Endovascular Edge-to-Edge Mitral Valve Repair
Short-Term Results in a Porcine Model

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Background — The edge-to-edge technique is an accepted method for the surgical repair of a regurgitant mitral valve. This study reports the initial use of an endovascular technology that enables a double-orifice edge-to-edge mitral valve repair without cardiopulmonary bypass in an animal model.

Methods and Results — Adult pigs (n=14) were anesthetized, and left thoracotomy was performed for epicardial echo imaging. Using femoral vein access, a steerable guide catheter was placed transseptally into the left atrium. An implantable clip designed to grasp and approximate the middle scallops of the anterior and posterior mitral leaflets was introduced through the guide catheter. The clip was opened in the left atrium, advanced through the mitral orifice, and retracted to grasp the leaflet edges. When a functional double-orifice valve was confirmed by echo, the clip was closed to coapt the leaflets and detached from the delivery catheter. Before final clip detachment, echo demonstrated a double orifice in all 14 animals. In 2 studies, the clip released from the anterior mitral leaflet. Retrospective analysis of echo images indicated an incomplete grasp of the anterior leaflet. Immediate postmortem examination revealed that the clip successfully approximated the middle scallops of the anterior and posterior leaflets in all 12 double-orifice studies.

Conclusions — This study demonstrates for the first time that an endovascular system can be successfully used to perform the edge-to-edge repair technique in a nondiseased porcine model. This technique is potentially applicable as a percutaneous catheterization laboratory procedure for the treatment of mitral regurgitation in humans. (Circulation. 2003;108:1990-1993.)

Key Words: mitral valve • regurgitation • catheterization
Figure 1. Surgical edge-to-edge repair looking at the mitral valve from the left atrium. A suture apposes the middle scallop of the posterior (top) and anterior (bottom) leaflets, creating a double-orifice valve.

Figure 2. A, Schematic of the CVRS guide catheter across the atrial septum. The clip delivery system is positioned through the guide. The clip is in the open position in the left ventricle, ready to be retracted to grasp mitral leaflets (see text). B, The distal end of the delivery system and the polyester-covered clip shown in the open position.

The Evalve Clip is a 2-armed, soft tissue approximation device that is constructed with regard to width and length of tissue apposition. It is designed to promote leaflet-to-leaflet healing around and into the device to maintain a point of permanent leaflet approximation.

Evalve Clip Delivery Protocol
The clip was advanced out the end of the guide catheter under fluoroscopic guidance. In a long-axis echo view, the distal tip of the clip was positioned ~1 cm above the mitral valve and the arms opened with the handle control mechanisms. The clip was then rotated in the short-axis view until the arms were perpendicular to the line of leaflet coaptation and the tip of the clip was above the desired point of coaptation of the middle scallops of the anterior and posterior leaflets (Figure 2). With the delivery catheter aligned with the long axis of the ventricle, the clip was advanced without rotation through the mitral orifice to a level just below the free edges of the leaflets. Leaflets were grasped by clip retraction against the leaflets timed to occur during systole. A thorough 2-dimensional and color Doppler echocardiographic evaluation was performed to confirm success of the grasp, including location of the clip, depth of tissue insertion within the clip arms, and absence of mitral insufficiency. If the result was deemed suboptimal, the clip was opened, advanced into the ventricle, and additional grasps were attempted. If major repositioning was indicated, the clip arms were inverted and the clip retracted into the atrium, where manipulations and adjustments could be performed distant from the chordae tendineae.

Once a successful grasp was confirmed, the clip arms were closed under fluoroscopic guidance. Further echocardiographic evaluation was performed to confirm successful creation of a functional double orifice. Until the final detachment steps, tissue could be released and the clip removed.

Evaluation Protocol
After the guide and delivery catheters were withdrawn, a detailed 2-dimensional and Doppler echocardiographic examination was performed. The animal was then euthanized according to the protocol. At postmortem, the left atrium was opened and the mitral valve inspected for evaluation of clip placement. The atrial and ventricular chambers and the inferior vena cava were exposed to look for catheter- or clip-induced damage. The valve was subsequently
excised for a more detailed inspection of clip placement and any possible trauma.

**Results**

Preintervention echocardiography demonstrated no significant mitral valve pathology or regurgitation. Transseptal puncture was successfully performed in all animals. Manipulation and steering of the catheter system in the left atrium allowed for precise positioning of the clip above the line of coaptation. The clip was opened in the left atrium and oriented appropriately in all 14 studies. The creation of a double orifice with central placement of the clip was prospectively confirmed in all animals. In 8 pigs, a double orifice was obtained with a single grasp; 4 animals required a second grasp, primarily as a result of inadequate initial leaflet approximation. One animal required 3 attempts, and 1 required 5 attempts. Three animals required the clip arms to be inverted and the system to be retracted back into the left atrium for repositioning.

After the clip was closed, echocardiography confirmed a functional double orifice without evidence of MR in all 14 pigs. After completely detaching the clip from the delivery catheter, a detailed echocardiographic study confirmed a functional double-orifice valve in 12 animals (Figures 3 and 4). Left ventricular fractional shortening remained normal, and there was no Doppler evidence of mitral stenosis or regurgitation. No hemodynamic instability was encountered during clip deployment in any of the studies.

In 2 animals, once the clip was released from the delivery catheter, it was noted that the clip was no longer attached to the anterior leaflet. On retrospective analysis of the fluoroscopic and echocardiographic images, it was observed that in both studies, the clip arms had not been fully opened to the correct position before grasping, and the partial grasp could be appreciated echocardiographically before detachment.

Duration of the studies, once transseptal access had been obtained, ranged from 45 to 90 minutes. Subsequent postmortem examination of the 12 pigs with a double orifice showed the desired central placement of the clip perpendicular to the line of leaflet coaptation. No significant inferior vena cava, right atrial, atrial septal, left atrial, leaflet, left ventricle, or chordal trauma was observed in any animal. This included the studies that required inversion of the clip for repositioning as well as the 2 in which the clip did not retain one leaflet. The clip successfully approximated the middle scallops of the anterior and posterior leaflets and was deployed perpendicular to the line of coaptation, creating a functional double-orifice valve.

**Discussion**

This study demonstrates for the first time the short-term success of a catheter-mediated mitral valve repair in a nondiseased porcine model. This is the first endovascular adaptation of the surgical edge-to-edge mitral valve repair. The clinical success and durability of the surgical edge-to-edge repair is documented.10 Ineffective coaptation of the mitral valve leaflets is the mechanical basis of MR and is only indirectly addressed by most conventional surgical repair techniques. By fastening the leaflets together, the edge-to-edge repair ensures a fixed area of coaptation, allowing the remainder of the line of coaptation to close physiologically without disturbing the subvalvular or annular architecture and function. This preserves, if not improves, left ventricular function, which can be of critical importance for patients with impaired left ventricular function.11 Isolated edge-to-edge repair has also, in an animal model, been shown to preserve exercise-induced annular dilatation.12

Improved postoperative functional status and overall freedom from reoperation for surgical edge-to-edge repair has been reported to be 95% at 6 years.10 This durability is not surprising because the mathematically modeled stresses and net force on the point of mitral valve coaptation are minimal.13 Systolic forces applied to the valve by the left ventricle at the coaptation site are not only parallel to the annulus, but the force on each leaflet is symmetric and opposite the force
on the opposing leaflet. This favors minimal systolic stress where coaptation occurs. The greatest stress on the leading edge of the leaflets and point of apposition occurs in diastole when the transvalvular gradient is typically only several millimeters of mercury. The surgical edge-to-edge repair in clinical series has not resulted in mitral stenosis.

The simplicity and proven efficacy of edge-to-edge repair make it attractive for an endovascular method of repairing either the structurally or functionally deficient mitral valve. The present study demonstrates that a mitral valve edge-to-edge repair can be successfully performed on the beating heart in an animal model without cardiopulmonary bypass using a catheter-based endovascular system. The clip was successfully deployed with successful approximation of the middle scallops of the anterior and posterior leaflets in the majority (12 of 14; 86%) of study animals. Retrospective analysis of the 2 cases in which the anterior leaflet was not well grasped revealed correctable deficiencies in technique, including improper clip arm opening and improper analysis of echocardiographic images. The porcine model provides a challenging model for demonstrating functionality of the endovascular CVRS for several reasons. The pig mitral valve leaflets are thinner than human leaflets, providing a potentially more rigorous test of the atraumatic features of the device and procedure. In addition, the porcine interatrial septum is a diminutive structure, and the pig’s left atrium provides limited space to manipulate the catheters, especially in comparison to the dilated left atrium associated with human MR. Through experience, it became evident that to perform a successful grasp in this model, the distal tip of the guide catheter needed to be located ≈2 cm above the plane of the annulus. The manipulations required to establish this height included crossing the septum at least 15 mm above the annular plane. It was also learned that to predictably grasp the leaflets, the clip arms should be open to at least 120°, and the center axis of the clip-delivery catheter needed to be positioned relatively perpendicular to the valve plane and in line with the long axis of the ventricle. Significant deviation in an anterior, posterior, medial, or lateral direction produced a suboptimal grasp. This deviation was appreciated with echocardiography and, given the design features of the catheter and the clip that allow for repositioning, easily corrected.

The present study is limited to the short-term evaluation of the endovascular edge-to-edge valve repair system. Long-term animal data are necessary to assess long-term device performance. Extended animal data (up to 12 months) are being analyzed. The clip system has also been evaluated in an animal model of MR for a design conformation and a better appreciation of its applicability and effectiveness. Although extrapolation to human pathology is difficult, it is possible that the clip system could have limited value in subsets of patients with extreme pathology including rheumatic disease, a ruptured papillary muscle, or extreme mitral annular dilatation.

This study introduces the first technology for endovascular edge-to-edge mitral valve repair. The safety and efficacy of the described system in humans experiencing MR remain to be proven; however, the success of placing the clip in a short-term animal model provides encouraging support for a human clinical trial. As a percutaneous intervention in the catheterization laboratory, the technique offers the opportunity for substantial reduction in the morbidity and trauma associated with mitral valve surgery. The technology could also provide a therapeutic alternative for patients with significant MR and advanced left ventricular dysfunction who would not survive the stress of a surgical intervention.

Acknowledgments
This study was supported by a grant from Evalve, Inc.

References
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Circulation. 2003;108:1990-1993; originally published online October 6, 2003;
doi: 10.1161/01.CIR.0000096052.78331.CA
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/108/16/1990

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