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

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Abstract

Objective: Orientation-related monoleaflet mechanical valve flow and velocity studies in the downstream are limited in mitral valve replacement studies. Methods: In five sheep, ventricular blood flow was visualized prior to the implantation of a Medtronic Hall tilting valve model. In six sheep, the implant orientation was either anatomical (disc aligned with the anterior leaflet) or anti-anatomical. The mitral subvalvular apparatus was preserved. Sheep were positioned within an 1.5 T field strength MR scanner (Magnetom Sonata; Siemens) to assess time-dependent three dimensional blood flow. Results: The preoperative ventricular velocity profiles presented negligible individual variances. Streamlines passed homogeneously without any spatial differences in flow velocities into the left ventricle. Starting from the anatomical position, blood entered mainly through the major orifice of the mechanical valve. The single artificial leaflet mimicked the rudder effect of the natural anterior mitral leaflet, preventing blood streaming directly towards the septum. The area with inhomogeneous blood velocities in the ventricle increased but not significantly from the preoperative status. The non-axial inflow not directed directly to the apex converted to a similar helix as observed in the preoperative cases. Anti-anatomical orientation of the prosthesis caused a significant increase in turbulence immediately after passing the mitral prosthesis. The main stream was changed so significantly that the blood flow shifted towards the septum and caused higher velocities of the stream profiles and turbulence apically. Conclusions: To achieve optimal hemodynamics, orientation of the mitral tilting valve has to be considered carefully, as has been long known from aortic valve replacement studies.

Keywords: Mitral valve prosthesis; Orientation; Intra-ventricular flow; Magnetic resonance Imaging

1. Introduction

Much is known in improving outcomes in mitral valve replacement [1—7]. Since 1993, the importance of chordal preservation techniques in maintaining improved left ventricular function has been well documented clinically. However, the wide variance in survival rates among different patient cohorts reveal that certain risk factors are yet to be elucidated.

The transvalvular flow characteristics of commonly used mitral prosthetic valves are well known [8—12], but the intra-ventricular 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 [13—15]. There are various methods that can easily be applied to demonstrate the influence of the orientation of the prosthetic valve substitute on the velocity profiles in the ascending aorta [13—16]. However, it is difficult to evaluate the velocity profiles in mitral cases regardless of methodology; therefore publications addressing the intra-ventricular flow effects of different orientations of asymmetrical monoleaflet prosthetic valves in the mitral position are rare [17,18].

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 intra-ventricular turbulence with preservation of annulo-ventricular integrity.

The following study was designed to clarify the question of whether there is an optimal orientation for a monoleaflet mitral prosthesis with regard to intra-ventricular flow.
2. Materials and methods

All animal studies were performed following the guidelines for animal experiments prescribed by Austrian law. Eleven 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, intra-ventricular blood flow, velocity profiles and the occurrence of intra-ventricular turbulence were measured preoperatively to evaluate the individual sheep-to-sheep variance. Additionally, these five animals served as blood donors.

In six 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 a half of the mid-third of the anterior mitral leaflet, a 23 mm Medtronic Hall mechanical prosthesis (Medtronic, USA) was implanted in two different positions:

(1) In the anatomical position \( (n = 3) \) with the disc aligned with the anterior leaflet (major orifice towards the posterior leaflet).

(2) In an anti-anatomical 180° position \( (n = 3) \) with the disc aligned with the posterior leaflet (major orifice towards the anterior leaflet).

The preserved segments of the anterior mitral apparatus as well as the preserved posterior leaflet were furled to the annulus by sutures used to insert the prosthesis. Following hemofiltration and weaning from cardiopulmonary bypass, the animals were kept stable for 3 h until a steady state was achieved. The sheep were transported to the magnetic resonance imaging device. During the early imaging period, one sheep (anatomical orientation) died of hypothermia; for the five remaining sheep, the mean imaging period was 2.6 h (2–5.4 h). All sheep were warmed using a 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 imaging method and calculations

Sheep were positioned laterally with their hooves forward in 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 standard two-dimensional FLASH (fast low angle shot) phase contrast cine sequences. 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 mm \( \times \) 320 mm, matrix of 128 \( \times \) 128 lines, slice thickness of 5 mm, repetition time \( \text{(TR)} = 25 \text{ ms} \), echo time \( \text{(TE)} = 3.3 \text{ ms} \) and flip angle \( \alpha = 15^\circ \) 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 performed with a dedicated software (“4D Flow”) in the following way: 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 control sheep presented negligible individual variances.

![Fig. 1. Preoperatively, blood streams homogeneously without differences in flow velocities into the left ventricle creating the apical vortex (for better visualization through-plane velocity components are omitted in all figures).](image-url)
In detail, the early diastole streamlines passed homogeneously without any spatial differences in flow velocities into the left ventricle (Fig. 1). The anterior leaflet of the mitral valve moving towards the interventricular septum created the asymmetric inflow tract in the expanding ventricle, blood did not enter the subaortic outflow tract. Blood flowed not directly towards the apex, but created a helix from the posterior wall and posterior-apical septum turning around the apex and moving up towards the anterior and antero-lateral wall. The major part of the blood volume is thus redirected towards the outflow tract. The dominant direction ran under the free edge of the anterior mitral leaflet, which moved, in the meantime, away from the septum. It protected from entering the inflow tract and created the large outflow tract (Fig. 2). Transient small amounts of recirculation, known as a mechanism to close the mitral valve, were seen beneath the valve.

In all operated sheep, prosthesis related artifacts occurred 1.5 cm downstream. A wedge-shaped dispersion of blood flow was created by the single artificial leaflet and was observed immediately downstream in contrast to the homogenous blood flow seen preoperatively. Stagnant flows seem to occur through the minor orifice of the valve.

The main direction of the inflow was dependent upon the orientation of the prosthesis itself.

Starting from the anatomical position, blood entered mainly through the large major orifice of the valve, the artificial leaflet prevented blood from streaming directly towards the septum (Fig. 3). The area with inhomogeneous and accelerated local blood velocities in the mid portion of the ventricle increased but not significantly from the preoperative status.

During the late systole, blood streamed homogeneously within the outflow tract, avoiding misdirection to the closed mitral valve prosthesis (Fig. 4).

Anti-anatomical orientation of the prosthesis caused a significant increase of turbulence immediately after passing the mitral prosthesis with mean maximal velocities of 1.5 m/s (variation between 1.0 and 1.2 m/s) in contrast to mean maximal 1.1 m/s (variation between 1.0 and 1.2 m/s) in the anatomical position. Also, in the anti-anatomical position, the main stream shifted towards the septum (Fig. 5). This was caused by the artificial leaflet and caused higher velocities of the stream profiles and turbulence apically.

Additionally, in the anti-anatomical position, the typical apical flow pattern of the blood helix was disturbed, the smooth flow of blood towards the apex was absent. However, changes compared to the anatomical position were more significant as comparing the preoperative status with the anatomical position. The disturbed physiological helical blood flow towards the apex was changed so significantly that the main direction of blood flow was different from the anatomical implanted cases.
The blood streamed directly towards the mitral valve prosthesis in an S-shaped manner (Fig. 6). Increased non-physiological turbulent flow pattern was observed in the aorta, to a lesser extent with the anatomical position. Additionally, the in- and out-streaming blood seemed to cross each other in the anti-anatomical orientation (Fig. 6) and the prosthesis seemed to stay open longer.

5. Discussion

The transvalvular flow characteristics of commonly used mitral prosthetic valves are well known, however, the orientation of the mitral valve prosthesis has not received the same clinical attention as aortic valve replacement cases. Potential hemodynamic disadvantages regarding the optimum orientation of mitral protheses had been the subject of debate.

Aortic valve replacement studies carried out by Kleine et al. [14] and Laas et al. [15] have demonstrated that, in patients with a normal aortic valve, ejection of the left ventricle follows a spiral course. With ongoing systole the highest velocities rotate counterclockwise 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 orientation of mechanical aortic prostheses has an impact.

In the case of mitral replacements, scarce research regarding the effects on the intra-ventricular blood flow on different orientations of prostheses is available [17,18].

There are two different theories surrounding the anatomical or anti-anatomical orientation of tilting valve prostheses [5,19—22]. Some authors recommend an anterior orientation, especially in smaller valves (27 mm or less) [5]. These adherents of anti-anatomical implanted valves say that the anterior leaflet oriented in an opposite position to the opening disc of the prosthesis increases the opening area, because, both, the disc as well as the anterior leaflet are open. Likewise, a significant number of surgeons favor the flow related viewpoint thinking that a more physiological orientation with the large orifice opening in a posterior fashion mimics the rudder effect of the natural anterior mitral leaflet and preserves the natural vortices of the left ventricle during diastole, preventing blood from streaming directly to the septum. This theory was proven by our study also. Additionally, the risk of disk impingement was discussed to be minimized if the larger orifice is oriented posteriorly [5,21,22].

In the clinical routine, prostheses are rotatable after implantation to prevent from the risk of leaflet impingements, and it might be that surgeons switch too rashly in fear of leaflet impingements without having in mind the enormous consequences of suboptimal orientated valves.

Magnetic resonance velocity mapping allows assessment of complete left ventricular blood flow and seems to be the
ideal tool to answer the presented topical question, i.e. which orientation in monoleaflet prostheses creates optimized flow pattern intra-ventricuarily.

Due to the spiral ejection manner of the left ventricle, flow profiles should remain asymmetric after mitral valve replacement. Asymmetry might also avoid instabilities by allowing entering, recirculating, and outflow streams to pass one another in the three-dimensional space without collision, the artificial leaflet moving away from the septum separates the outflow from the inflow tract. At a 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. Spatial distribution and temporal development of turbulent stress close and far off downstream of the tilting mitral valve with its high value of blood velocities along the large orifice correlated well with the superimposed structure of the prostheses itself. This characteristic is well known, but does it influence the helical blood flow? Since 2000, the asymmetric direction of flow has been investigated, but does it influence the helical stream of the tilting mitral valve with its high value of blood development of turbulent stress close and far off downstream of the tilting mitral valve with its high value of blood velocities along the large orifice correlated well with the superimposed structure of the prostheses itself. This characteristic is well known, but does it influence the helical blood flow? Since 2000, the asymmetric direction of flow through the heart is theoretically discussed [23–25]. And what does it mean for the cardiac output and for the outcome of the patient? The anti-anatomical position, where the large orifice is oriented perpendicular to the opening axis of the native valve leaflets offered the worst results, the freedom of the blood to enter the ventricular cavity is limited (Fig. 6).

As this study has proven that most of the stroke volume with ongoing systole is ejected into the direction of the anterior and anterior-lateral wall, blood does not leave the outlet portion of the ventricle disordered, but in a very homogeneous, asymmetrical and in a smooth manner without any turbulence. So the implantation of an asymmetric mitral valve prosthesis must have an impact to the ejected blood in that manner that it seems to mimic the physiological status [23–25].

The limitations of this present study are that while the correlation to humans seems to be permitted, all preoperative experimental findings in sheep concerning the intra-ventricular blood flow were consistent with those in the in-vivo MR-studies in healthy volunteers. However, this must be proven clinically with patients with a prosthetic mitral valve. The second limitation is that just a small number of sheep have been investigated, but between all preoperative sheep (as well as between all healthy volunteers, additionally among themselves) no variances in blood flow patterns could be observed. The third limitation is that we did not correlate the flow patterns with the postoperative hemodynamics and therefore to the possible clinical outcome in humans.

The Medtronic tilting valve prosthesis presented less changed patterns of intra-ventricular blood flow up to the apical area if implanted anatomically (major orifice towards posterior leaflet). Blood flow downstream of the tilting valve changed with the anti-anatomical orientation of the valve prosthesis, however, it did not provide a physiological flow pattern. The asymmetrically constructed valve showed a tendency towards better performance if the larger orifice is oriented towards the posterior leaflet, thereby mimicking the function of the native anterior leaflet. However, the differences in flow patterns between the physiologic valve and the optimal positioning is not so significant as the difference between different orientations. To achieve an optimized hemodynamic situation and thus minimize the risk of postoperative valve-related complications, orientation of the valve has to be considered carefully during implantation.

In the future the asymmetric flow profile of a tilting valve must next be compared with the flow profiles of a bileaflet valve [17], to answer the questions if a bileaflet valve seems to be less susceptible to a suboptimal orientation and if an optimal rotated tilting valve is superior to an anatomically implanted bileaflet prosthesis.

In conclusion, a method for quantitative assessment of left ventricular blood flow patterns using magnetic resonance imaging has been employed to detect the consequences of different orientations of mitral valve prosthesis. There may be a link between hemodynamics and orientation of the mitral prostheses. Clinical studies are required to transfer the results of the animal experiment to humans and to answer the question if the orientation of the prosthesis might be an additional risk factor in postoperative outcomes.

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References


