded vectors. Results: The preoperative ventricular velocity profiles presented negligible individual variances. Streamlines passed homogeneously without any spatial differences into the left ventricle. Starting from the anatomical position, the areas with inhomogeneous and accelerated local blood velocities increased in comparison to the preoperative status. Rotating the prosthesis until it was in a 45° position caused a significant increase in turbulence immediately downstream; fluids stagnated longer at the apex. In the anti-anatomic orientation, mean velocities decreased. In all three positions, but less so in the anatomical position, the flow pattern of the blood helix at the apex was disturbed. The intraventricular flow patterns between protheses in the three orientations were, however, not significant when compared to the differences between physiologic intraventricular flow and any of the postoperative measurements. Conclusions: To achieve optimal hemodynamics, rotation of the mitral valve has to be considered carefully, as has long been known from aortic valve replacement studies. To this end, a method for qualitative assessment of left ventricular blood flow patterns was developed.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Mitral valve prosthesis; Orientation; Intraventricular flow; Magnetic resonance imaging

1. Introduction

There is ample information on how the outcome can be improved for recipients of mitral valve replacement [1]. Since 1993, the importance of chordal preservation techniques in maintaining left ventricular geometry and improving function has been well documented clinically. Nonetheless, the wide variance in the survival rates of different mitral valve replacement patient cohorts remains unexplained.

Aortic valve replacement studies have demonstrated the influence of the orientation of the prosthetic valve substitute within the valve annulus on the hemodynamic profile in the downstream area [2–4]. There are various methods that can easily detect the effects of different aortic valve orientations on the velocity profiles in the ascending aorta but they cannot be applied in vivo to the mitral valve [2–10].

The transvalvular flow characteristics of commonly used mitral prosthetic valves are well known [12–14]; however, the intraventricular flow in relation to the orientation of the mitral valve prosthesis has not received the same clinical
attention as the downstream area in aortic valve replacements [2–4,15]. Only a few publications have addressed the intraventricular flow effects of different orientations of symmetrical bileaflet prosthetic valves in the mitral position [14,16,17].

The following study was designed to clarify the question of whether there is an optimal orientation for a bileaflet mitral prosthesis with regard to intraventricular flow, but not to determine which orientation is associated with symmetrical leaflet motion. Magnetic resonance (MR) imaging was used in animals under in vivo conditions to determine blood flow changes within the left ventricle, velocity profiles and the occurrence of intraventricular turbulence with preservation of annulo-ventricular integrity.

2. Material and methods

All animal studies were performed following the guidelines for animal experiments prescribed by Austrian law. Ten healthy sheep of bodyweight 35–40 kg were used in these studies.

All animals were premedicated with thiazine hydrochloride (2 mg/kg intramuscularly). General anesthesia was achieved using fentanyl (5 µg/kg), propofol (3 mg/kg) and pancuronium (0.1 mg/kg) prior to laryngoscopically guided endotracheal intubation. Adequate anesthesia was maintained with isoflurane 1–2 vol.% and repetitive doses of fentanyl and pancuronium. All animals received Ringer’s solution for volume replacement. For successful weaning from cardiopulmonary bypass, dopamine (1–10 µg/kg) or epinephrine (0.05–0.5 µg/kg) was administered to stabilize the circulation. After induction of anesthesia, all animals were provided with an arterial and central-venous access for hemodynamic monitoring.

In five sheep, intraventricular blood flow, velocity profiles and the occurrence of intraventricular turbulence were measured preoperatively to evaluate the individual sheep-to-sheep variance. These five animals served as blood donors.

In five further sheep, a median sternotomy was performed in the usual manner and a normothermic extracorporal circulation was established via cannulation of the iliac artery and the jugular vein, in which a double-staged venous cannula was inserted. After cross-clamping of the aorta, 600 ml of St Thomas Hospital cardioplegia was given initially to achieve cardiac arrest. After opening the left appendage and excision of less than half of the mid-third of the anterior mitral leaflet, a 23 mm Edwards Mira 9600 mechanical prosthesis (Edwards Lifesciences®, Irvine, CA, USA) was implanted in one of three positions:

1. In the anatomic position (n = 3) with the two major orifices aligned with the anterior and posterior leaflet commissures (transversely orientated valve);
2. With a 45° rotation (n = 1), whereby the two major orifices are turned counter-clockwise 45° from the native leaflets; or
3. In an anti-anatomic 90° position (n = 1) (the anteroposterior prosthesis axis is aligned from the middle of the aorta to the middle of the posterior annulus).

Following hemofiltration and weaning from cardiopulmonary bypass, animals were kept stable for 3 h until a steady-state was achieved. The sheep were then transported to the Cardiac MR Siemens Magnetom imaging device. During the early imaging period, one sheep (anatomic orientation) died of hypothermia; for the four remaining sheep, the mean imaging period was 2.5 h (2–5.2 h). All sheep were warmed using the Bear Hugger system. Following the imaging studies, the sheep were sacrificed in deep anesthesia with a high intravenous dose of potassium chloride.

3. Magnetic resonance (MR) imaging method and calculations

Sheep were positioned laterally with their hooves forward in a plastic box within a 1.5 T field strength MR scanner (Magnetom Sonata; Siemens, Erlangen, Germany). MR investigations were performed ECG-gated under continuous artificial inspiration with a circular polarized body array coil.

To assess time-dependent three-dimensional blood flow velocities, the sheep’s left ventricles were covered completely with two-dimensional FLASH (fast low angle shot) phase contrast cine sequences [11]. These sequences typically produce two types of images: velocity-compensated, anatomical images and phase images displaying the magnetization phase, which is proportional to velocity in one direction. Whereas the parameters field of view of 320×320 mm, matrix of 128×128 lines, slice thickness of 5 mm, repetition time TR = 25 ms, echo time TE = 3.3 ms and flip angle α = 15° were constant for all studies, velocity encoding was adapted between 75 and 130 cm/s. Depending on the sheep’s heart rate and left ventricular dimensions, imaging time for the velocity field determination was between 50 and 80 min. Determination and visualization of the measured three-dimensional velocities were computer assisted and used non-commercial software. Phase images were used to calculate the left ventricular time-dependent, three-dimensional velocity fields. Velocity data were projected onto corresponding velocity-compensated images to visualize anatomical structures. Three-dimensional velocities were displayed as color-encoded vectors. The length of a vector as well as its respective color represents the absolute value of the velocity whereas the direction of the vector indicates the direction of the velocity.
4. Results

The preoperative ventricular blood dynamics and the velocity profiles from the five sheep presented negligible individual variances. In the early diastole, streamlines passed homogeneously without any spatial differences in flow velocities into the left ventricle (Fig. 1). In detail, the anterior leaflet of the mitral valve moving towards the interventricular septum created an asymmetric inflow tract in the expanding ventricle. The dominant direction ran under the free edge of the anterior mitral leaflet and blood did not primarily enter the subaortic outflow tract. The inflow characteristics of the native mitral valve presented an asymmetrical central and non-axial inflow that was not directed to the apex but created a helix from the posterior wall and posterior-apical septum that reversed at the apex and moved up the anterior and anterior-lateral wall. The fully formed vortex at the site of deceleration of the entering flow translated the vortex structure toward the subaortic area (Fig. 2).

Transient small branches of the main vortex, the mechanism responsible for closing the mitral valve, were seen beneath the valve. The closing mechanism of the anterior leaflet created the large outflow tract.

In all operated sheep, prosthesis-related artifacts 1.5 cm were seen downstream.

When the valve with its central flow design is fully open, high velocity jets through each of the three orifices of the valve could be readily detected; however, the central jet from the area of the hinge lines dominated with greater velocity. The two major orifice jets were directed outward and attached to the central jet. Increased turbulence due to the housing of the prosthesis was observed immediately downstream in contrast to the homogeneous blood flow preoperatively. The main direction of all three jets was dependent on the orientation of the prosthesis itself; additionally, the preserved original leaflets affected the inflow.

Starting from the anatomical position, blood entered through the artificial leaflets as well as the hinge area; the preserved native anterior leaflet prevented blood from flowing directly to the septum, entering the outflow area. The areas with inhomogeneous and accelerated local blood velocities in the mid-portion of the ventricle increased when compared to the preoperative status (Fig. 3). Rotating the prosthesis until it was in a 45° position caused a significant increase in turbulence immediately downstream (Fig. 4); in the apical area, propagation velocity decreased and the fluids stagnated longer at the apex. A further turn to the anti-anatomical orientation decreased mean velocities (Fig. 5).

In this 90° position, the main stream of flow was characterized by the three jets from the prosthesis as well as...
from the native leaflets, both limiting the freedom of blood to move and causing higher velocities of the stream profiles and turbulences as compared to the anatomical position.

In all three positions, but less so in the anatomical position, the typical apical flow pattern of the blood helix at the apex and the homogeneous translation of energy to the subvalvular area were disturbed. The physiological apical helical blood flow was so significantly altered that the increased and non-physiological turbulent flow pattern could still be seen within the aorta (Fig. 6).

The intraventricular flow patterns between protheses in the three orientations, however, were not significant when compared to the differences between physiologic intraventricular flow and any of the postoperative measurements.

5. Discussion

The transvalvular flow characteristics of commonly used mitral prosthetic valves are well known [12–14]; little attention has been paid to the intraventricular flow related to different orientations of the mitral valve prosthesis [14,16,17].

Aortic valve replacement studies [2–4,15] demonstrated that, in patients with a normal aortic valve, ejection from the left ventricle follows a spiral course. With ongoing systole, the highest velocities rotate counterclockwise by 90° so that at end-systole the highest velocities are found on the right aortic wall. Detailed comparative studies of velocity fields and turbulent stresses downstream of different aortic valve prostheses indicate that rotation of mechanical aortic prostheses has an impact [2–4].

Unlike aortic valve replacements, in the case of mitral valve prostheses there is almost no basic research on the effects of different orientations of the prosthesis on blood flow. Not only is the area immediately distal to the prosthesis of importance but all intraventricular areas during diastolic and systolic movements are of specific interest as well.

Surgical implantation practice in the 1980s was to position a bileaflet valve in the anatomic position in an attempt to cooperate with nature. Later, bileaflet mitral valve implants were moved to the anti-anatomic position, because of the ‘lazy’ late closure of the posterior leaflet and the potential risk of leaflet impingement by the posterior left ventricular wall that is present with the anatomical position. The anatomic position was also held responsible for posterior leaflet thrombosis [16–19], especially in cases of excessive bulging of a hypertrophied septum. Baudet [16],
However, outlined that embolic events and valve thrombosis occurred clinically with either orientation.

In one of the rare prospective randomized trials [20] comparing the St Jude Medical and the Medtronic Hall prostheses in the mitral position, 76 bileaflet valves were implanted and oriented either anatomically or anti-anatomically; two cases of valve thrombosis were reported in a 10-year survival analysis. Echocardiographic studies have favored the use of a bileaflet valve oriented in the anti-anatomic position, because asynchronous leaflet closure was found to be reduced in this specific orientation. Laub [17] confirmed this experimentally. Regarding the lazy leaflet, Ohta [19] found, independent of valve orientation and with a computer simulation of the St Jude Medical mitral valve, that asymmetrical leaflet motion and unpredictable leaflet position occurred during different flow situations. Feng [18] presented a three-dimensional time-dependent model of this fluttering in the CarboMedics prosthesis as well as in St Jude Medical valves. This unsteady effect on the flow across valves has also been seen in tilting disc valves [21,22]. In view of these facts, the discussion on the relationship between different valve orientations and the ‘lazy leaflet’ is still open. However, these investigators focused on leaflet motions and not on left ventricular flow patterns, as does the present study.

An intriguing aspect of the left heart dynamics is the hypothesized occurrence of diastolic vortices within the ventricular chamber. The initial vortex supports filling by shunting inflow kinetic energy and converts the vertical motion into rotational kinetic energy. The principle fluid phenomenon involved in the left ventricular diastolic flow is related to the presence of the vortex structure that develops with the strong jet entering through the mitral valve [6].

In ‘asymmetrically’ constructed valves, such as the native mitral valve, the optimal orientation of a ‘symmetry-symmetrically’ constructed mitral prosthesis might show a significant impact on left ventricular blood flow, especially since the recognition of the spiral ejection pattern of the left ventricle. From an apical view, this rotational pattern is induced in the blood flow by the twisting motion of the heart [23,24].

Asymmetry might also avoid instabilities by allowing entering, recirculating and outflowing streams to pass one another in the three-dimensional space without collision, where the anterior leaflet moves away from the septum and again divides the outflow from the inflow tract. At the ventricular level, change in direction is such that the recoil away from ejected blood is in a direction that can enhance rather than inhibit ventriculo-atrial coupling.

The visualization of energy loss, turbulences and cavitation in axial flow was clearly evident in the present study. When the valve was fully open, high velocity jets through each of the three orifices of the prosthesis could be detected. The valve acts as an obstruction to the forward flow of blood through the valve area and this, coupled with the high velocity jets, caused different intraventricular flow patterns. Additionally, the helical structure at the apical area was different; even within the aorta, and the flow differed from the physiological situation.

With anatomical implantation, the fact that the sling effect was perfect seems to be a major advantage. Results were poorest with the 45° position, where the central hinge between the leaflets is oriented either anatomically or perpendicular to the opening axis of the native valve. Retrograde velocities were more pronounced in the outflow compartment, especially at the level of the deflected anterior mitral leaflet tip. The intraventricular vortex was formed earlier and was enlarged, and initial velocities were higher. Later, the velocity decreased and caused stagnation of the blood in the apical area with a suboptimal wash-out effect.

With the anti-anatomic position during the initial diastolic phase, a wake was generated and remained attached to the valvular edge of the anterior leaflet longer. There is nothing anatomical about an anatomically implanted bileaflet valve with a hinge line that runs across the orifice from side to side; however, with this positioning, the flow characteristics remain more natural, with a homogeneous wash-out, than with both other orientations. The difference between all three variations is, however, less significant than compared with the intraventricular flow situation observed in a natural mitral valve.

This study may permit correlation to the clinical situation because all the preoperative experimental findings on intraventricular blood flow in sheep were totally consistent with in vivo MR studies in healthy human volunteers.

A potential limitation of the present study is that the number of animals undergoing mitral valve replacement was small, but no individual variances in the assessment of blood flow patterns were observed in the sheep scanned preoperatively. Although no inotropic substances were administered during the MRI procedure and although postoperative heart frequency was within the physiological range, postoperative hemodynamics differed individually and might affect the flow pattern. We present no data concerning the symmetrical or asymmetrical leaflet motion and it is as yet unknown whether the design of the Edwards Mira bileaflet valve alone or that of all bileaflet valves shows this orientation-related left ventricular spatial flow pattern.

The next step would be to compare the asymmetric flow profile of a bileaflet valve with a tilting valve, to answer the questions of whether a bileaflet valve is less susceptible to a suboptimal orientation and whether an optimally rotated tilting disc valve is superior to an anatomically implanted bileaflet prosthesis.

The blood flow downstream of the Mira Edwards bileaflet valve changed with rotation of the valve prosthesis and never achieved the physiological flow pattern. The symmetrically constructed valve showed a tendency towards better left ventricular flow performance if the orifices faced the major flow parallel to the region of the anterior leaflet. To achieve optimal hemodynamics, with
less energy loss thanks to the preserved helical structure of the intraventricular blood flow, rotation of the valve has to be considered carefully during implantation, as has long been known from aortic valve replacement studies.

MR velocity mapping allows highly accurate, simultaneous three-directional blood velocity measurements in time resolved images and seems to be the ideal tool to answer the question at hand, i.e., which orientation in bileaflet prostheses creates an optimal intraventricular flow pattern. In the present study, spatial distribution and temporal development of turbulent stress nearby and far off downstream from the bileaflet mitral valve correlated well with different valve orientations.

A method for qualitative assessment of ventricular blood flow patterns due to different orientations of mitral valve prostheses using MR imaging was developed. Whether one of these flow patterns is more favorable regarding both left ventricular kinetics and prosthetic valve function in the long term is a subject for further clinical studies.

Acknowledgements

We thank Rainer Rienmüller, Professor for Radiology and Bruno Rigler, Professor for Cardiac Surgery, from the Divisions of Radiology and Cardiac Surgery of the Medical University of Graz for their scientific support.

References


Appendix A. Conference discussion

Dr O. Alfieri (Milan, Italy): From a practical point of view, did you change something in your practice on the basis of this study? Do you have any clear-cut message on how to put a bileaflet valve?

Dr Macchler: The message is that we should never implant a tilting disk valve anti-anatomically, and the second message is that if a bileaflet is implanted anti-anatomically, the flow is not so nice as with an anatomical tilting disk valve. But I think you cannot say that there is any difference...
between an anatomically implanted bileaflet and anatomically implanted disk valve.

**Dr T. David (Toronto, Canada):** It is a bileaflet world, and so I am going to leave the single leaflet aside. At least in North America, we don’t replace a mitral valve with a single leaflet mechanical valve anymore. It was something we did in the 1970s, and when St Jude was introduced in the 1970s, we swung entirely to the St Jude valve.

What we learned in the early 1980s, and it made sense to a surgeon like myself who repaired a lot of mitral valves, that I should implant the St Jude valve in an anatomic position, that is, I tried to imitate nature because most of the flow in a normal mitral valve is subaortic. Well, we very soon learned that was a bad orientation for that valve because the posterior leaflet became lazy in low cardiac output states, and would not and close fully, increasing the risk of thrombosis. I actually lost a patient in the intensive because of this problem back in early 1980s. We learned to orient the valve into an anti-anatomic position to prevent thrombosis.

Now you are telling us that this is the wrong thing to do.

Mr Ascione: I was interested to know if you have preserved the subvalvular apparatus? Have you observed a higher thrombosis rate with this orientation?

**Dr Maechler:** You are correct. In our daily routine we always implant the St Jude in mitral cases in the anatomical position, that is, I tried to imitate nature because most of the flows are subaortic. Well, we very soon learned in this helix theory, then we must say that due to the spiral ejection of the left ventricle, flow profiles should remain asymmetrically after mitral valve replacement, and if you say you would like to get an asymmetrical flow in the left ventricle, then you can’t implant a bileaflet valve.

**Dr David:** And how about in patients with atrial fibrillation? The opening and closure of mitral valves are different.

**Dr Maechler:** I just can bring our results with sinus rhythm. So far we have done no studies with atrial fibrillation. This might be another point.

Mr R. Ascione (Bristol, UK): I am not sure I picked this up right, but did you preserve the mitral subvalvular apparatus? By doing so on both anterior and posterior leaflets one might minimize changes in LV geometry, which in turn might have an effect on flow pattern.

**Dr Maechler:** I didn’t get your question.

Mr Ascione: I was interested to know if you have preserved the subvalvular apparatus.

**Dr Maechler:** Yes, we have preserved the whole subvalvular apparatus, and we just cut off 50% of the segment A2, because we tried to implant larger valves, and so we just resected 50% of this segment A2. The rest of the subvalvular apparatus of the anterior leaflet and the whole posterior leaflet had been preserved.

**Dr J. Laas (Bad Bevensen, Germany):** As one of the co-workers I first would like to give credit to Bob Frater who basically found out as the very first one, I think as early as in 1969, that the optimum orientation for tilting disk valves is the position when the larger orifice is directed towards the posterior leaflet.

And I would like to make a comment to the question and the comments of Tirone. I have changed my practice completely, and in the mitral position I only implant tilting disk valves anymore.

**Dr R. Frater (Bronxville, New York):** I would like to start by making a plea for not using the term anatomical for a transversely orientated bileaflet valve. There is nothing anatomical about a valve with a hinge line that runs across the orifice from side to side. We don’t have valves like that. We have a hinge that is way up in front.

And what Dr David mentioned is I think the most important point, that if you have a small orifice, not a normal size orifice but a small orifice with a transversely orientated bileaflet valve, there is in some cases, depending on what is subvalvular, interference with the motion of that leaflet.

Basically what happens is the current goes through, forms a vortex, bounces off the papillary muscles and comes back, and those leaflets are so sensitive to flow that it keeps the leaflet fluttering on the posterior side, and it is a vulnerable leaflet under those circumstances.

Now, you have to get away from that, you have to insert it in the position with an anteroposterior axis, and put up with the fact that that lovely sling effect may not be perfect in that circumstance. It is clearly a choice. And I don’t have any doubt about the choice if I am using a bileaflet valve to put it with the axis from the middle of the aorta to the middle of the posterior annulus.

**Mr A. El Gamel (London, UK):** I just wanted to ask you something about the details of the experiment. Usually the flow is affected by the hemodynamics of these animals, and I wondered how did you manage during transport and the MRI scanner to keep blood pressures and filling pressures and everything the same and did you use any inotropes at all, because that will make the comparison difficult with the small number of animals?

**Dr Maechler:** You are absolutely correct. I mean, between flow patterns and hemodynamics is a large difference, and we didn’t measure the consequences in hemodynamics. The only thing that we tried is that all sheep showed the same frequency, but it was not possible that the sheep had the same hemodynamic data.