Mitral valve annular downsizing forces: Implications for annuloplasty device development

Morten O. Jensen, PhD,[a] Jesper L. Honge, MD, PhD,[a] Jon A. Benediktsson, MS,[a] Andrew W. Siefert, MS,[b] Henrik Jensen, MD, PhD,[a] Ajit P. Yoganathan, PhD,[b] Teresa K. Snow, PhD,[c] J. Michael Hasenkam, MD, PhD, DMSc,[d] Hans Nygaard, DMSc,[a] and Sten L. Nielsen, MD, PhD, DMSc[a]

Objective: Mitral valve repair with annulus downsizing is a popular surgical procedure for functional mitral regurgitation. We investigated the effects of externally applied downsizing on the observed in-plane forces and valvular dimensions.

Methods: Five animals were included in an acute porcine study. Three traction sutures were anchored at the right fibrous trigone (T) and suspended across the annulus for externalization at the P1, P2, and P3 annular segments. The annulus was downsized with the sutures in controlled increments while measuring the tension force in the sutures. Downsizing percentages ranged from a 2% to 32% reduction of the T-P distances. Sonomicrometry was used to measure the resulting valvular dimensions.

Results: No difference in force was found between the P1, P2, and P3 segments across all levels of downsizing. The peak forces at 32% downsizing were 1.2 ± 0.9 N, 1.5 ± 1.0 N, and 0.8 ± 0.2 N for the T-P1, T-P2, and T-P3 segments, respectively. The maximum total suture forces in the mitral plane during downsizing increased from 0.12 ± 0.03 N to 3.5 ± 1.3 N ($P < .005$). Sonomicrometry showed a decrease in the systolic thickening of the posterior myocardial wall at the annular level with annular downsizing (0%-32%) from 5 ± 3 mm to 1 ± 1 mm ($P < .05$).

Conclusions: Segmental mitral valve annulus downsizing increased in-plane traction suture forces and has a significant influence on the in-plane biomechanics. These results have implications for device design in terms of mechanical strength requirements and can be used to supplement boundary conditions for computational left heart models. (J Thorac Cardiovasc Surg 2014;148:83-9)

ACD

Downsizing the mitral valve (MV) annulus with annuloplasty is a popular surgical procedure to increase leaflet coaptation and restore valvular competency, especially in functional mitral regurgitation. A wide selection of devices exists in many different sizes, shapes, and with varying flexibility properties. The optimal device often is debated because some argue that one annuloplasty ring works for all and others advocate the use of dedicated etiology-specific devices or rings.[1,2] New innovative devices exist that use external approaches to reshape the MV annulus. These include percutaneous transvenous mitral annuloplasty, percutaneous septal-lateral diameter shortening, and ventricular approaches using external restraint devices.[2-5]

Detailed 3-dimensional dynamic morphology of the MV with and without annuloplasty is well documented.[6-11] However, the observed largest deformation in the MV apparatus does not necessarily match the location of the largest forces,[12] which is an important concept because images can be deceiving. Hence, components defining a framework for the free body diagram of the MV apparatus to map the complete force balance of the valve has been reported with in vitro and in vivo measurements of the annular in-plane forces,[13-16] annular out-of-plane forces,[12] chordal forces,[17] and papillary muscle forces.[18,19]

To fully understand the impact of a repair technique using an annuloplasty device to downsize the MV annulus, it is important to investigate the force in the device as the downsizing progresses. This information is relevant also to understand how downsizing affects the rest of the MV apparatus.[20] The hypothesis for this study was that annuloplasty devices used for downsizing the MV annulus experience a force load that is dependent on dynamic annular motion, myocardial contractility, and the amount of downsizing applied. We aimed to investigate this by using externally

From the Department of Cardiothoracic and Vascular Surgery,[a] Institute of Clinical Medicine, Aarhus University Hospital, Skejby, Aarhus, Denmark; Wallace H. Coulter School of Biomedical Engineering,[b] Georgia Institute of Technology and Emory University, Atlanta, Ga; School of Applied Physiology,[c] Georgia Institute of Technology, Atlanta, Ga; and Department of Health,[d] Aarhus University, Aarhus, Denmark.

This research project was funded by the Danish Heart Foundation grant #07-4-B248-A1380-22362, the A.P. Møller Foundation for the Advancement of Medical Science, Snedkermester Sophus Jacobsen og Hustru Astrid Jacobsens Fond, Hørslev Fonden, Aase og Ejnar Danielsens Fond, The Danish Medical Association Research Fund, Helga og Peter Kornings Fund, Arvid Nilssons Fond, and the Central Denmark Region Health Science Research Fund.

Disclosures: Authors have nothing to disclose with regard to commercial support.

Received for publication April 8, 2013; revisions received June 26, 2013; accepted for publication July 12, 2013; available ahead of print Sept 16, 2013.

Address for reprints: Morten O. Jensen, PhD, Department of Cardiothoracic and Vascular Surgery, Aarhus University Hospital, Skejby, 8200 Aarhus N, Denmark (E-mail: dr.morten.jensen@gmail.com).

0022-5223/$36.00

http://dx.doi.org/10.1016/j.jtcvs.2013.07.045

Abbreviations and Acronyms
LV = left ventricular
MV = mitral valve

manipulated traction sutures that measure the effects of continuous downsizing on valve dimensions and observed suture forces. This information has implications on device design in terms of mechanical strength requirements as well as mathematic modeling and simulations of the MV.

MATERIALS AND METHODS

Surgical Protocol

Five mixed Yorkshire and Danish Landrace pigs with a mean body weight of 80 kg were used in an acute experimental set-up. All animals were bred under standard laboratory conditions and the experiment complied with the guidelines from the Danish Inspectorate of Animal Experimentation, which also approved the current study. Animals were sedated with an intramuscular injection of midazolam (0.5 mg/kg) before transport. Upon arrival to the laboratory, the animals received 30 mg intravenous etomidate and then were intubated and coupled to a ventilator. Continuous analgesia was maintained during the experiment with intravenous fentanyl (10 mg/kg/h) and propofol (4 mg/kg/h). Muscle relaxation was obtained by infusion of 12 mg/h rocuronium. The pigs were euthanized with an injection of 50 mL 20% pentobarbital directly into the left ventricle at the end of each experiment. Details of the animal model have been described previously.[17]

Transducer Implantation and Exteriorization

After establishment of cardiopulmonary bypass and cardiac arrest, the MV was exposed through a left atriotomy and a small incision was made in the apex of the heart for sonomicrometry crystal localization. Three polytetrafluoroethylene (Gore-Tex 2-0 traction sutures; W. L. Gore & Associates, Inc, Flagstaff, Ariz) were anchored at the right trigone (T) and suspended across the MV annulus and exteriorized through the posterior annulus at the 3 lateral scallops: the P1 scallop, the center of the posterior annulus (P2 scallop), and the P3 scallop. The right (posterior) trigone was chosen because of the high concentration of fibrous tissue suitable for anchoring as well as exteriorization direction of the sutures through the posterior annulus, allowing the sutures to exit the heart on the anterior side. The epicardial points at which the suture was exteriorized from the posterior annulus segments were chosen because of their easily identifiable and evenly distributed locations. Miniature strain gauge–based force transducers[21] were attached to each suture and suspended at a central location in the annulus (Figure 1).

The transducers were calibrated before and after experiments to ensure measurement accuracy. The mean value of the 2 calibration constants was used. The difference between the calibration constants before and after experiments was consistently less than 10%, equaling a maximum error from calibration within the range of forces observed in this study of $\pm$0.2 N. Use of the average minimized the risk of difference in calibration, translating into significant differences in measured values. Based on previous experience from measurements in the MV apparatus, the transducers were calibrated in a force range of 0 to 5 N in steps of 1 N.[18,19,21,22] This type of transducer has been used successfully in previous in vivo studies, showing high accuracy, resolution, and frequency response for intracardiac measurements.[17,21]

The externalized end of each suture was stabilized with a rubber pad and fed through a flexible channel of spherical pearls (Figure 1). This enabled the downsizing length to be manipulated along the direction of each suture during measurements by using a customized caliper device.[22] At each level of annular downsizing, the force in individual sutures could be measured.

To assess the cyclic 3-dimensional geometry of the mitral annulus, 7 sonomicrometry crystals were placed in the annulus and 1 crystal was placed in the apex as illustrated in Figure 1 (Sonometrics Corporation, London, Ontario, Canada).[12] The crystals placed around the annulus were used to verify the actual downsizing measured as the decrease in the trans-annular T-P distance. This was compared with the reduction of total length of the suture extending from the right trigone, across the annulus, and through the ventricular wall (Figure 1). The apex crystal was placed to define a reference direction in case 3-dimensional analysis was necessary. Before closure of the cardiac cavities, pressure catheters were placed in the left ventricle and left atrium to monitor left ventricular and left atrial pressure, respectively.

Downsizing and Force Measurements

Signals from the strain gauges were monitored continuously during the experiments. Baseline was defined as the point at which the sutures were no longer slack and was determined by tightening the sutures until a clear, periodic force signal variation was observed.[22] Subsequently, the sutures were tightened incrementally on a beating heart, with an interval of 2 mm at a time. All sutures were tightened at the same interval before the distance and force measurements were recorded.

Sonomicrometry was used to quantify myocardial thickness at each level of T-P downsizing. Because the suture length was kept constant during each measurement, systolic thickening of the myocardial wall was measured as the difference between the maximum and minimum distance between the T and P1, P2, and P3 crystals.

Data Acquisition

A data recording was made simultaneously from strain gauges, pressure catheters, and sonomicrometry crystals for each interval of suture tightening. Strain gauge bridge completion, supply current, and data acquisition was performed with dedicated hardware (compact DAQ model 9172 and NI-9237; National Instruments, Austin, Tex). Left ventricular and left atrial pressures were acquired with Mikro-Tip pressure catheters (SPC-350MR; Millar Instruments, Inc, Houston, Tex) and digitalized by a dedicated hardware module (compact DAQ model 9215; National Instruments). Strain and pressure data were recorded with custom-built virtual instrumentation software, using graphic programming (LabVIEW version 8.2; National Instruments). Sonomicrometry data were recorded on a system consisting of an external ultrasound transceiver and a dedicated PC with a digital circuit board installed (Sonometrics Corporation).

Data Analysis

Midsystole and mid-diastole were defined as center points between maximum rate of increase and decrease of left ventricular (LV) pressure (dP/dt). An ensemble average of 10 heart cycles was used to find the maximum and minimum values of the absolute force for each measurement. The total force from the trigone to the P1, P2, and P3 segments (T-P1, T-P2, and T-P3) was found by adding the forces from the individual segments. Cyclic traction forces were found as the variation within each heart cycle and were calculated as the difference between the absolute maximum and the absolute minimum force.

Sonomicrometry distance measurements of the trans-annular diameters were used to determine the effect of the external tightening on the annulus diameter and compression of the myocardial tissue.

Force magnitudes were reported as a function of annulus downsizing percentage relative to the baseline trans-annular diameter for each subject. This percentage was calculated by using a conversion function correlating the suture tightening and sonomicrometry data (see the Results section for more detail).