Direct imaging of bileaflet mechanical valve behavior in the tricuspid position

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Received 23 September 2005; received in revised form 20 February 2006; accepted 23 February 2006; Available online 3 May 2006

Abstract

Objective: The optimal orientation of a bileaflet mechanical valve for tricuspid valve replacement (TVR) has not yet been determined. The aim of this study was to use fiberoptic cardioscopy to evaluate the effect of orientation of a mechanical valve implanted in the tricuspid position on bileaflet mechanical valve behavior.

Methods: Twelve pigs (50—59 kg) underwent TVR with a St. Jude Mechanical Heart Valve (25 mm standard cuff model) after cardioplegic arrest. The mechanical valve was implanted horizontally in six pigs (Group H), and vertically in another six pigs (Group V). The heart was perfused with pellucid Krebs—Henseleit solution in situ and the mechanical valve behavior was observed with a fiberoptic endoscope during different heart rates (HRs) induced by ventricular pacing (60, 90, 120, 150 min⁻¹). All images were recorded on a high-speed video system every 4 ms. The closing time lag (CTL) between the valve leaflets was calculated and compared between the two groups.

Results: In Group H, the lower valve leaflet tended to open incompletely and close earlier than the upper leaflet. The calculated CTL was 303/60 ms, 65/48 ms, 40/9 ms, and 40/26 ms at pacing HRs of 60, 90, 120, and 150 min⁻¹, respectively. In contrast to Group H, there was little difference in CTL between the right and left leaflets in Group V. The calculated CTL was 9/12 ms, 11/10 ms, 1/3 ms, and 6/7 ms at pacing HRs of 60, 90, 120, and 150 min⁻¹, respectively. There were significant differences in CLT between the two groups at each ventricular pacing rate (P < 0.01).

Conclusions: Orientation of an implanted bileaflet valve in the tricuspid position significantly influenced leaflet motion. In a horizontal orientation, the lower valve leaflet opened incompletely and closed earlier than the upper leaflet. These results suggest that the gravity might affect leaflet motion and that bileaflet mechanical valves should be implanted vertically in TVR to prevent abnormal leaflet motion and thrombus formation.

Keywords: Tricuspid valve replacement; Cardioendoscopy; Mechanical heart valve; Animal model

1. Introduction

Although tricuspid valve replacement (TVR) is a relatively rare procedure, it is one of the principle procedures in cardiac surgery. Only limited studies have been done on TVR, and the choice of valve prosthesis in TVR remains controversial [1—3]. Although a bioprosthetic valve is preferred for TVR rather than a mechanical valve in many institutions due to a lower risk of thromboembolism [4], there have been studies reporting good clinical results using a mechanical valve in the tricuspid position [5,6]. The prognosis of patients undergoing TVR has been reportedly worse than patients undergoing mitral valve replacement [5,7,8]. Further investigations are required to improve patients’ prognoses after TVR.

In the present study, the dynamic characteristics of a bileaflet mechanical heart valve implanted in the tricuspid position of pigs were analyzed using cardiac endoscopy. Although this type of experimental study has been performed previously in the mitral position, it has not yet been performed in the tricuspid position [9]. Assuming that thrombogenesis may be related to inappropriate movement of the leaflets, we determine the effect of valve orientation in the tricuspid position and heart rate (HR) on leaflet motion after TVR.

2. Materials and methods

2.1. General preparation

Twelve pigs (body weight: 50—59 kg) were used in this study. They were anesthetized with ketamine chloride...
(10 mg/kg, intramuscularly) and thiamylal sodium (75 mg, intravenously). Tracheostomy was performed and an endotracheal tube (I.D. 7.5 mm) was inserted. General anesthesia was maintained by inhalation of isoflurane under mechanical ventilation (model ARF-850E, Acoma Co., Tokyo, Japan). The animal was placed in the supine position and a median sternotomy was performed. The pericardium was fully opened. Right atrial pressure, right ventricular pressure, and ascending aortic pressure were monitored. Heparin (300 units/kg) was given intravenously and a coronary perfusion cannula (I.D. 2 mm) was introduced into the ascending aorta. A cannula (24 Fr) was also inserted into the superior vena cava (SVC) and inferior vena cava (IVC) for infusion of pellucid Krebs—Henseleit solution (Krebs—Henseleit solution contents (g/L): NaCl 6.9, KCl 0.35, CaCl₂ 0.19, MgSO₄ 0.15, KH₂PO₄ 0.16, NaHCO₃ 2.1, glucose 1.1; electrolytes (mM): Na⁺ 143, K⁺ 5.9, Cl⁻ 125.2, Ca²⁺ 2.5, glucose 6.0, osmolarity 300 mOsm/L), and regulation of right ventricular preload. An additional cannula (24 Fr) was inserted into the main pulmonary artery (MPA) for regulation of right ventricular afterload. The left ventricle was vented with a catheter (14 Fr) positioned in the apex (Fig. 1).

The distal part of the ascending aorta was cross-clamped and cold (4 °C) St. Thomas solution (Miotecter Kobayashi, Tokyo, Japan) was administered immediately. Topical cooling was performed with iced saline solution. The SVC and IVC were ligated and the right atrium (RA) was incised obliquely. The three tricuspid valve leaflets were completely resected along with their chordae. TVR was performed using a bileaflet mechanical heart valve (St. Jude Medical, standard cuff model 25 mm) and 2-0 polyester continuous sutures.

Pigs were divided into two groups of six pigs each according to the orientation of the bileaflet mechanical valve: a horizontal group (Group H) and a vertical group (Group V).

After the right atrium was closed by 4-0 polypropylene continuous sutures, the coronary arteries were perfused through the ascending aorta with pellucid Krebs—Henseleit solution warmed to 37–38 °C and bubbled with a mixture of oxygen (95%) and carbon dioxide (5%). The mean perfusion pressure was maintained at 70–80 mmHg. After 10–15 min of empty beating, the right ventricle (RV) was also perfused with pellucid Krebs—Henseleit solution through the SVC and IVC to maintain a right ventricular preload of 10–20 cmH₂O. The afterload of the right ventricle was maintained at 20–30 cmH₂O. Two monopolar pacing wires were placed on the right ventricle for pacing. A fiberoptic endoscope (Olympus BF type 40, Olympus Corp., Tokyo, Japan) was inserted into the right atrium. The mechanical heart valve motion was then observed endoscopically with the heart beating. The RV was paced using a pacemaker (model EDP 30/s; Biotronik Inc., Berlin, Germany) at rates of 60, 90, 120, and 150 beats per minute. The motions of the mechanical heart valves were recorded by a high-speed video system (model HSV-500³, NAC Inc., Tokyo, Japan, 250 frames per second).

2.2. Image analysis of the mechanical valve movement

The images of the mechanical valve motion recorded by a high-speed video system were analyzed every 4 ms. The time when each leaflet began to open (opening time (OT)) and the time when each leaflet finished closing (closing time (CT)) was determined. We subtracted OT from CT to determine the open period (OP) of each leaflet. We defined the difference between the OP of each leaflet as the closing time lag (CTL). Usually both leaflets opened simultaneously and only closing time was different between the leaflets. Therefore, the CLT reflects the time period between the closures of the two leaflets. We measured the effect of HR on the CTL within each group. The CTL at each HR was also compared between the two groups.

2.3. Statistical analysis

The computer software package StatView 4.5 (Abacus Concepts, Berkeley, CA, USA) for Macintosh (Apple Computer...
Inc., Cupertino, CA, USA) was used for statistical analysis. Data are presented as mean ± standard deviation (SD). The Mann–Whitney U-test was used to compare the preoperative hemodynamic variables and the CTL between Group H and Group V. A repeated measures analysis-of-variance followed by Scheffe test was used to compare the CTL differences among the different HRs in Group H. A Kruskal–Wallis test was used to compare the CTL differences among the different HRs in Group V, since these data did not follow a normal distribution.

2.4. Animal care

All animals in this study were treated in compliance with the Guide for the Care and Use of Laboratory Animals published by the National Institute of Health (NIH Publication No. 86-23, Revised 1985) and with the European Convention on Animal Care. All procedures were also approved by the Animal Research Committee of the Saga University Faculty of Medicine.

3. Results

3.1. Preoperative values of the animals

The pig body weight used in these experiment groups was 52.8 ± 2.8 kg in Group H and 54.9 ± 2.4 g in Group V. There was no significant difference between the two groups (P = 0.26). Preoperative hemodynamic values in each group are listed in Table 1. There were no significant differences in any of the preoperative hemodynamic parameters between Group H and Group V.

3.2. Qualitative analysis of the leaflet motions

In the horizontal orientation, the lower valve leaflet motions appeared abnormal with incomplete opening and early closing. The abnormal lower leaflet motions were more obvious at lower HRs. In contrast, the upper leaflet motion appeared almost normal even at lower HRs. In the vertical orientation, both leaflets moved symmetrically in general.

3.3. Analysis of CTL in Group H

From an analysis of the video-taped images, we found that the mechanical valve leaflets began opening at the same time regardless of HR in both groups. In Group H, the lower valve leaflet tended to close earlier than the upper leaflet (Fig. 2, Video 1). This was especially true at HR 60 compared with the other HRs (Fig. 3). The calculated CTL at HR of 60 min⁻¹ (30 ± 60 ms) was significantly longer than the CTLs at HRs of 90 min⁻¹ (65 ± 48 ms, P < 0.0001), 120 min⁻¹ (40 ± 9 ms, P < 0.0001), and 150 min⁻¹ (40 ± 26 ms, P < 0.0001). There was no significant difference in CTLs comparing HRs of 90, 120, and 150 min⁻¹ (Fig. 3).

3.4. Analysis of CTL in Group V

In Group V, the CTL between the right and left leaflets was similar even at a rate of 60 min⁻¹ (Fig. 4, Video 2). In Group H, the lower valve leaflet tended to close earlier than the upper leaflet, whereas in Group V no such tendency was observed. In Group V, the right leaflet closed earlier than the left leaflet in some cases and later than the left leaflet in other cases. The CTLs at all of the HRs observed in Group V were much shorter than CTLs in Group H. The calculated CTL was 9 ± 12 ms, 11 ± 10 ms, 1 ± 3 ms, and 6 ± 7 ms at pacing HRs of 60, 90, 120, and 150 min⁻¹, respectively (Fig. 3). There were no significant CTL differences among the different HRs in this group.

3.5. The CTL analysis under the different valve orientations

The CTLs were compared in two groups at the same HR. The CTL at each HR studied in Group V was much shorter than the CTL at the same HR in Group H (P < 0.01) (Fig. 3).

4. Discussion

In the present study, TVR with valve implantation in the horizontal position led to abnormal leaflet motion with incomplete opening and early closing of the lower leaflet. An asymmetrical movement of the bileaflet mechanical heart valve implanted into the tricuspid position horizontally was quantitatively revealed by measuring the closing time lag using a high-speed video system that recorded leaflet position every 4 ms. Observations of native valve motion in working dog hearts with an endoscope have been reported previously [10,11]. However, the direct observation of bileaflet mechanical valve motion in the tricuspid position in the working pig heart in situ has never been reported. Direct observation of the heart valve in an isolated working heart perfused with crystalloid solution has been reported [12]. In that study, a pig heart was completely excised and attached perpendicular to the experimental apparatus. In contrast, we used pig hearts in situ to preserve the natural physiological influence of gravity on the mechanical valve leaflets.

### Table 1

Preoperative hemodynamic variables in Groups H and V

<table>
<thead>
<tr>
<th></th>
<th>Group H (n = 6)</th>
<th>Group V (n = 6)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (min⁻¹)</td>
<td>89.0 ± 17.6</td>
<td>95.5 ± 17.0</td>
<td>0.34</td>
</tr>
<tr>
<td>AoS (mmHg)</td>
<td>77.8 ± 7.4</td>
<td>81.8 ± 5.0</td>
<td>0.42</td>
</tr>
<tr>
<td>AoD (mmHg)</td>
<td>50.7 ± 10.0</td>
<td>54.8 ± 4.2</td>
<td>0.58</td>
</tr>
<tr>
<td>AoM (mmHg)</td>
<td>69.2 ± 8.4</td>
<td>73.3 ± 1.9</td>
<td>0.38</td>
</tr>
<tr>
<td>RAS (mmHg)</td>
<td>6.3 ± 5.9</td>
<td>10.7 ± 4.4</td>
<td>0.58</td>
</tr>
<tr>
<td>RAD (mmHg)</td>
<td>1.2 ± 2.4</td>
<td>1.0 ± 2.1</td>
<td>0.58</td>
</tr>
<tr>
<td>RAM (mmHg)</td>
<td>3.7 ± 4.1</td>
<td>7.5 ± 2.6</td>
<td>0.52</td>
</tr>
<tr>
<td>RVS (mmHg)</td>
<td>25.7 ± 6.9</td>
<td>27.5 ± 6.5</td>
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</tr>
<tr>
<td>RVD (mmHg)</td>
<td>1.5 ± 3.6</td>
<td>2.0 ± 2.8</td>
<td>0.09</td>
</tr>
<tr>
<td>RVM (mmHg)</td>
<td>17.5 ± 4.3</td>
<td>18.8 ± 3.6</td>
<td>0.08</td>
</tr>
</tbody>
</table>

No significant differences were detected between the groups. Data are presented as mean ± SD. P-values were calculated by the Mann–Whitney U-test. AoS, systolic aortic pressure; AoD, diastolic aortic pressure; AoM, mean aortic pressure; RAS, systolic right atrium pressure; RAD, diastolic right atrium pressure; RAM, mean right atrium pressure; RVS, systolic right ventricle pressure; RVD, diastolic right ventricle pressure; RVM, mean right ventricle pressure.
Kiyota et al. [13] reported closing behavior of a bileaflet mechanical valve in the pulmonary position using a low-pressure mock circulation system in vitro. They suggested that gravity affected the bileaflet mechanical valve closure in a low-pressure system like the right ventricle and showed earlier closure of the lower valve leaflet in the horizontal valve orientation. We also showed the same behavior of a bileaflet mechanical heart valve implanted into the tricuspid position horizontally in the working pig heart in situ. Although Kiyota et al. observed earlier closure of the right-sided than the left-sided leaflet in vertical valve orientation, we could not measure a significant CTL difference between the two valve leaflets in Group V. They suggested the existence of a hemodynamic force created by the angle of flow affecting the closing motion of the valve in the vertical valve orientation. We speculate that the difference in results of the previous study [13] compared to ours was due to the experimental apparatus. They simulated bileaflet valve behavior in the pulmonary position. Their experimental apparatus produced a right-angled direction of flow through the bileaflet mechanical valve. In contrast, we placed the bileaflet mechanical valve in the tricuspid position in the present study so that the flow direction through our mechanical valve was relatively straight during diastole. Therefore, there was minimal CTL between the right and left leaflets in Group V in our study. These results suggest that the optimal orientation of a bileaflet mechanical valve in the tricuspid position should be vertical to prevent abnormal leaflet motion.

We speculate that thrombogenesis after TVR with a bileaflet mechanical heart valve implanted horizontally might be related to abnormal leaflet motion with incomplete opening and early closing of the lower leaflet. In a previous study of the St. Jude Medical bileaflet mechanical heart valve in sheep by Okazaki et al. [14], microthrombus formation was reported at the downstream edge of the pivot implanted in the mitral position. In general, the pivotal area is a potential site of thrombogenesis in mechanical heart valves. With abnormal leaflet motion and incomplete opening and early closing, the pivotal area may not be adequately flushed out. Thus, any abnormal motion of the leaflet should be prevented to decrease the risk of thrombus formation, particularly in the pivotal area.

With regard to the influence of HR on mechanical valve motion, as HR increased, the CTL tended to become shorter in Group H. This suggests that the combination of a horizontal orientation of the implanted mechanical heart valve in the tricuspid position and bradycardia might increase the risk of
thrombus formation. Bradycardia itself after TVR with a mechanical heart valve might be a risk factor for abnormal leaflet motion together with a reduced washout of the hinge mechanism.

Although a patient after TVR is actively moving and the orientation of the valve may change when the patient is awake, the orientation of the valve may be horizontal while the patient is sleeping in the supine position, which may result in abnormal leaflet motion with inadequate opening. Usually the heart rate is lower during sleep than during activity. Thus, the risk of thrombus formation at the hinge may increase during sleep in the supine position with a horizontal orientation of the mechanical valve.

5. Study limitations

This study used data that were collected during ventricular pacing in a working pig heart and the effects of sinus rhythm and atrial fibrillation (AF) were not considered. It is possible that the leaflets of the mechanical valve would move more symmetrically due to the atrial kick during sinus rhythm. On the other hand, it was expected that the mechanical valve leaflets would move more asymmetrically during AF due to an irregular HR. The effects of right ventricular dysfunction, pulmonary arterial hypertension, and blood viscosity, which might influence mechanical valve motion in the tricuspid position clinically, were not evaluated in the present study.

In addition, it was so difficult to observe the mechanical valve motions from just the right front endoscopically, and thus we were unable to measure the exact opening angles of each mechanical valve leaflet at the various HRs in the two groups.

6. Conclusions

In the horizontal orientation, the lower leaflet opened incompletely and closed earlier than the upper leaflet by the gravity. It might be better that bileaflet mechanical valves were implanted vertically in the tricuspid position to prevent strange leaflet motions during sleep in the supine position. The abnormal leaflet motion was more obvious at relatively lower HRs. Bradycardia after TVR with a bileaflet mechanical heart valve might be a risk factor for abnormal leaflet motion affected by gravity in the clinical setting.

References


Appendix A. Conference discussion

**Dr P. Kappetein (Rotterdam, The Netherlands):** There are not so many people I think in the world who do these kind of experiments, so you are lucky that there is somebody in the audience who has done these kind of experiments, Dr Van Rijk-Zwikker. I don’t know if you want to make a comment on it. You have extensively worked on the mitral valve and direct visualization.

**Dr G. Van Rijk-Zwikker (The Netherlands):** I wasn’t planning to comment, but anyway, about 10 years ago we did similar experiments with the Carbomedics valve in the mitral position and decided that the cause of that asymmetrical leaflet, as we called it, was caused by the asymmetrical ventricle and the orientation of the valve in respect to that asymmetrical ventricle. Both the right and left ventricles are asymmetrical, and as soon as you deploy in your vertical situation a symmetrical inflow, the leaflet will behave simultaneously. And if you then change the valve by 90°, you will get an asymmetrical inflow and an asymmetrical outflow, and that is the reason why we think the valve leaflet behaves like it does, similar in your model.

**Dr Ikeda:** Do you want to comment on this or do you attribute the same reason to the asymmetrical opening of the leaflets in your model?

**Dr Elghobary (Nantes, France):** What about in humans when the patient gets off of the table and stands up? This would change the position completely from vertical to horizontal.

**Dr Ikeda:** In the clinical situation, the orientation of the mechanical heart valve is changing according to the movement of the patient. In general, the heart rate tends to lower when we are sleeping. That means we are in a supine position with lower heart rate. So we thought that the mechanical valve should be implanted in the vertical orientation.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ejcts.2006.02.052.