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Effect of an artificial ring on mitral valve function

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ABSTRACT

Differences of the effect of annuloplasty rings on the mitral annulus and leaflets, and differences between types of annuloplasty rings are not well known. We analyzed annular motion and leaflet movement with a rigid or flexible ring and without a ring using an isolated swine working heart model. Hearts of 10 swine (weight: 40–50 kg) were used for a rigid ring (n=5) and a flexible ring (n=5). Four ultrasound crystal tips were fixed around the annulus and an annuloplasty ring was implanted in the isolated heart. In the working heart mode, measurement of mitral annular dimension was acquired by sonomicrometry. Images of mitral valve motion were acquired by a high-speed video camera. The same analyses were performed after removing the artificial ring. The antero-posterior diameter of the diastole distance was significantly reduced in the flexible ring (21.59±0.71 mm) and rigid ring (15.93±1.88 mm) compared with no ring (23.51±2.01 mm). The flexible ring made the transverse diameter shrink significantly more than did the rigid ring. The contraction range of the transverse diameter was significantly smaller in the flexible ring compared with no ring. The duration of opening to closing of the mitral leaflet with the rigid (124.7±4.4 ms) and flexible rings (107.9±3.5 ms) was significantly shorter than that with no ring (168±36.5 ms). Annuloplasty rings allow simplicity of leaflet motion, regardless of the type of artificial ring. In a flexible ring, the mitral annulus shows a vertically long shape, suggesting preservation of posterior annular movement.

Keywords: mitral valve, annuloplasty ring, heart physiology, isolated heart model

INTRODUCTION

The mitral valve apparatus complex consists of five anatomical structures, including an annulus, leaflet, chordae, papillary muscle, and left ventricular wall. These structures have their own motion, but all components move harmonically in cooperation with each other during the cardiac cycle. Function of the mitral valve contains leaflet excursion, annular motion, chordae and papillary muscle movement, and left ventricular wall motion. Annular motion is an important function in which geometry dynamically changes for three dimensions throughout the cardiac cycle. If the annuloplasty ring restricts annular motion, it is unclear whether or how restricted annular motion affects movements of other components. A prosthetic annuloplasty ring used in

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mitral valvuloplasty is thought to restrain movement of the mitral annulus. In particular, restraint of the mitral annulus leads to a change in the opening and closing behavior of leaflet excursion as previously described.[1] However, the relationships of a mitral annuloplasty ring and mitral leaflet movement in detail are unclear.

The prosthetic annuloplasty rings are generally classified into three different types including a rigid ring, semi-rigid ring and flexible ring. They each have their own theoretical concepts and advantages. Selection of a ring depends on the preference of each surgeon. Among the three types of prosthetic annuloplasty ring, differences in mitral valve function have been reported in many clinical studies,[2] but ex vivo experimental research is scarce.

This study aimed to compare mitral valve movement between a rigid ring and a flexible ring. Leaflet motion was investigated to precisely determine leaflet excursion by a high-speed digital video camera, and mitral annular dynamics was assessed by sonomicrometry using a swine working heart model *ex vivo*.

MATERIALS AND METHODS

We have previously reported the isolated working swine heart system using crystalloid perfusate for investigation of valvular physiology.[3-5] In this study, we applied the same working heart system, and five swine were used for the rigid ring and five for the flexible ring. The research protocol was approved by the Nagoya University Laboratory Research Animal Care and Ethics Committee. The investigation conformed to the Principles of Laboratory Animal Care formulated by the National Society for Medical Research and the Guide for the Care and Use of Laboratory Animals published by the National Institute of Health, as revised in 1996.

PREPARATION OF SWINE

Ten Landrace and Yorkshire swine weighing 40 to 50 kg were used for this study. Anesthesia was induced with intramuscular ketamine hydrochloride (7.5 mg/kg) and atropine sulfate (0.5 mg). Anesthesia was maintained with inhalation of 0.02% to 0.04% halothane after endotracheal intubation with a 5.5-mm tube and mechanical ventilation. The heart was exposed via median sternotomy. After cross-clamping of the descending aorta, 500 ml of cold St. Thomas solution (Miotecter, Kobayashi Pharmaceutical Co., Ltd., Osaka, Japan) was infused via the right carotid artery to the coronary arteries. The heart and lungs were extracted after complete cardiac arrest was confirmed.

INSTRUMENTATION AND MEASUREMENTS

Isolated heart apparatus

The details of our isolated working heart apparatus have been previously described and are briefly summarized.[3] This apparatus was designed to perfuse the isolated heart either in the Langendorff mode or in the working heart mode (Fig. 1). The main characteristic of our system is the possibility of a clear view of intracardiac structure movement because of crystalloid perfusate. Modified Krebs–Ringer solution (NaCl 120.0 mmol/L, KCl 4.0 mmol/L, $MgSO_4$ 1.3 mmol/L, NaH_2PO4 1.2 mmol/L, $CaCl_2$ 1.2 mmol/L, glucose 11.0 mmol/L) that was oxygenated by a mixed-gas bubbling system with 10 L/min oxygen and 0.5 L/min carbon dioxide was circulated around the circuit by a roller pump. Fluid temperature of the main reservoir was maintained at

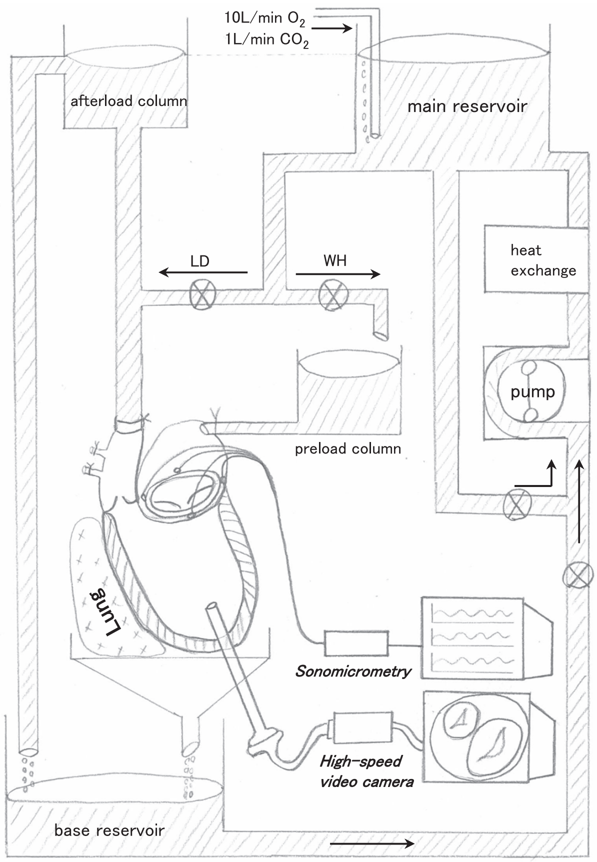

Fig. 1 Isolated working heart apparatus.
Four crystal tips and an artificial ring are fixed through left atriotomy. A rigid endoscope connected to a high-speed digital video camera system is introduced via the apex. LD, Langendorff mode; WH, working heart mode.

38°C. The settled level of the preload column could be changed to regulate inflow to the left atrium. Langendorff perfusion was created by the circuit from the main reservoir, which was placed 100 cm higher than the heart, to the coronary ostium through the connected aorta. The working heart mode was switched from Langendorff perfusion by the circuit from the main reservoir to the left atrium through the preload column and finally to the afterload column filled by ejected perfusate.

Experimental method and protocol

After cardiac arrest by infusion of cardioplegic solution, the heart and lungs were extracted en bloc. Through left atriotomy, four crystal tips were fixed around the mitral annulus by sawing two ties using 6-0 polypropylene. A prosthetic annuloplasty ring was then placed using a 2-0 braided polyester suture in a horizontal mattress. After closure of the left atrium, an additional 250 ml of cardioplegia was re-infused to the coronary arteries, and the heart was connected to the working heart apparatus. Pressure study catheters, electrocardiogram wires, and a cannula, which were connected to the aorta and the left atrium, were placed within 20 minutes, and coronary perfusion was resumed in the Langendorff mode. At 20 minutes after reperfusion, a stable heart beat was confirmed and an endoscope was introduced into the left ventricle via the apex. After perfusion was changed to the working heart mode, video images, sonomicrometry, and hemodynamic data were acquired simultaneously. After perfusion was set back to the Langendorff mode, the closure line of the left atrium was re-opened, and the prosthetic annuloplasty ring was carefully removed while the heart kept beating. After closing the left atriotomy, video images, sonomicrometry, and hemodynamic data acquisition were performed once again under the working heart mode as a control (no ring group). Each five examples were studied for rigid rings and flexible rings. For a rigid ring, we used the Carpentier-Edwards Classic Annuloplasty Ring (Edwards Lifesciences, Irvine, CA, USA), and as the flexible ring, we used the Cosgrove-Edwards Annuloplasty System (Edwards Lifesciences, Irvine, CA, USA). Sizing of the artificial rings was performed to match the distance between the trigones. As a result, the size of all artificial rings used in this study was 26 mm.

Hemodynamic measurements

For ex vivo pressure studies, one 5 Fr micromanometer-tipped catheter (MPC-500, Millar Instruments, Houston, TX, USA) was introduced into the mid-position of the left ventricle via the apex and the other was inserted into the left atrium via the left atrium appendage. Epicardial electrodes were applied to obtain electrocardiograms. The measured data were recorded online on our multiple acquisition system (Leg-1000; Nihon Kohden Corp., Tokyo, Japan and Dipp-Motion 2D; Ditect Co., Ltd., Tokyo, Japan). Dipp-Motion 2D software enabled these data to synchronize with simultaneously obtained video images.

High-speed video camera system

A high-speed video camera (Fastcam-PCI; Photron, Inc., Tokyo, Japan) was connected to a 10-mm diameter rigid endoscope (Olympus Corp., Tokyo, Japan). The endoscope was introduced to the left ventricle through the apex, and intraventricular movements were visualized. The images were recorded at 250 fps (4-ms increments) with 512 × 480 resolution and were directly stored on a computer hard disk.

For the purpose of evaluation of the above-mentioned images in an axis in time, the durations of opening, fully open, closing, and fully closed were calculated. The durations were presented by the ratio when one cardiac cycle was assumed as 100%. Atrial pacing by 100 beats per minute was performed for uniformity of one cardiac cycle.

Sonomicrometry system

The sonomicrometry system was used for analysis of distance and dimension of the mitral annulus. Four ultrasonic tips of 2 mm in diameter were implanted on the mitral annulus. Two crystals were placed for the anteroposterior diameter and the other two crystals for the transverse diameter. The distance of each tip was obtained simultaneously. In this study, the antero-posterior diameter and the transverse diameter in diastolic and systolic phases were measured. The differences between both phases are shown as the contraction range. The value obtained by dividing the contraction range by the diameter of the diastolic phase (diastole distance) was the contraction ratio.

Data analysis

Time-synchronized video images, pressure, and electrocardiograms were analyzed using Dipp-Motion 2D software every 4 ms. Timing of intracardiac events were counted along the time axis during five consecutive cardiac cycles, and the mean was adopted as the representative value of each run. Two groups were compared using the unpaired t-test or the Mann–Whitney U-test. A p value less than 0.05 was considered statistically significant.

RESULTS

Mitral annular motion

The measurements of the antero-posterior and transverse diameters in the diastolic and systolic phases are shown in Table 1. The antero-posterior diameter in the diastolic phase (diastole distance) was significantly reduced in both the flexible and rigid ring compared to no ring (p=0.04, p<0.01, respectively). This finding indicated that prosthetic annuloplasty ring reduces the antero-posterior dimension of the mitral annulus. Furthermore, the rigid ring made the annulus reduction significantly more than did the flexible ring (p<0.05). This effect of annular reduction was also found for the transverse diameter. However, in contrast to the antero-posterior dimension, the flexible ring made the transverse diameter reduction significantly more than did the rigid ring (p=0.039). This finding showed that the rigid ring significantly reduces the antero-posterior diameter and the flexible ring reduces the transverse diameter, as shown by the annular shape (Fig. 2). The contraction range, which indicated the difference between the diastolic distance and the systolic distance, is shown for each ring group in Table 1. The contraction range of the rigid ring was significantly smaller in the antero-posterior (p=0.006) and transverse diameters (p=0.012) than that of no ring. Additionally, the contraction ratio of the rigid ring was lower in both diameters compared with that of the flexible ring and no ring. The contraction range of the antero-posterior diameter in the flexible ring was not significantly different compared with that of no ring (p=0.33). However, the contraction range of the transverse diameter in the flexible ring was significantly smaller than that with no ring (p=0.04). This finding indicated that antero-posterior contractility was preserved in the flexible ring. With regard to the contraction ratio, there were no significant differences among the groups. However, the contraction ratio of the rigid ring was the lowest in both diameters, and that of the flexible ring was lower than that

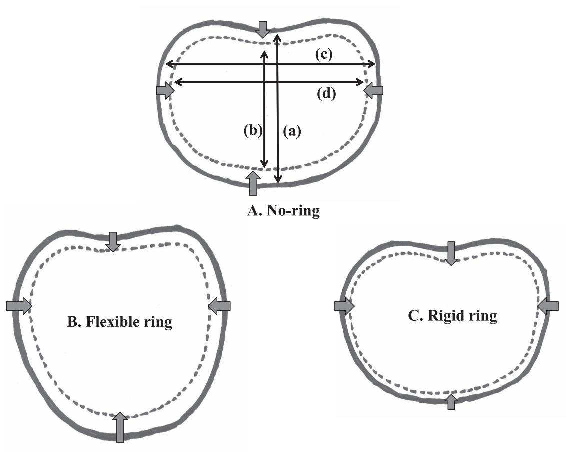

Fig. 2 Image of mitral annular motion with artificial rings and no ring.
The solid line shows the diastolic phase and the dotted line shows the systolic phase. A, no ring; B, flexible ring C, rigid ring. In the flexible ring, the annular shape is vertically long, and the contraction range is preserved around the posterior annulus. (a) Diastolic distance of the antero-posterior diameter; (b) systolic distance of the antero-posterior diameter; (c) diastolic distance of the transverse diameter; and (d) systolic distance of the transverse diameter.

Table 1 The measurements of mitral annular diameter of diastole and systole.

	Diastole distance (mm)	Systole distance (mm)	Contraction range (mm)	Contraction ratio (%)
Antero-Posterior Diameter				
Flexible ring	21.59±0.71 *	19.97±0.92 *	1.62±0.23	7.5±1.3
Rigid ring	15.93±1.88 *,**	15.18±2.15 *	0.76±0.34 *,**	5.0±2.8
No ring	23.51±2.01	21.58±2.12	1.93±0.62	8.2±2.9
Transverse Diameter				
Flexible ring	18.51±0.16 *	17.53±0.99	0.98±0.84 *	5.3±4.6
Rigid ring	21.97±3.86 *,**	21.22±3.45 *	0.74±0.75 *	3.2±2.9
No ring	26.95±1.25	24.87±1.44	2.08±0.54	7.8±2.1

*; Significance against No ring ($p<0.05$)
**; Significance against Flexible ring ($p<0.05$)

with no ring. This finding indicated that the rigid ring restricted annular mobility.

Video images

Videos images of leaflet motion were captured by a high-speed video camera. The camera was inserted through the left ventricular apex. The acquired images show the mitral valve from the left ventricle. Fig. 3a shows a mitral valve with a rigid ring. Fig. 3b shows a mitral valve with a flexible ring. In the case of an artificial ring, especially in the rigid ring, the mode of the leaflets appeared simplified and monotonous.

Opening and closing behavior of the mitral valve

Motion time analysis of the mitral valve leaflet from opening to closing through fully opened was performed using a high-speed video camera (Table 2). The duration of the opening to closing time of the mitral leaflet was significantly shorter in the rigid ring ($p=0.05$) and flexible ring ($p=0.02$) compared with no ring. Therefore, the total duration of leaflet movement became shorter if a ring was placed, regardless of whether the ring is rigid or flexible. The opening time of the rigid ring was significantly shorter than that with no ring ($p=0.04$). Moreover, the closing time of the rigid ring tended to be shorter than that with no ring ($p=0.08$), and the closing time of the flexible ring was significantly shorter than that with no ring ($p=0.02$).

DISCUSSION

There is controversy regarding selection of annuloplasty rings. Different types of annuloplaty rings are used in mitral valve annuloplasty. The flexible ring is an antithesis of the rigid ring, and both rings are different in their advantages and disadvantages. In fact, selection of a ring tends to depend on the surgeon's preference. Many clinical studies have reported differences between both artificial rings, but few ex vivo studies have investigated mitral annular motion. We observed annular movement and leaflet motion with a flexible ring, a rigid ring, or without an artificial ring in an isolated swine working heart model. Currently, a semi-rigid ring, which has the advantages of a flexible ring and a rigid ring, is widely used. However, clarifying specific characteristic of a rigid ring or a flexible ring is important. Moreover, new types of

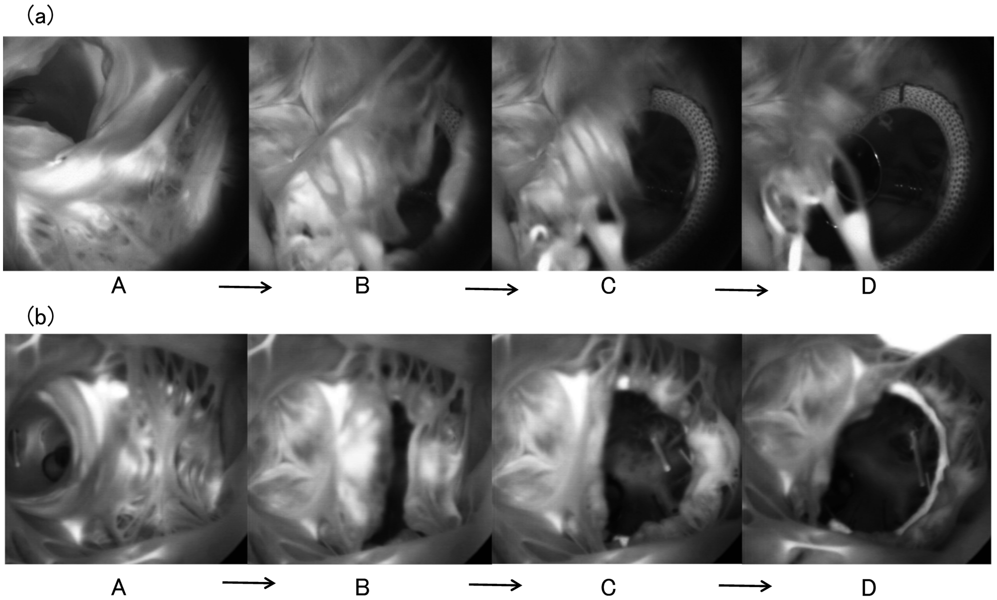

Fig. 3 The pictures of intracradiac view from left ventricular apex.
The frames are picked up during 1 cardiac cycle from the high-speed video file. (a) Rigid ring in mitral position. (b) Flexible ring in mitral position. A: aortic valve open. B: the beginning of mitral valve open. C: half opening of mitral valve. D: full open status of mitral valve.

Table 2 Duration of each phase of mitral valve motion.

Time count (ms)	Mitral Valve Open Status		
	Opening	Full open	Closing
Rigid ring	124.7±4.4 (*p*=0.05)		
	44.7±5.0 (*p*=0.04)	9.2±2.2 (*p*=0.19)	70.8±9.2 (*p*=0.08)
Flexible ring	107.9±3.5 (*p*=0.02)		
	47.6±11.1 (*p*=0.16)	11.4±2.1 (*p*=0.26)	49.0±9.6 (*p*=0.02)
No ring	168.0±36.5		
	56.1±7.2	10.5±0.8	101.3±29.5

The *p* value means against No ring.

artificial rings are being developed with a three-dimensional design. Therefore, a more detailed investigation is required to estimate motion and physiology of the mitral annulus with ring annuloplasty. Our investigation of mitral annular motion was performed by imaging analysis for the time axis using a high-speed digital video camera and also by dimension analysis for the spatial axis using sonomicrometry.

Basic investigations on mitral valve physiology have been performed by a research group of Stanford University using analysis of dimensions of the mitral complex using radiopaque markers.[6,7] Van Rijik-Zwikker et al examined cinefluoroscopic images of the mitral valve with ring annuloplasty at implantation and 3 to 4 weeks after implantation in vivo, and videoendscopic images at 6 weeks after implantation in the isolated heart.[8] We investigated mitral valve function with different types of artificial rings by our own experimental method as previously reported.[3,4] An advantage of this model is the possibility of comparison with and without a prosthetic annuloplasty ring in the same heart. Extracting a prosthetic annuloplasty ring from the beating heart only takes approximately 5 minutes, and cardiac function is not altered before and after ring extraction. An isolated heart continues to function with acceptable cardiac performance for approximately 3 hours.[3] Therefore, we can obtain data with a ring as ring annuloplasty and also record data of the same quality of cardiac function after extraction of the ring (no ring group). We investigated the relationship between movement of the mitral annulus and motion of the valve leaflet. We clarified that leaflet motion became simplified and restricted by an artificial ring and that the mitral annulus showed a vertically long shape in the case in flexible ring annuloplasty.

Leaflet motion of the mitral valve, especially posterior leaflet motion, is restricted by an annuloplasty ring. Green et al[7] compared a flexible ring (Duran ring) with a semi-rigid ring (Physio-ring) to focus on the closing phase of leaflet motion. They showed restriction of the posterior leaflet by both types of rings. Van Rijik-Zwikker et al[8] showed immobilization of the posterior leaflet with images that focus on the opening phase of leaflet motion. In the cardiac cycle, these studies[7,8] emphasized motion of both leaflets in the closing and opening phases. In our study, we evaluated annular movement during the cardiac cycle from the opening phase to the closing phase through to the fully open phase. We observed simplicity of leaflet behavior due to the annuloplasty ring. In fact, the present study showed that the duration of leaflet behavior was shorter than that in cases without a ring.

In this study, the anteroposterior and transverse diameters were shortened with a prosthetic annuloplasty ring. The rigid ring reduced the contraction ratio of annular movement. In video images, the normal mitral valve shows dynamic movement cooperating with annular movement and leaflet motion.[4] Therefore, we speculate that dynamic movement of the mitral valve intrinsically consists of two factors, which are annular movement and leaflet motion. However, when there is an artificial ring, which reduces annular movement, mitral valve motion becomes simplified because of the lack of one of these factors. This could be the reason why mitral valve motion appeared to become simplified and monotonous in our video images. This explanation supports our result of shortening the duration from opening to closing of the mitral valve in the case of a prosthetic annuloplasty ring.

In this study, the shape of the annulus with a rigid ring appeared rectangular (or landscape), and the shape of that with a flexible ring appeared vertically long. The annulus became rectangular because the shape of the rigid ring itself is rectangular. In the case of a flexible ring, the horizontal axis is restricted by fibrous tissue of the trigon. Conversely, the vertical axis depends on mobility of the posterior annulus. In this study, the contraction range of the antero-posterior diameter in the flexible ring was significantly larger than that of the rigid ring. This finding indicated preservation of posterior annular movement.

Study limitations

In our study, the ring size was selected according to an usual clinical criterion by fitting the distance between both trigones. Annular size with a rigid or flexible ring was smaller than that without a ring. Ring annuloplasty is performed in a dilated mitral annulus clinically. However, the present study did not use a diseased dilated heart and the annulus was downsized. We also investigated the annulus by two axial dimensions, but did not represent the three-dimensional geometric structure, called the saddle-horn shape.

CONCLUSIONS

An annuloplasty ring leads to simplified and monotonous leaflet motion, regardless of the type of valve ring. The duration of opening, fully open, and closing of the mitral leaflet is shorter with both types of rings than without a ring. In cases with a flexible ring, the annular shape becomes vertically long. This indicates preservation of posterior annular movement.

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CONFLICT OF INTEREST

The authors declare that there are no conflicting financial or non financial interests relevant to this manuscript.

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